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Estimation of Longshore Sediment Transport Rate for a Typical Pocket Beach Along West Coast of India

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ABSTRACT

Estimation of Longshore Sediment Transport Rate (LSTR) in the littoral zone is essential for managing and developing any coastal zone. Numerical models are powerful tool to understand and investigate various processes responsible for LSTR in a systematic manner since direct measurement of LSTR is a difficult task. A one dimensional LITDRIFT model was implemented along the Vengurla coast for estimation of LSTR and to analyze the sensitivity of each input parameters towards the computation of LSTR. Major input parameters required for the estimation of LSTR are nearshore wave climate, bathymetry, and sediment characteristics. The nearshore wave data at a depth of 15 m were collected using wave rider buoy in 2015 is used in the present study. Field observations were carried out to survey the regional bathymetry and sediment characteristics. Annual net LSTR along Vengurala coast is relatively less and varies from −7778 to −9015 m^3 with an average of −8511 m^3. The net direction of LSTR is towards south and gross LSTR is 1.18×10^5 m^3/year. The LSTR reveals more sensitivity to coastline orientation and wave direction. A 1° changes in coastline angle and wave direction causes approximately 3000 m^3/month difference in LSTR. Moreover, wave height, wave period, and bed roughness has an important role for controlling LSTR. The model results help to identify the role of each parameter contributing towards LSTR estimation and a similar model approach can be applied to other coasts for estimating LSTR in an accurate way.

ARTICLE HISTORY

KEYWORDS
Longshore Sediment Transport Rate (LSTR); LITDRIFT; sensitivity analysis; wave climate

1. Introduction

Physical processes associated with sediment transport in and around the breaker zone are highly complex (Mafi et al. 2013). Varying nearshore topography, wave induced currents and highly irregular flows make this environment extremely dynamic. Waves breaking near the coast mobilize the sediment around the breaker zone and the currents generated by the waves transport the sediment along and across the coast (Bergillos et al. 2017a). A thorough knowledge of Longshore Sediment Transport Rate (LSTR) in the littoral zone is essential for implementing any structure on the coast (CEM 2006). Direct measurement of sediment transport in the surf zone is not an easy task, and hence LSTR has been estimated by various researchers using different approximations. The measured beach profiles at regular intervals were used for estimation of LSTR (Pilkey and Richter 1964; Wright and Short 1983; Troels et al. 2004). Empirical/bulk formulas (Komar and Inman 1970; Wang et al. 1975; CERC (USACE) 1984; Walton and Bruno 1989; Bayram et al. 2001; Kamphius 2002; Kumar et al. 2003; Bayram et al. 2007; Mil-Homens et al. 2013; Shanas and Kumar 2014; Chempalayil et al. 2014; Bergillos et al. 2016,

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2017b) and numerical models (Rao et al. 2009; Noujas et al. 2014, 2016; Prasad et al. 2016; Pradhan et al. 2017; Bergillos et al. 2017b) are the methods adopted for the estimation of LSTR.

Several studies have been conducted along the Indian coast for estimation of LSTR (Reddy 1976; Prasannakumar 1985; Veerayya and Pankajakshan 1988; Chandramohan and Nayak 1992; Hanamgond 1993; Chandramohan et al. 1993; Chandramohan et al. 1994; Jayappa 1996; Sajeev et al. 1997). These studies revealed that the LSTR is variable, bi-directional, and season dependent. However, quantitative determination of LSTR along the west coast has been made only at a few localities (Sajeev et al. 1997; Kumar et al. 2003; Kurian et al. 2009; Chempalayil et al. 2014; Shanas and Kumar 2014; Noujas et al. 2014, 2016). Kunte and Wagle (2001) have compiled the studies of littoral sediment transport along west coast of India, during the last three decades (1970 – 2000). Kumar et al. (2003) measured the Longshore Sediment Transport Rate (LSTR) across the surf zone of central west coast of India using sediment traps. Measured LSTR was compared with the values calculated based on three routinely used empirical formulas such as CERC, Walton & Bruno and Van Rijin formulae. Wave refraction pattern and their role in sediment redistribution along the South Maharashtra coast is studied by Anup et al. (2008). Numerical models and field observations were used to study the littoral sediment transport along Ennore on the southeast coast of India (Rao et al. 2009). Shanas and Kumar (2014) employed the well- known four empirical formulae for estimating the LSTR. Additionally, they studied the variation in LSTR considering different data intervals and concluded/found that for accurate estimates of LSTR, the data interval should be 3 h or less.

However, none of the studies assured the best suitable empirical formulae applicable for all coastal segments. Different empirical formulae for estimation of LSTR (Sajeev et al. 1997; Kumar et al. 2003; Chempalayil et al. 2014; Shanas and Kumar, 2014) has been suggested. The empirical formulae are often used for LSTR estimation due to non availability of extensive field data (Shanas and Kumar 2014). Major draw backs of the empirical formulae like CERC is that there is no dependence of wave period, beach slope, breaker type and grain-sizes (Smith 2006). Kumar et al. (2003) compared the LSTR values based on Walton & Bruno with measured values and they found that the average measured LSTR was 0.65 times the value calculated using Walton & Bruno equation and suggested that Van Rijin formulae is most suitable for calculating LSTR along the central west coast of India. On the other hand, Chempalayil et al. (2014) and Shanas and Kumar (2014) reported Kamphuis formulae was acceptable for estimating the LSTR along the central west coast of India.

The present study is an attempt to compute LSTR using a third generation numerical model at Vengurla coast, central west coast of India (Figure 1). The model allows consideration of all the dominant factors such as wave height, wave direction, wave period, bathymetry, and sediment characteristics which are responsible for Longshore Sediment Transport. Numerical modeling was also carried out to evaluate the sensitivity of various input parameters towards LSTR estimation.

2. Region settings

Vengurla is a typical pocket beach in south Maharashtra, west coast of India and features a tropical monsoon climate. The study region is about 5 Km length pocket beach between two headlands (Figure 1). Sand dunes are present throughout the backshore of the study region. There is a seawall of about 0.8 Km length along the southern sector and a paved path about 0.4 Km in the northern part. Field photographs are depicted in Figure 2 for better understanding of the study region. In the study area, the highest (~2 m) seasonal average significant wave height (H_s) is during the monsoon period (June –September), and the annual average H_s is ~ 1 m (Amrutha et al. 2015). The tidal range at Vengurla is 2.3 m during the spring tide and 1.3 m during the neap tide, and the tides are predominantly mixed semi-diurnal. The predominant wave directions north of the study region are SW, WSW, W, and WNW. The southwesterly waves move the sediment northwards, whereas the WNW waves transport the sediment southwards (Anup et al. 2008). However, negligible annual net sediment transport was observed in the vicinity of Vengurla based on Shore Protection Manual equation (Chandramohan and Nayak 1992).

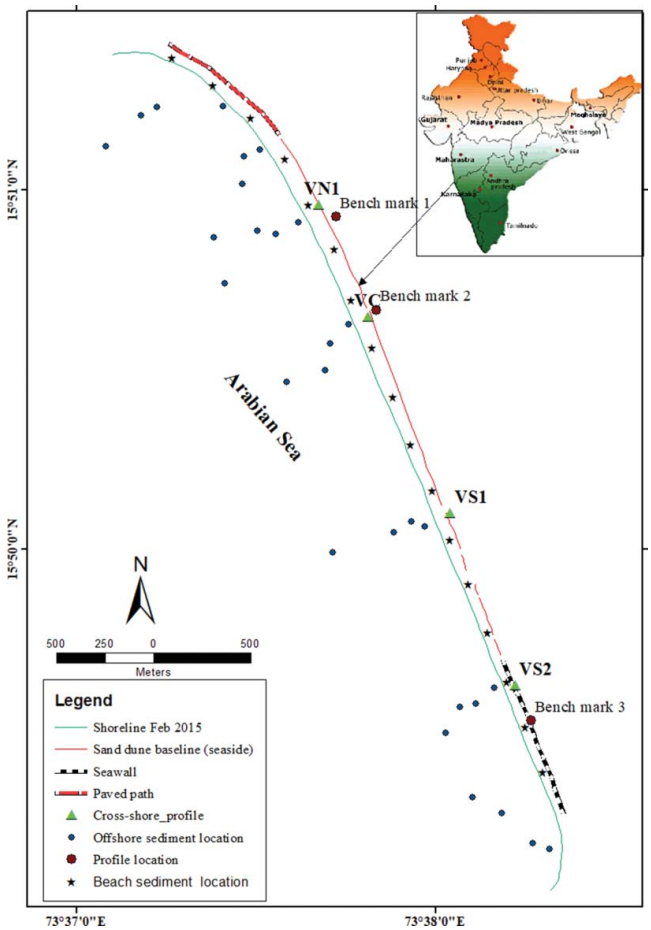

Figure 1. Study region and sediment sampling location at Vengurla (South Maharashtara coast).

Figure 2. Field Photographs; a) Northern sector, b) Paved path, c) Central sector, d) Sand dune in northern sector, e) Sand dune in southern sector and f) Seawall in southern sector.

3. Data and methodology

Systematic field survey was conducted during 2015 to collect waves, bathymetry and sediments for estimation of LSTR along Vengurla coast.

3.1. Data collection

In this study, LSTR was estimated using 0.5 Hr interval wave data collected for one complete year. Waves were measured using the Datawell directional waverider buoy at a depth of 15 m (15.83265° N, 73.5681° E) from January to December 2015. Data were recorded continuously at 1.28 Hz, and data for every 30 minutes were processed as one record.

Bathymetric survey was carried out using CEESCOPE echo-sounder for nearshore in a closed interval of 250 m during February 2015. The survey was carried out along transects normal to the shore extending up to 12 m depth. For getting accurate bathymetry while interpolating, alongshore transects were also collected at depths of 1.5, 3, 5, 6, and 9 m. The echo-sounder was integrated with Global Positioning System (GPS) for accurate positions. Shoreline data was also collected during low tide period and, beach profiles were measured in the shore-normal direction from the vegetative line to the lowest low water mark during spring tide period when a maximum stretch of the beach was exposed. For this, a Leica SR 500 Real Time Kinematic Global Positioning system (RTK GPS) with position accuracy of ± 1 cm and elevation accuracy of ± 2 cm was used.

Sediment data was collected along 7 transects from beach backshore to 8 m depth. The nearshore depths are 1.5 m, 3 m, 5 m, and 8 m (Figure 1). The collected Sediments were analyzed for texture and subjected to statistical analysis using GRADISTAT (Blott and Pye 2001) following logarithmic (original) Folk and Ward (1957) graphical measures.

3.2. Model description

Sediment transport along the study area has been computed using LITDRIFT model of LITPACK software developed by Danish Hydraulic Institute (DHI 2014). It provides a detailed deterministic description of the cross-shore distribution of longshore sediment transport and calculates the net/gross littoral transport for a section of coastline over a specific design period. LITDRFIT consists mainly of two computation steps: longshore current calculation (hydrodynamic model) and sediment transport computation (sediment transport model, STP). The cross-shore distribution of longshore current, wave height and setup for an arbitrary coastal profile, is found by solving the long and cross-shore momentum balance equations. The hydrodynamic model includes a description for regular and irregular waves, influence of tidal current, wind stress and non-uniform bottom friction as well as wave refraction, shoaling and breaking.

The sediment transport model, STP forms the basic sediment transport description from combined wave and current action. In combined waves and current the turbulent interaction in the near bed boundary layer is of importance for the bed shear stresses as well as for the eddy viscosity distribution. The basis for the sediment transport description is the model for turbulent wave-current boundary layers of Fredsøe (1984). Total sediment load is split into bed load and suspended load, which are calculated separately. Transport of non-cohesive material as bed load is calculated according to the model presented by Engelund and Fredsøe (1976). The vertical variation of suspended sediment concentration is calculated from vertical diffusion equation for suspended sediment (Fredsøe et al. 1985). Total sediment transport is dominated by transport contributions from areas where wave breaking occurs. The point selection procedure therefore gives preference to points in this area. This gives the distribution of sediment transport across the cross-shore profile, which is integrated to obtain the total longshore sediment transport rate. The grid spacing of cross-shore profile was taken as 5 m and Sediment transport computed for each grid points across cross-shore profile by STP model.

Bathymetric data, shoreline, and beach profiles were combined together and interpolated using MIKE 21 Mesh Generator for obtaining the continuous bathymetry and land elevation of the study

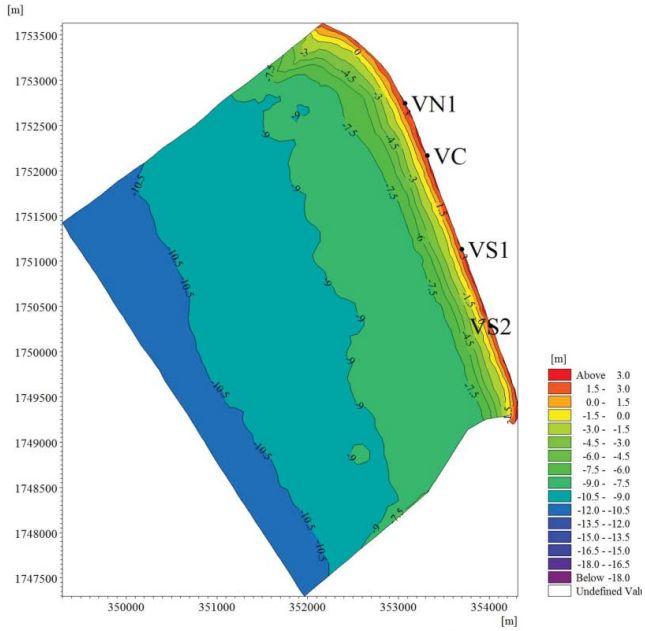

Figure 3. Bathymetry and cross-shore profile location along Vengurla.

area (Figure 3). Geographical co-ordinates are projected into Universal Transverse Mercator (UTM) co-ordinates during interpolation.

3.3. Model setup

The major inputs for LITDRIFT model are bathymetry, nearshore wave climate and sediment characteristics. The bathymetry is given as cross-shore profiles. Cross-shore profile starts from offshore, where water depth is chosen for modelling and extends up to two or three grid points in to the beach. The cross-shore profiles were generated from four locations for estimation of LSTR (Figures 3 and 4). The grid spacing of cross-shore profile was taken as 5 m for accurate representation of bathymetry.

Chempalayil et al. (2014) reported that the offshore wave angle and offshore wave height has more influence on the LSTR estimation during monsoon than the post monsoon season and hence, wave data collected during June was used for sensitivity analysis (Figure 5). Majority of waves are coming from WSW & W during June and westerly waves show higher magnitude in the significant wave height (H_s). Wave data collected during 2015 at the same location was used for annual LSTR estimation (Figure 6).

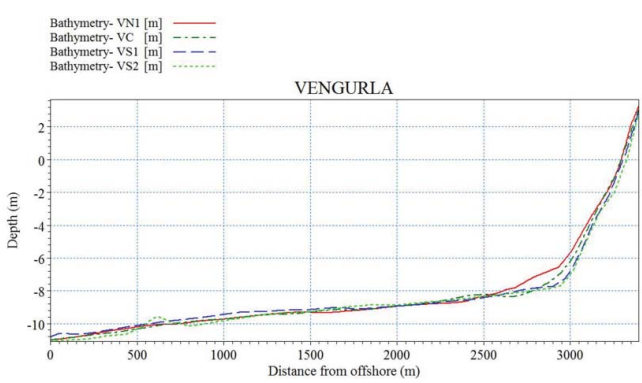

Figure 4. Cross-shore profiles used for modeling.

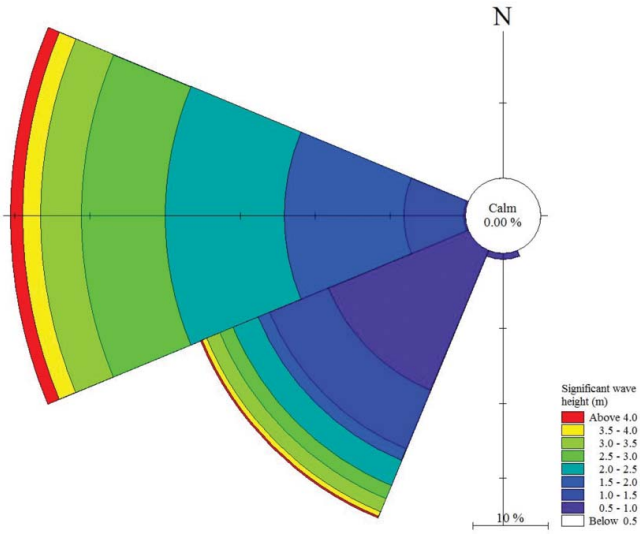

Figure 5. Wave rose diagram during the month of June.

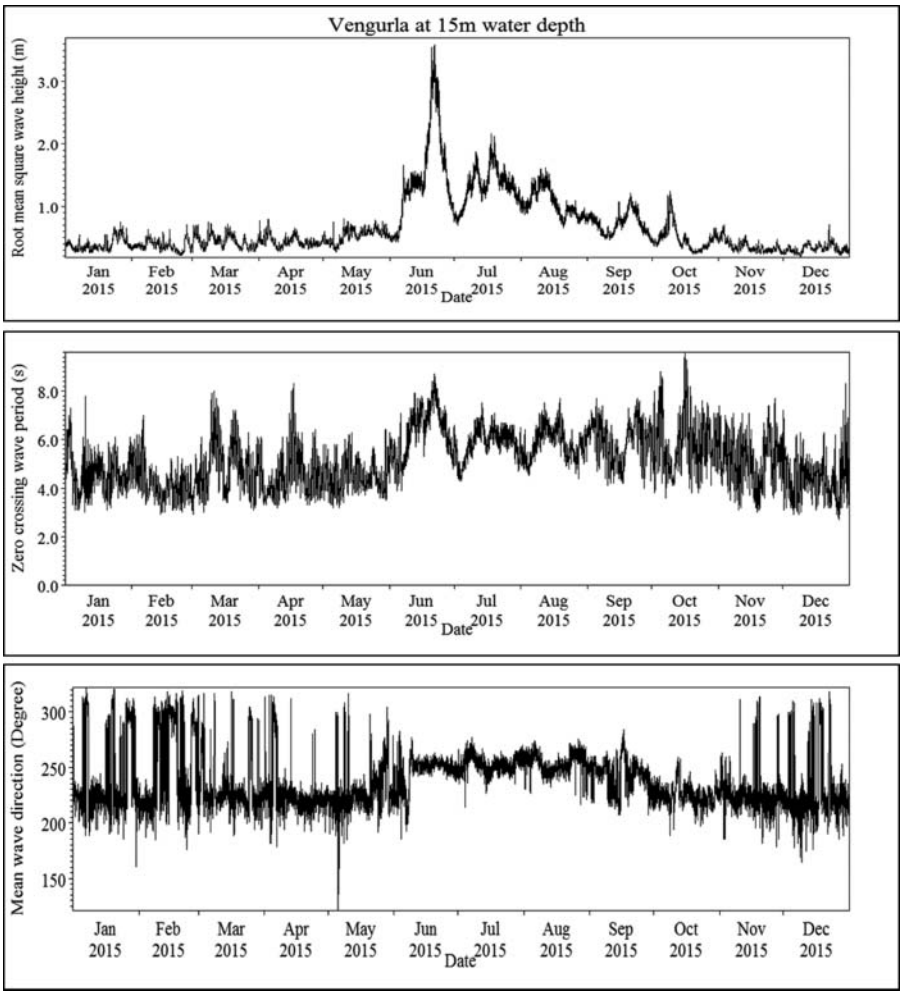

Figure 6. Wave climate off Vengurla during the year 2015.

Table 1. Sediment characteristics used for LSTR modeling.

Parameter	Sensitive Analysis	Annual drift
Grain diameter	0.2 mm	0.06 to 0.52 mm
Bed roughness	0.004 m	0.0013 to 0.01 m
Fall Velocity	0.0386 m/s	0.0041 to 0.261 m/s
Geometrical spreading	1.5	1.5

Sediment characteristics like grain diameter (d_{50}), bed roughness, fall velocity, and geometrical spreading (SQRT (d_{84}/d_{16})) were given along with cross-shore profiles. Constant sediment characteristics have been used for sensitive analysis and measured sediment characteristics have been used for annual LSTR estimation (Table 1). The measured sediment characteristics (d_{50}) from beach and offshore were given across the respective depth of cross-shore profile position (grid) and synthesized for remaining cross-shore profile grids.

The most important factor in the calibration of model is the accuracy of the input data. As mentioned earlier for this particular study 0.5 Hr interval one year wave data, fine resolution bathymetric data and sediment data which collected across 7 transects were used. The bed roughness is the basic calibration parameter in LITDRIFT.

4. Results

4.1. Wave characteristics at 15 m depth off Vengurla (offshore)

The wave data collected from January to December, 2015 were used for LSTR estimation. The root mean square wave height (H_{rms}) occurred between 0.18 to 3.59 m in 2015. H_{rms} is calculated from H_s (H_{rms} = 0.71× H_s). During January-May, H_{rms} is less than 1 m and starts to increase with the onset of monsoon (Figure 6). Maximum H_{rms} about 3.6 m was observed on 21st June and the second highest peak was reported during mid July (2.2 m). H_{rms} starts to diminish from second week of October and it is less than 1 m during rest of the year. The zero crossing wave period (T_z) is in the range 2.7 to 9.6 s and mean value of 5.2 s. Mean wave direction shows large fluctuation during January to May and during monsoon (June – September) it ranged from 185°–284° with a mean value of 249° (Figure 6).

4.2. Nearshore wave characteristics

Wave climate at 15 m depth was transferred to nearshore using *Transfer Wave Climate* option available in LITPACK model for better understanding of transformation process. The cross-shore profile at central Vengurla (VC in Figure 4) has been used as bathymetry for this purpose. Wave characteristics at 7 m depth show no much variation when compared to 15 m water depth (Figure 7). H_{rms} is in the range of 0.5 to 3.4 m at depth of 7 m and maximum H_{rms} is only 1.27 m at a depth of 2 m. Due to depth induced breaking criteria (H/D = 0.8 where 'H' is wave height & 'D' is water depth), majority of waves during the monsoon months undergo breaking at depth of 2 m while some waves break at 5 m depth during June (Figure 7).

Waves undergoes refraction when approaching the coast and tries to align with coastline orientation. The coastline normal along central Vengurla coast is 248° N and hence wave direction is more than 248° is decreasing and less than 248° is increasing due to refraction and it is more prominent at depth of 2 m during first fortnight of the month of August (Figure 8).

4.3. Nearshore sediment characteristics

Nearshore sediment data were collected across the 7 transects of Vengurla as described earlier (Figure 1). Sediment close to the shore is mainly composed of sand particles. The grain size is observed

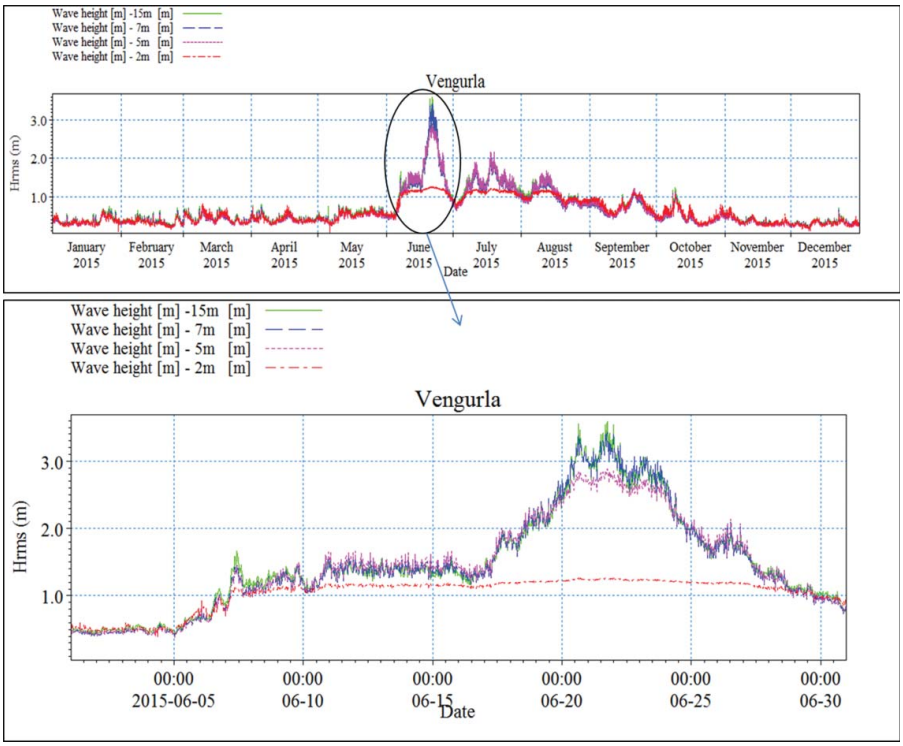

Figure 7. Wave height variation in nearshore of Vengurla during the month of June.

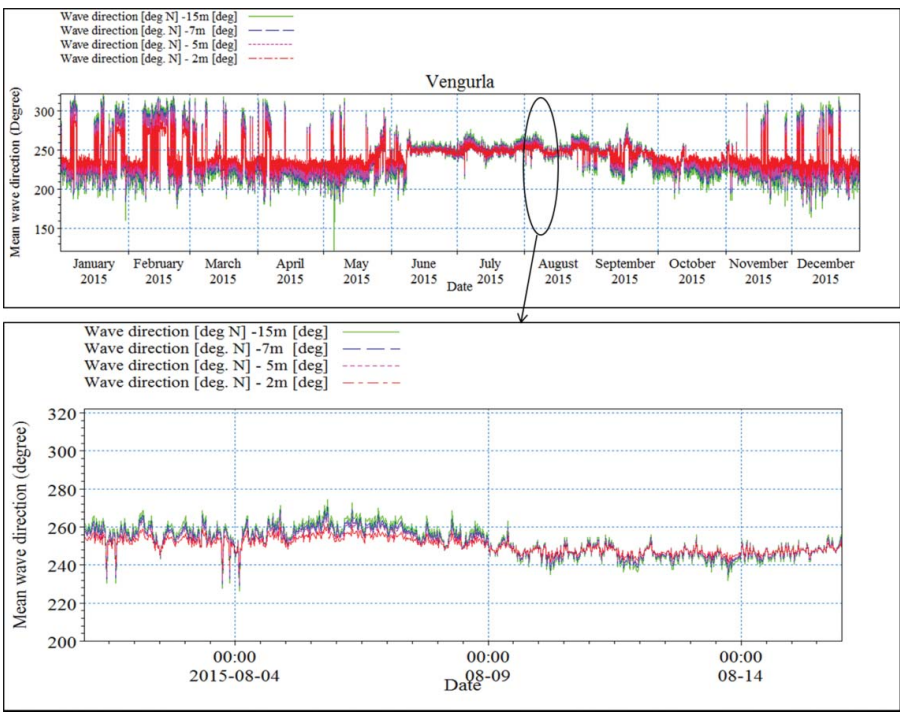

Figure 8. Wave refraction during first fortnight of August, Vengurla.

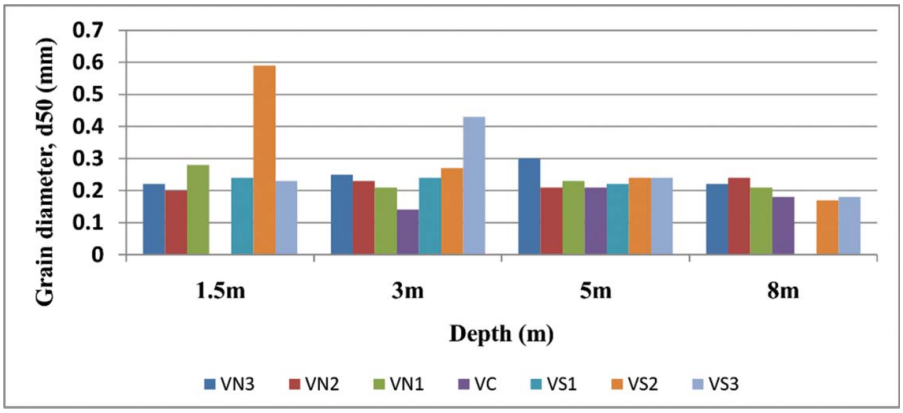

Figure 9. Nearshore sediment grain size distribution at Vengurala during Feb, 2015.

to decrease towards the offshore region (Figure 9). The southern sector has comparatively higher grain size than the northern sector.

4.4. Annual longshore sediment transport rate

As mentioned earlier, wave climate off Vengurla during the year 2015 was used for annual LSTR estimation. LSTR estimated in four locations using above mentioned wave climate, cross-shore profiles and measured nearshore sediment characteristics. The annual net LSTR varies from −7778 to −9015 m^3 with an average of −8511 m^3 (Table 2). The average gross sediment transport is 1.18×10^5 m^3. The bed roughness is tuned and realistic LSTR obtained when bed roughness is twenty times of grain diameter is given as the roughness ($20 \times d_{50}$). Monthly variation of LSTR is shown in Figure 10. The LSTR is towards north, except during February and June-August. The maximum LSTR is observed in June and the direction is towards south. The LSTR during the month of February is negligible. The southerly LSTR is higher compared to northerly LSTR.

4.5. Sensitivity analysis

Coastline angle, nearshore wave climate and sediment characteristics are the major factors responsible for the LSTR. Sensitive analysis was carried out in detail using measured wave data of June. This was done by changing one parameter at a time and model run is performed by giving other parameters as constant.

The contribution of wave height (H_{rms}), wave period (T_z), mean wave direction, grain diameter, bed roughness and fall velocity for sediment transport examined by 10% increase of each parameter and model run was carried out without changing any other parameters. Total 11 run was performed for each parameter including the initial run. The net sediment transport shows an increasing trend, corresponding to the increase of wave height (Figure 11). The net drift for initial conditions of model is 12581 m^3/month and is up to five times higher, when the wave height is increased hundred percent from the initial value and the other parameters are kept

Table 2. Spatial variation of annual LSTR along Vengurla.

Location	Net (m^3/yr)	Gross (m^3/yr)
VN1	−8758	1.16×10^5
VC	−8493	1.2×10^5
VS1	−7778	1.2×10^5
VS2	−9015	1.15×10^5
Average	−8511	1.18×10^5

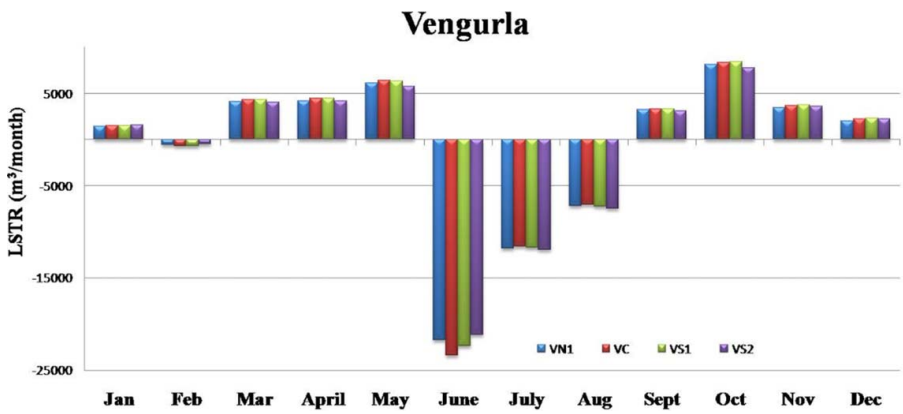

Figure 10. Spatial variation of monthly LSTR along Vengurla coast.

constant (Table 3). Similarly, net sediment transport increases with increase of wave period, but, comparatively low value is observed with wave height response (Figure 11). Net drift doubled for hundred percent increase of wave period (Table 3).

The actual coastline angle of Vengurla is 248° N with respect to true north and the mean wave direction is of 244° N. Hence the wave inclination angle is 4° with respect to coastline angle and model run performed by increasing 10% of inclined wave angle in each run. The response of inclined wave angle is much lower compared to wave height and more or less equal to with wave period (Figure 11). Inclined wave angle is very less with coastline and hence, a ten percent increase corresponds to 0.4° increase of wave angle change in each run. This may be the reason for less variation of LSTR for increasing wave angle (Table 3). Net LSTR falls up to twenty percent with increase in grain diameter and shows a marginal increase for further increase in grain diameter (Figure 11).

In general, an increase in the median grain size will decrease LST rates in the surf zone. However, Coastal and Hydraulic Engineering Technical Note (CHETN) argues this is clearly a simplistic view of surf zone sediment dynamics (David 2005). CHETN discusses the details of bed-load and suspended load transport, and classical bed-load regime is shown to encompass two distinct modes of transport. Four LST models with varying levels of complexity were discussed to show how they incorporate the physics of grain size variation and its effect on the transport rate. A more realistic (though still highly simplified) approach would be that, for fine grain sediments, suspended load transport should

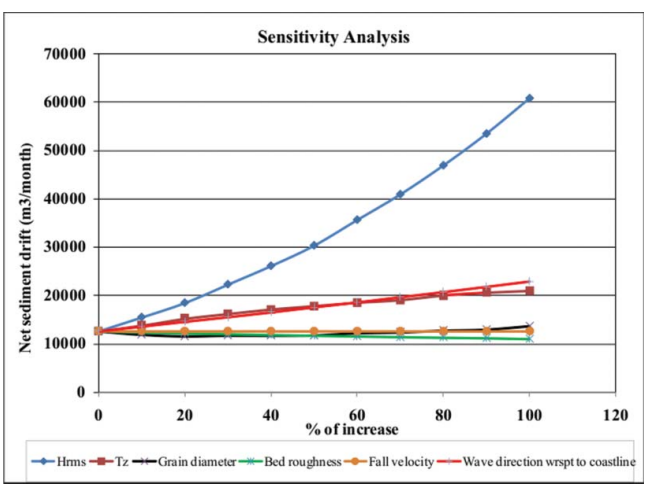

Figure 11. Sensitivity analysis results of longshore sediment transport.

Table 3. Sediment transport response for various input parameters.

% of increase	Net drift for increasing H_{rms} (m^3/month)	Net drift for increasing T_z (m^3/month)	Net drift for increasing wave direction (m^3/month)	Net drift for increasing d_{50} (m^3/month)	Net drift for increasing bed roughness (m^3 /month)	Net drift for increasing fall velocity (m^3/month
0	12581	12581	12581	12581	12581	12581
10	15453	13743	13567	11867	12360	12581
20	18431	15173	14568	11542	12162	12581
30	22250	16173	15514	11690	11984	12581
40	26083	17121	16508	11665	11819	12581
50	30303	17819	17554	11729	11670	12581
60	35617	18540	18579	12198	11532	12581
70	40898	19079	19649	12362	11380	12581
80	46894	20036	20698	12723	11261	12581
90	53464	20621	21790	12930	11150	12581
100	60794	20988	22899	13655	10984	12581
Initial conditions	Coastline angle = 248°N, H_{rms} = 1.36 m, Tz = 6.3 s, mean wave direction = 244°N, d_{50} = 0.2 mm, Bed roughness = 0.004 m, Fall velocity = 0.0386 m/s Wave angle with respect to coastline = 4°					

dominate and, transport rate depends on grain diameter. For coarse sands, sheet flow bed-load transport should dominate, and the transport rate should be nearly independent of grain size. The net sediment transport decreases corresponding to the increase of bed roughness. There is no change of net sediment transport for increasing fall velocity. The details of computations are given in Table 3.

From the sensitivity analysis, it is clear that the wave height, wave direction and wave period are more sensitive towards LSTR estimation and, in corroboration with earlier studies (Chempalayil et al. 2014; Shanas and Kumar 2014). Comparatively, grain diameter and bed roughness contributed less towards sediment transport. The change in fall velocity up to hundred percent increase did not make any change in LSTR.

The effect of coastline angle for sediment transport was examined by giving averaged nearshore wave climate for 30 days and constant sediment characteristics. Initially, model run was performed using actual coastline angle i.e. 248° with respect to North. The cross-shore profile (VC in Figure 4) was used for the modeling. The estimation of change in LSTR for different coastline angles is depicts in Figure 12a. The original coastline angle is marked as zero and coastline angle is increased to one degree at each time step and the model run was performed up to 10° coastline angles. When coastline angle was changed by 1°, approximately 2872 m^3/month of change in LSTR occurred.

Similarly, model run was performed by increasing the wave direction by one degree in each run and initial run was performed on the original wave direction (244° N). The wave direction increased up to 10° change and the net drift corresponding to wave direction is given below (Figure 12b). The original wave direction is taken as zero in the graphical representation (Figure 12b). When wave direction

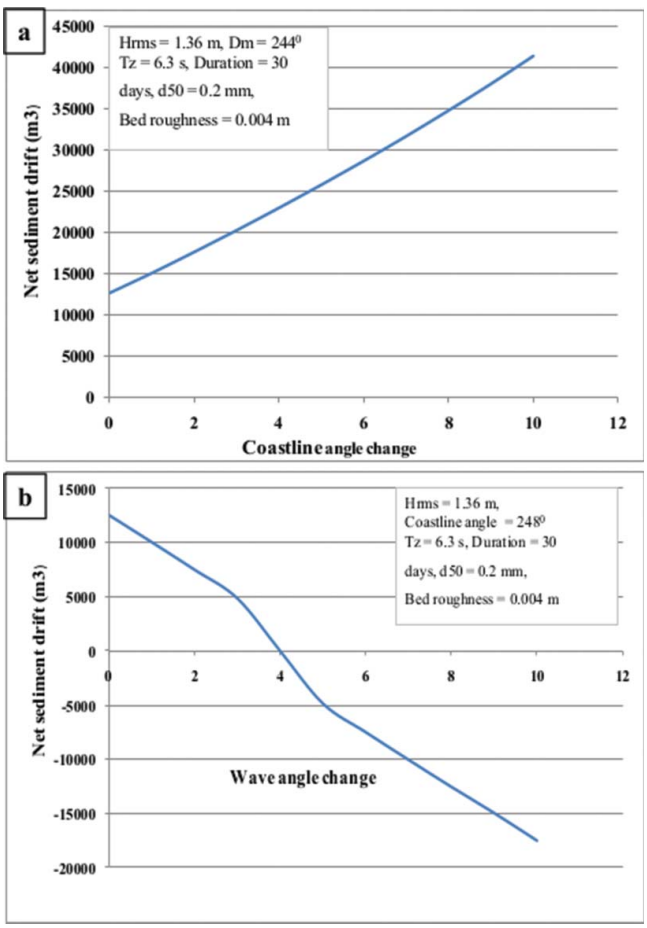

Figure 12. Response of LSTR a) coastline angle change, b) wave angle change.

Table 4. Comparison of LSTR from present study and literature.

Month	Net LSTR at VC (From LITDRIFT model; m^3/month)	Net LSTR (Chandramohan et al. 1993; m^3/month)
January	1514	−296
February	−756	−2595
March	4321	6837
April	4459	−929
May	6430	−7551
June	−23377	−63054
July	−11563	−12165
August	−7087	3739
September	3311	15612
October	8362	2112
November	3677	2442
December	2215	2808

*In LITDRIFT sediment transport estimated in every 30 minutes interval.

exactly matches the coastline angle, it was observed that there is no alongshore sediment transport and in such case, wave is perpendicular to the coastline. Moreover, by this time only cross-shore transport exists and there is no longshore transport. When wave angle is changed by 1°, approximately 3014 m^3/month variation in LSTR occurs.

Sensitivity analysis of LSTR estimate made by Chempalayil et al. (2014) shows that coastal inclination is the prominent factor in determining LSTR than incident wave angle. In this study it is distinctly observed that both the wave angle and coastal inclination are equally important for LSTR estimation.

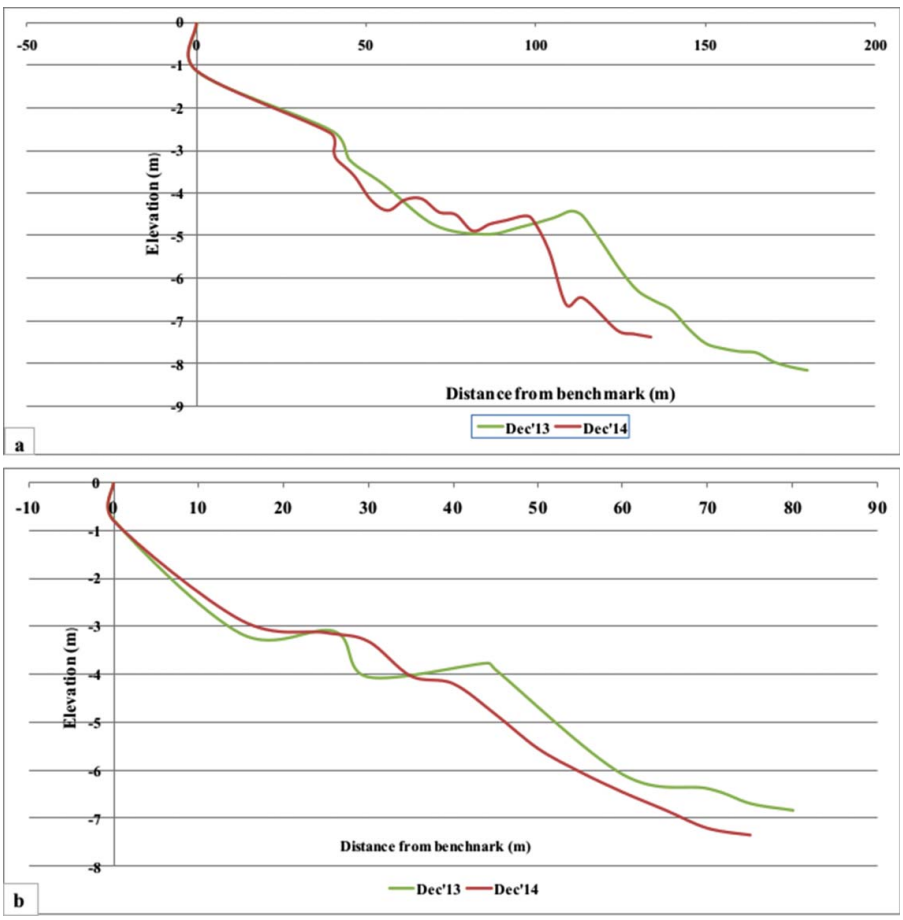

Figure 13. Beach profile comparison at Vengurla a) Central b) South.

Table 5. Annual Sediment transport computed from beach profiles and LITDRIFT model.

Location	Lat.	Long.	Volume change (m^3/m)	Remarks
BM2	15.8444	73.6306	−61.62	Close to 'VC'
Longshore distance of Central sector (VC to VS1) = 980 m				
Net sediment transport lost from Central sector (beach profile) = −61.62 × 980 = −60388 m^3/yr				
Net sediment transport in Central sector (LITDRIFT) = VC + VS1 = −16271 m^3/yr				
BM3	15.8253	73.6378	−16.85	Close to 'VS2'
Longshore distance of Southern sector (VS1 to VS2) = 970 m				
Net sediment transport in the Southern sector (beach profiles) = −16.85 × 970 = −16345 m^3/yr				
Net sediment transport in Southern sector (LITDRIFT) = VS1 + VS2 = −16271 m^3/yr				

5. Discussion

The present modeling result in gross sediment transport rate is in close agreement to that reported by Chandramohan et al. (1993). However, the net sediment transport of −8511 m^3 obtained in the present model study is comparatively lesser. Chandramohan et al. (1993) using measured daily longshore currents and LEO (Littoral Environmental Observation) reported that LSTR at south of Vengurla (Uba Danda beach) is −53040 m^3/year and direction is towards south. They have used Walton equation for computation of sediment transport and gross sediment transport is 1.2×10^5 m^3/year. In their study, sediment transport in June is about −63000 m^3 and from model result is it is about −24000 m^3 (Figure 10) and more or less comparable results was obtained in other months (Table 4). The direction is opposite during the months of January, April-May and August. They have used daily average visually observed wave data while this study used 0.5 Hr interval measured wave data for better and more accurate estimates of LSTR, the wave data interval should be 3 h or less (Shanas and Kumar 2014). Moreover, the present study used fine resolution bathymetry and sediment characteristics for various depths for getting accurate LSTR. Chandramohan et al. (1993) used visual observed wave parameters during 1989–1990, Whereas the this present study used measured wave data for the year 2015. The study conducted by Chandramohan and Nayak (1992) also reported that south Maharashtra coast has negligible annual net LSTR.

The model results were also compared with the sediment transport rate calculated from beach profiles in 2014. Unfortunately there is no one year beach profile data available in 2015 and hence, the profile data of 2014 were used for comparison. There is no much variation of wave climate for the year 2014 & 2015 (ICMAM 2017) and hence expected similar sediment transport rate from profiles in both years. Beach profile data during December 2013 and December 2014 were taken for computing sediment transport from beach profiles. Beach volume was computed and it is multiplied with longshore distance between profiles for getting sediment transport rate in that sector. Beach profiles showed erosion in central and southern sector of Vengurla (Figure 13a and b). The beach profile location 'bench mark 2 (BM2)' is close to 'VC' (central sector) of LITDRFIT sediment computation location while the beach profile location "bench mark 3 (BM3)' is close to 'VS2' (southern sector) of LITDRFIT sediment computation location. Net volume of sediment lost from Southern sector of Vengurla coast from model result and beach profiles were in close agreement (Table 5).

6. Conclusion

Longshore Sediment Transport Rate (LSTR) is estimated along the Vengurla coast using LITDRIFT model. LSTR is estimated at four locations using numerical model by giving measured wave climate of 30 minutes interval, fine resolution bathymetry and nearshore sediment characteristics as input. The annual net LSTR along Vengurala coast varies from −7778 to −9015 m^3 with an average of −8511 m^3. The net direction of LSTR is towards south and the gross LSTR is 1.18×10^5 m^3/year. The model result is comparable with available literature in the vicinity of the study region. Sensitivity analysis was carried out with coastline angle, wave parameter and sediment characteristics for understanding the role of each parameter in sediment transport. Coastline angle and wave direction are more sensitive to LSTR estimation. A 1° change in coastline angle and wave direction causes approximately 3000 m^3/month changes in LSTR. Moreover, wave height, wave period and bed roughness has an important role for controlling longshore sediment transport. The net LSTR is observed to be five times higher

than the original rate corresponding to hundred percent increase in wave height, and it is two times higher for hundred percent increment in wave period. Net LSTR decreases corresponding to increase in bed roughness. The model results are dependable for any coastal development activities of this coast and also be used for shoreline evolution modeling along this sector.

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References

Amrutha, M. M., V. S. Kumar, S. Sharma, J. Singh, R. Gowthaman, and R. S. Kankara. 2015. Characteristics of shallow water waves off the central west coast of India before, during and after the onset of the Indian summer monsoon. *Ocean Engineering* 107:259–70. doi:10.1016/j.oceaneng.2015.07.061.

Anup, R. G., N. Angusamy, and G. V. Rajamanickam. 2008. Wave refraction patterns and their role in sediment redistribution along South Konkan, Maharashtra, India. *GeoActa* 7:69–79.

Bayram, A., M. Larson, and H. Hanson. 2007. A new formula for the total longshore sediment transport rate. *Coastal Engineering* 54:700–10. doi:10.1016/j.coastaleng.2007.04.001.

Bayram, A., M. Larson, H. C. Miller, and N. C. Kraus. 2001. Cross-shore distribution of longshore sediment transport: Comparison between predictive formulas and field measurements. *Coastal Engineering* 44:79–99. doi:10.1016/S0378-3839(01)00023-0.

Bergillos, R. J., A. López-Ruiz, M. Ortega-Sánchez, G. Masselink, and M. A. Losada. 2016. Implications of delta retreat on wave propagation and longshore sediment transport – Guadalfeo case study (southern Spain). *Marine Geology* 382:1–16. doi:10.1016/j.margeo.2016.09.011.

Bergillos, R. J., G. Masselink, and M. Ortega-Sánchez. 2017a. Coupling cross-shore and longshore sediment transport tomodel storm response along a mixed sand-gravel coast under varying wave directions. *Coastal Engineering* 129:93–104. doi:10.1016/j.coastaleng.2017.09.009.

Bergillos, R. J., C. Rodríguez-Delgado, and M. Ortega-Sánchez. 2017b. Advances in management tools for modelling artificial nourishments in mixed beaches. *Journal of Marine Systems* 172:1–13. doi:10.1016/j.jmarsys.2017.02.009.

Blott, S. J., and K. Pye. 2001. GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26(11):1237–48. doi:10.1002/esp.261.

CEM (Coastal Engineering Manual). 2006. Washington, D.C: U.S Army Coastal Engineering Research Centre. (6 volumes).

Chandramohan, P., and B. U. Nayak. 1992. Longshore sediment transport model for the Indian west coast. *Journal of Coastal Research* 8(4):775–87.

Chandramohan, P., V. S. Kumar, B. U. Nayak, and K. C. Pathak. 1993. Variation of longshore current and sediment transport along the south Maharashtra coast, west coast of India. *Indian Journal of Geo-Marine Sciences* 22:115–18.

Chandramohan, P., V. S. Kumar, B. U. Nayak, and N. S. N. Raju. 1994. Surf zone dynamics along the coast between Bhatkal and Ullal, West Coast of India. *Indian Journal of Geo-Marine Sciences* 23:189–94.

Chempalayil, S. P., V. S. Kumar, G. U. Dora, and G. Johnson. 2014. Near shore waves, long-shore currents and sediment transport along micro-tidal beaches, central west coast of India. *International Journal of Sediment Research* 29:402–13. doi:10.1016/S1001-6279(14)60054-8.

Danish Hydraulic Institute (DHI). 2014. *User manual and reference guide for LITPACK and MIKE 21*. Horsholm, Denmark.

King, D. B., Jr. 2005. *Influence of grain size on sediment transport rates with emphasis on the total longshore rate*. Vicksburg, MS: Coastal and Hydraulics Engineering Technical Note, ERDC/CHL CHETN-II-48, U.S. Army Engineer Research and Development Center.

Engelund, F., and J. Fredsøe. 1976. A sediment transport model for straight alluvial channels. *Nordic Hydrology* 7:296–306.

Fredsøe, J. 1984. The turbulent boundary layer in combined wave current motion. *Journal of Hydraulic Engineering* 110 (HY8):1103–20. doi:10.1061/(ASCE)0733-9429(1984)110:8(1103).

Fredsøe, J., O. H. Andersen, and S. Silberg. 1985. Distribution of suspended sediment in large waves. *Journal of Waterway, Port, Coastal and Ocean Engineering* III(6):1041–59. doi:10.1061/(ASCE)0733-950X(1985)111:6(1041).

Folk, R. L., and W. C. Ward. 1957. Brazos river bar-a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27:3–26. doi:10.1306/74D70646-2B21-11D7-8648000102C1865D.

Hanamgond, P. T. 1993. *Morphological and sedimentological studies within Kavada Bay and Belekeri Bay beaches, Uttara Kannada district, Karnataka, West coast, India*. Unpublished Ph.D. thesis, 265, Dharward, India: Karnataka University.

ICMAM PD. 2017. Coastal circulation for sediment transport and shoreline change studies along south Maharashtra coast. Project Report. Chennai, India, 136 p.

Jayappa, K. S. 1996. Longshore sediment transport along the Mangalore Coast, West coast of India. *Indian Journal of Geo-Marine Sciences* 25:157–59.

Kamphius, J. W. 2002. *Along-shore transport of sand. Proceedings of the 28th International Conference on Coastal Engineering*. ASCE. pp. 2478–90.

Komar, P. D., and D. L. Inman. 1970. Longshore sand transport on beaches. *Journal of Geophysical Research* 75:5914–27. doi:10.1029/JC075i030p05914.

Kumar, V. S., N. M. Anand, P. Chandramohan, and G. N. Naik. 2003. Longshore sediment transport rate—measurement and estimation, central west coast of India. *Coastal Engineering* 48:95–109. doi:10.1016/S0378-3839(02)00172-2.

Kunte, P. D., and B. G. Wagle. 2001. Littoral transport studies along west coast of India- A review. *Indian Journal of Geo-Marine Sciences* 30:57–64.

Kurian, N. P., K. Rajith, L. Sheela Nair, T. S. Shahul Hameed, M. V. RamanaMurty, S. Arjun, and V. R. Shamji. 2009. Wind waves and sediment transport regime off the south-central Kerala coast, India. *Natural Hazards* 49:325–45. doi:10.1007/s11069-008-9318-3.

Mafi, S., A. Yeganeh-Bakhtiary, and M. H. Kazeminezhad. 2013. Prediction formula for longshore sediment transport rate with M5′ algorithm. Proceedings 12th International Coastal Symposium (Plymouth, England). *Journal of Coastal Research* Special Issue No. 65:2149–54. doi:10.2112/SI65-363.1.

Mil-Homens, J., R. Ranasinghe, J. V. T. de Vries, and M. J. F. Stive. 2013. Re-evaluation and improvement of three commonly used bulk longshore sediment transport formulas. *Coastal Engineering* 75:29–39. doi:10.1016/j.coastaleng.2013.01.004.

Noujas, V., K. V. Thomas, and K. O. Badarees. 2016. Shoreline management plan for a mudbank dominated coast. *Ocean Engineering* 112:47–65. doi:10.1016/j.oceaneng.2015.12.006.

Noujas, V., K. V. Thomas, L. Sheela Nair, T. S. Shahul Hameed, K. O. Badarees, and N. R. Ajeesh. 2014. Management of shoreline morphological changes consequent to breakwater construction. *Indian Journal of Geo-Marine Sciences* 43(1):54–61.

Pilkey, O. H., and D. M. Richter. 1964. Beach profiles of a Georgia barrier island. *Southeastern Geology* 6:11–19.

Prasad, R., L. S. Nair, N. P. Kurian, and T. N. Prkash. 2016. Erosion and heavy mineral depletion of a placer mining beach along the south-west coast of India: Part I— Nearshore sediment transport regime. doi:10.1007/s11069-016-2368-z.

Prasannakumar, S. 1985. *Studies on sediment transport in the surf zone along certain beaches of Kerala*. Unpublished Ph.D. thesis, 110, Cochin: Cochin University of Science and Technology.

Rao, V. R., M. V. Ramana Murthy, M. Bhat, and N. T. Reddy. 2009. Littoral sediment transport and shoreline changes along Ennore on the southeast coast of India: Field observations and numerical modeling. *Geomorphology* 112:158–66. doi:10.1016/j.geomorph.2009.05.015.

Reddy, M. P. M. 1976. Longshore sediment transport model for the Indian west coast. *Indian Journal of Geo-Marine Sciences* 5:152–62.

Sajeev, R., P. Chandramohan, V. Josanto, and V. N. Sankaranarayanan. 1997. Studies on sediment transport along Kerala coast, south west coast of India. *Indian Journal of Geo-Marine Sciences* 26:11–15.

Shanas, P. R., and V. S. Kumar. 2014. Coastal processes and longshore sediment transport along Kundapura coast, central west coast of India. *Geomorphology* 214:436–51. doi:10.1016/j.geomorph.2014.02.027.

Smith, E. R. 2006. *Long-shore sediment transport rate incorporating wave orbital velocity fluctuations*. Vicksburg, MS: Coastal and Hydraulics Engineering Technical Note, ERDC/CHL TR-06-18, U.S. Army Engineer Research and Development Center.

Pradhan, S., S. K. Mishra, R. Baral, R. N. Samal, and P. K. Mohanty. 2017. Alongshore sediment transport near tidal inlets of Chilika Lagoon; East coast of India. *Marine Geodesy* doi:10.1080/01490419.2017.1299059.

Troels, A., N. Jorgen, G. J. Stine, and J. Julie. 2004. Longshore sediment transport and coastal erosion at Skallingen, Denmark. *Danish Journal of Geography* 104:5–14. doi:10.1080/00167223.2004.10649499.

USACE. 1984. Vol. 1, Vicksburg, Mississippi: Shore Protection Manual, Coastal Engineering Research Center.

Veerayya, M., and T. Pankajakshan. 1988. Variability in wave refraction and resultant near shore current patterns: exposed versus sheltered beaches along North Karnataka, west coast of India. *Indian Journal of Geo-Marine Sciences* 17(2):102–10.

Walton, T. L., Jr., and R. O. Bruno. 1989. Long-shore transport at a detached breakwater, Phase-II. *Journal of Coastal Research* 65(9):667–68.

Wang, H., R. A. Dalrymple, and J. C. Shian. 1975. Computer simulation of beach erosion and profile modification due to waves. In *Proceedings Symposium of Modelling Technique, American Society of Civil Engineers (San Francisco, California)*. pp. 1369–84.

Wright, L., and A. Short. 1983. Morphology of beaches and surfzone in Australia. In *Handbook of coastal processes and erosion*. P. D. Komar Ed., 35–64. California: CRC Press.