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ORIGINAL PAPER

Erosion and heavy mineral depletion of a placer mining beach along the south-west coast of India: Part I— Nearshore sediment transport regime

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Abstract The Chavara coast of southwest India is well known for its rich beach placer deposits which are being commercially exploited by the industries. Replenishment of these resources, which consist of heavy minerals of varying densities, by the hydrodynamic processes is essential for maintaining the stability of the coast as well as sustenance of mining. Rich concentrations of heavy minerals were reported consistently in the beach sediments of this coast in the past, but a systematic reduction in the concentration of the heavies has been reported during the past one-and-a-half decades. This paper, the first in a series of three, emanates from a programme of study launched to understand the mechanisms that manifest the reported changes in the morphology and mineralogy along this coast. In this study the longshore and cross-shore sediment transport rates along this coast have been estimated adopting numerical model studies. The validated LITDRIFT and LITPROF modules of the LITPACK modelling system have been used for computing the longshore and cross-shore sediment fluxes in the surf zone and innershelf region. The net annual longshore sediment transport is northerly in the surf zone where as it is southerly in the innershelf. Detailed analysis of the computed results shows domination of onshore transport over offshore transport. The beach volume change estimated from the measured beach profile on the other hand shows a reduction in the annual replenishment. The domination of the onshore flux as seen in the computations is actually not reflected in the field observations, and this can be attributed to the influence of excessive sand mining by the industries.

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1 Introduction

The Neendakara–Kayamkulam coastal sector of length 22 km located in the southwest Indian coast (Fig. 1) is world famous for its rich placer deposits, also called as black sand. This coastal stretch popularly known as the Chavara coast is subjected to rampant beach sand mining because of its heavy mineral resources which consists of ilmenite, zircon, rutile, monazite, garnet, and sillimanite. Since 1930, the Indian Rare Earths Ltd. (IREL) and its predecessor companies have been engaged in beach sand mining along the Chavara coast for extraction of heavy minerals. The Kerala Minerals and Metals Ltd. (KMML), another Public Sector Undertaking situated at Chavara entered the scene in 2000 with large-scale mining of beach sand along the coast. As per the available data (Kurian et al. 2012), the mining of beach sand by both these firms together is much beyond the annual replenishment by the hydrodynamic forces (Black et al. 2008; Rajith 2006). This type of unsustainable mining can undoubtedly have a negative impact on the stability of the coast and its adjoining areas, and can lead to depletion of heavy mineral resources.

The depletion in heavy mineral concentration along the Chavara coast during the last decade is a major concern for the industries as it badly affects their economic sustainability. According to Prakash and Verghese (1987), the total heavy mineral content in the beach sediments of this coast varied between 24 and 96 % with the northern Chavara-Azhikkal sector showing high concentrations. Kurian et al. (2001) as part of their field investigations conducted during 1995 had estimated higher concentrations of the heavy mineral in the beach sediments and observed that it was even up to 100 % during the monsoon period. Further field investigations carried out along the same coastal stretch by Kurian et al. (2002) later in 2000 also indicated high concentration of heavy minerals, as much as 80 %, but at the same time observed a general reduction in the concentration of heavies at the mining site of Vellanathuruthu located in the southern sector of the coast. Since then the heavy mineral content in the beach sand along the Chavara coast has been showing a decreasing trend as is evident from the recent estimates of IREL (2010). This in turn has adversely affected the firms engaged in beach sand mining for heavy mineral extraction. The increased rate of mining over the years also has led to caving in of the shoreline to the extent of 120–200 m at certain critical locations like the Vellanathuruthu and Kovilthottam mining sites which certainly can be considered as a shoreline stability issue needing immediate attention.

Thus the present morphological and mineralogical scenario of the Chavara coast offered an interesting case for a detailed investigation to understand the mechanisms that manifest these changes. A programme of study partly sponsored by the Indian Rare Earths Ltd. was taken up in 2010 and was completed recently. The results of the investigation are presented in 3 parts. The first part which is presented here is a study of the nearshore sediment transport regime based on field measurements and numerical modelling studies. The second paper encompasses a detailed study of the sedimentology and mineralogy of the beach and innershelf delineating the factors responsible for the depletion in the heavy mineral content. An analysis of the long term morphological changes of the beach and the innershelf, and its integration with the sediment transport regime is presented in the last paper.

This paper is the first in the series encompassing a study of the nearshore sediment transport regime of the coast.
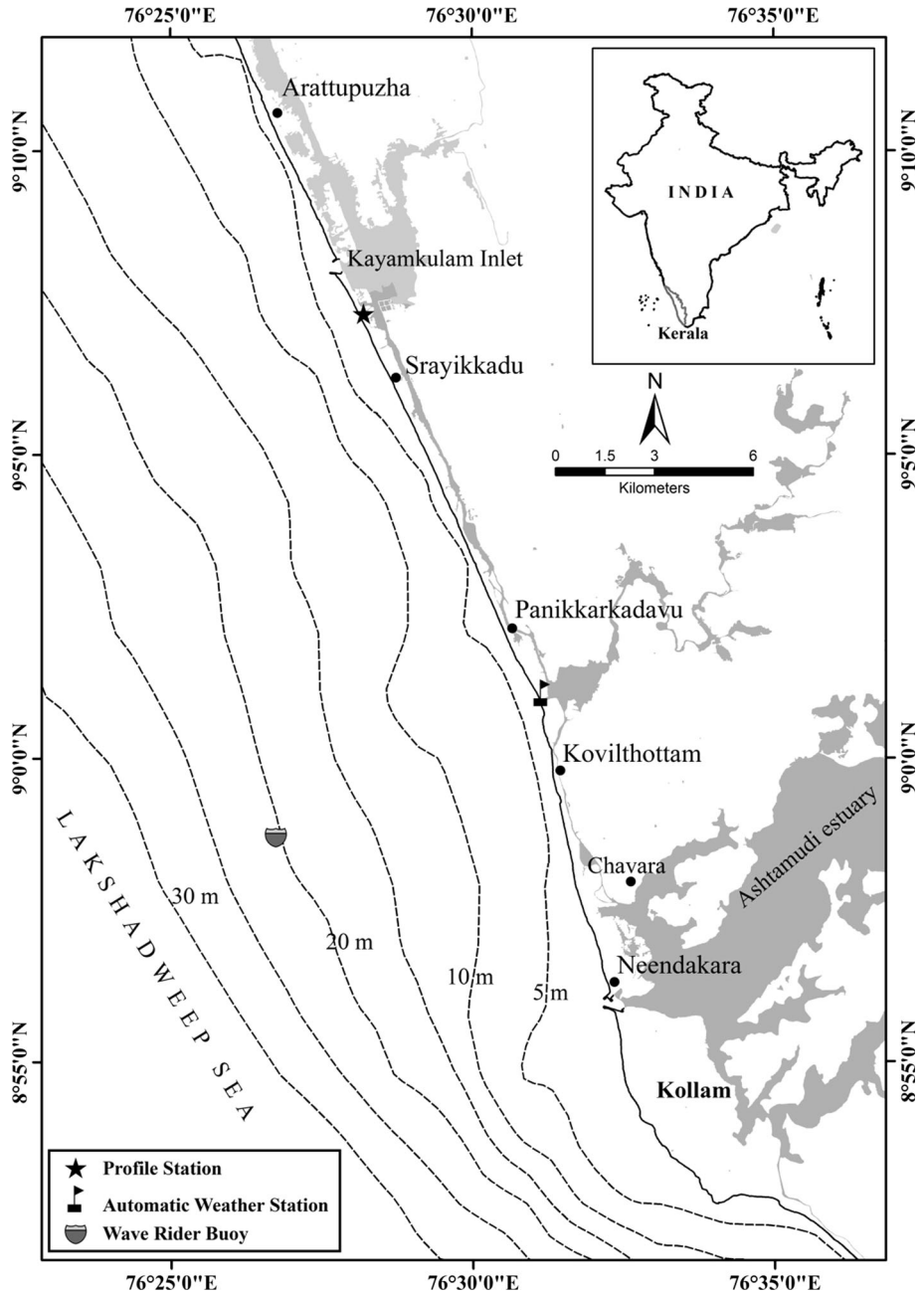
Fig. 1 Study area extending from the Neendakara inlet in the south to the Kayamkulam inlet in the north, SW coast of India. The sites of deployment of wave rider buoy, automatic weather station and beach profile station are shown

2 Nearshore sediment transport

The stability of a beach is decided by the sediment transport processes induced by various hydrodynamic processes coupled with human-induced activities in the beach and innershelf. The sediment transport pattern/processes of a coast is dependent on the hydrodynamic forces viz. waves, currents, tides and wind which vary both temporally and spatially. The changes in beach and innershelf morphology are in turn influenced by the sediment transport processes. Identification of the sources/sinks of sediments into/out of the system (Hume et al. 1999), and their quantification (Rosati 2005) are essential in assessing the stability of the beach.

Literature on experimental and numerical modelling studies was carried out to understand the sediment transport in general with particular reference to the longshore and cross-shore components along the south-west coast of India are scanty. A review of the available literature reveals that most of the studies are based on the littoral environmental observation (LEO) which involves calculation of the longshore sediment transport (Prasannakumar et al. 1983; Chandramohan and Nayak 1991; Jena and Chandramohan 1997; Sajeev et al. 1997). Prakash and Prithviraj (1988) estimated the longshore transport direction in relation to the three seasons by using the textural parameters of the foreshore sediments along the Paravur–Purakkad coast in Kerala. Jose et al. (1997) studied the longshore transport at three different locations with varying littoral characteristics along the SW coast using the wave energy flux method. Chandramohan et al. (1990) and Sanil Kumar et al. (2001, 2006) computed the longshore sediment transport rates along the Indian coast using measured wave data. The MIKE21 numerical modelling suite was used by Babu et al. (2003) for computation of the sediment transport along the Mangalore coast. Oliveira and Contente (2013) studied numerical model in the laboratory and prototype scales using LITPROF model, and the performance was evaluated using the Brier Skill Score. The profile evolution in both scales was compared after reducing the results from the prototype scale to the laboratory scale and concluded that the profile erosion prediction was overestimated in the laboratory scale, whereas it was underestimated in the prototype scale. Sheela Nair et al. (2015) computed the annual net longshore transport for the Kollam coast, adopting Kamphuis formula, for which 1-year measured wave was used.

Rajith et al. (2008) after detailed study of the erosion/accretion pattern along the Chavara coast concluded that in addition to the natural hydrodynamic forces, anthropogenic activities like sand mining and construction of seawalls/breakwaters have also contributed to the beach erosion/accretion along the coast. Black et al. (2008) in their attempt to estimate the beach sediment budget of the Chavara coast identified a closed sedimentary circulation system on a regional scale described as 'step ladder' and concluded that there was a dynamic equilibrium prevalent in the area. This was based on extensive hydrodynamic measurements and numerical modelling studies carried out during 1999–2001. Numerical models were developed by Kurian et al. (2009) to simulate the wave and sediment transport regime of the innershelf of the south-central Kerala coast. It was reported that the net annual longshore sediment transport was southerly in the innershelf and northerly in the surf zone. These counter directional transports were linked by the cross-shore transports which exhibit a seasonal reversal in its direction. Stable beaches were found to prevail in the locations where there was a balance between the longshore and cross-shore transport. At locations where the balance was affected the imbalance manifested itself in the form of erosion/accretion as the case may be.

In the Indian scenario where a major portion of the coast is under constant threat of erosion due to various factors (Sreekala et al. 1998; Malini and Rao 2004; Hanamgond and

Mitra 2007; Hegde et al. 2009; Roy Chowdhury and Sen 2013; Udhaba Dora et al. 2014; Rajawat et al. 2015), very few attempts have been made till date to understand the coastal processes and the related sediment transport pattern. Barring the studies by Black et al. (2008), studies involving estimation of individual contribution due to both longshore and cross-shore transports and their impact on the beach volume which are very important for assessing the stability of the coast are lacking. Micro-level studies that deal with the sediment transport of a coast in general and the associated cross-shore and longshore sediment transports along the innershelf and beach-surf zone region are essential to address all the major issues related to coastal stability as eventually it can also affect the adjoining coast. The placer deposit rich Chavara coast of Kerala with its retreating shoreline and declining level of heavy mineral concentration is one such example which needs a detailed study to identify the causative factors responsible for the degradation of the coast. Reports on the caving in of the beach at the mining sites and the alarming rate of depletion of the heavy mineral content in the beach sediment during recent years, as reported by the firms engaged in beach sand mining, have given impetus for undertaking a comprehensive study on the sediment transport regime of the nearshore of this coast.

3 Area of study

The study area is a 22 km costal stretch located along the southwest coast of India, extending from the Neendakara inlet in the south to the Kayamkulam inlet in the north. This coastal sector which is situated in the Kollam district of the southern state of Kerala in India is popularly known as the Chavara coast (Fig. 1). It is a micro-tidal coast with a climatic regime dominated by southwest monsoon and has a moderate wave energy level (Baba and Kurian 1988; Kurian 1989). The Chavara coast in general has an orientation in the SSE-NNW direction. Breakwaters constructed at the Neendakara and Kayamkulam inlets facilitate fishing harbours in the estuarine regions of these locations. In addition 26 groins of varying dimensions have been constructed during the past 5 years as shore protection measures. The coast exhibits significant variation in the orientation along the southern and northern parts with noticeable dents at the mining sites of Vellanathuruthu–Ponmana and Kovilthottam due to caving in of the shoreline. The southern part of the coastal stretch from the Neendakara inlet to the Vellanathuruthu mining site is oriented 345°N while the northern sector is 334°N. The continental shelf is of moderate slope with the 20, 50 and 100 m isobaths at approximate distances of 7, 26 and 54 km, respectively, from the shoreline. Further south of the Neendakara inlet, at the Thangassery headland, there is a sharp change in the shoreline orientation from 350° to 290°N with steeper bathymetry towards south (Baba and Kurian 1988). Kallada River is the major riverine system along this coast. This river which was debouching considerable amount of sediments into the Ashtamudi estuary (Prakash and Prithviraj 1988) is reported to be bringing in very little sediments of late (Black and Baba 2001).

4 Data and methodology

4.1 Field data collection

The field programmes included measurements of wind, wave and littoral environmental parameters and shoreline mapping for the 1 year period of January to December 2014. Of

these the wave and wind data were recorded continuously at intervals of half and 1 h, respectively. The LEO was done monthly following standard procedures (Schneider 1981). Shoreline measurements were also taken every month using a Trimble Juno GPS.

For collecting the coastal wind data, an Automatic Weather Station (Campbell Scientific) was installed at a height of 10 m above MSL on the beach at Chavara. The wave data for the study were from the directional Wave Rider Buoy (Datawell make) deployed off Chavara, Kollam in 22 m water depth at about 9 km from the shore jointly by Indian National Centre for Ocean Information Services (INCOIS) and National Centre for Earth Science Studies (NCESS) for the real-time validation of Ocean State Forecast issued daily by the INCOIS. The buoy is preset for the collection and transmission of data at half an hour interval. The important wave parameters such as significant wave height, peak period, zero-crossing period, predominant wave direction etc. are derived from the respective first-, second- or fourth-order spectral moments derived from FFT analysis (Datawell wave rider reference manual 2009).

The standard level and staff method has been adopted to measure the beach profile. Monthly beach profile measurements were taken at Srayikkadu (Fig. 1) located 2 km south of the Kayamkulam inlet for a period of 1 year from January to December 2014. Site-specific surficial and beach sediment sample collection at regular intervals were also carried out as part of the study. The data collected underwent thorough quality checks and were further used for the analysis and numerical modelling work. Detailed analyses and interpretation of the data collected viz. wind, wave, beach profile, shoreline position etc. are presented in the next section except for the sediment characteristics and grain size distribution part which are covered in the accompanying article (Part-II, Prakash et al. 2016).

4.2 Estimation of longshore transport

Bulk formulae viz. the CERC and Kamphuis, and LITDRIFT module of the LITPACK modelling suite by the Danish Hydraulic Institute (DHI) are used for the computation of the Longshore Sediment Transport (LST). The selection of an appropriate method for the computation of the LST depends on the applicability as well as adaptability of the technique for the coast and the dependence of the various parameters like the breaker wave height, wave period, nearshore slope, sediment grain size, etc. which greatly influence the sediment transport.

4.2.1 CERC formula

The Coastal Engineering Research Centre (CERC) formula (U.S. Army Corps of Engineers, Shore Protection Manual 1984), which is based on field measurements, is commonly used for predicting the total Longshore Sediment Transport (LST) rate. Accuracy of the CERC formula is believed to be ±30–50 % as several parameters that logically might influence the LST like the breaker type and grain size are excluded in the formula (Wang et al. 2002; Smith et al. 2004).

The total rate of longshore transport (Q) according to the CERC formula (U.S. Army Corps of Engineers, Shore Protection Manual 1984) is computed using the equation

$$Q = (H^2 C_g)_b [A \sin(2\theta_{bs})] \tag{1}$$

H is the wave height, C_g is the wave group speed given by linear wave theory, the subscript b denotes wave breaking condition, θ_{bs} is the angle of breaking waves to the local shoreline, A is a non-dimensional parameter defined as

$$A = \frac{K}{16\left(\frac{\rho_s}{\rho_w} - 1\right)(1 - P)} \tag{2}$$

where K is an empirical co-efficient, treated as a calibration parameter, taken as 0.58, ρ_s is the density of sand taken as 3000 kg/m^3 for quartz sand, ρ_w is the density of water taken as 1025 kg/m^3 for seawater, and P is the porosity of sand on the bed (taken to be 0.4).

The equation used for calculating the breaker wave height for depth-limited wave breaking is given by

$$H_b = \gamma d_b \tag{3}$$

where γ is the breaker index, generally taken as 0.78 and d_b is the breaker depth.

Knowing H_b, the breaker depth can be calculated, and this in turn is used for obtaining the wave group speed using the shallow water approximation given by

$$C_d = \sqrt{g d_b} \tag{4}$$

4.2.2 Kamphuis formula

Kamphuis (1991, 2002) formula takes into account all the important parameters like the breaker height, breaker angle, sediment grain size, bed slope, and also the effect of swells included in the form of the peak wave period. This is particularly important for the Chavara coast as it shows the influence of swells throughout the year. The formula proposed by Kamphuis for the estimation of the LST is

$$Q_{vol} = 6.4 \times 10^4 H_{sbr}^2 T_{op}^{1.5} m_b^{0.75} D_{50}^{-0.25} \sin^{0.6}(2\theta_{br}) \tag{5}$$

where Q_{vol} is the total immersed volume in m^3/year, H_{sbr} is the breaker wave height, T_{op} is the peak wave period, m_b is the bottom slope up to two wave lengths offshore of the breaker line, D_{50} is the mean grain size and θ_{br} is the breaker angle with respect to the shore normal.

4.2.3 LITDRIFT module of LITPACK

LITPACK is an integrated modelling system used for modelling of littoral processes and coastline kinetics. LITDRIFT is one of the major modules available in the LITPACK modelling suite used to calculate the longshore current and the littoral drift in a coastal environment. The LITDRIFT module simulates the cross-shore distribution of wave height, setup and longshore current for an arbitrary coastal profile (Danish Hydraulic Institute 2004). The longshore and cross-shore momentum balance equations are solved to give the cross-shore distribution of the longshore current and the wave setup. Wave decay due to breaking is modelled, either by an empirical wave decay formula or by a model of Battjes and Janssen (1978). The major assumption in the LITDRIFT module is that uniform conditions exist along the straight coast. The shore-parallel momentum balance defined in Eq. (6) given below is used to determine the longshore current velocity profile.

$$\tau_b - \frac{d}{dy}\left(\rho E D \frac{du}{dy}\right) = -\left(\frac{dS_{xy}}{dy}\right) + \tau_w + \tau_{cur} \tag{6}$$

where τ_b is the bed shear stress due to the longshore current, ρ is the density of water, E is the momentum exchange coefficient, D is the water depth, u is the longshore current

velocity, y is the shore normal coordinate, S_{xy} is the shear component of the radiation stress, τ_w and τ_{cur} are the driving forces due to wind and coastal current, respectively. The relation between u and τ_b is established by the model of Fredsoe (1984).

The LITDRIFT calculates the net/gross littoral transport over a specific design period. Important factors, such as linking of the water level and the profile to the incident sea state, are included. The input data given for defining the physical conditions of the sediment transport are the cross-shore profile, hydrodynamic data which includes the water level, wave, current and wind data. The depth of closure has been arrived at based on Hallermeier (1981). The output of the LITDRIFT module provides a detailed deterministic description of the cross-shore distribution of the longshore sediment transport for an arbitrary bathymetry for both regular and irregular sea states.

4.3 Estimation of cross-shore transport

The LITPROF module of the LITPACK suite of programs developed by DHI (Danish Hydraulic Institute 2004, 2008) is used for the simulation of the cross-shore profile changes at Srayikaddu—the same representative location which was selected for LST estimation. The site-specific model developed using the LITPROF module is used to study the evolution of a cross-shore profile under the influence of temporally varying wave conditions. The model accounts for all the important phenomena in the nearshore region such as shoaling, refraction, bed friction and wave breaking. The model is based on the assumption that the longshore gradient in hydrodynamic and sediment conditions is negligible and that the depth contours are parallel to the coastline. The offshore boundary condition for running this model is defined by specifying time varying wave conditions. The wave parameters given as input are the root-mean-square wave height (h_{rms}), mean wave period and the mean wave direction. The model calculates vertical variations of turbulence, shear stress and mean flow for which the effects of asymmetry of the wave orbital motion, mass flux in progressive waves, surface rollers and the wave setup are considered. For waves approaching the coast at an angle, the longshore currents are calculated from the wave induced radiation stress gradients.

The sediment transport is calculated from an intra-wave hydrodynamic model where the time evolution of the bed boundary layer is resolved. The basic equation used is the continuity equation for sediment transport given as

$$\frac{\partial h}{\partial t} = -\left(\frac{1}{1-n}\right)\frac{\partial q_s}{\partial x} \tag{7}$$

where h is the bed level, q_s is the cross-shore transport and n is the porosity of the bed material. The LITPROF module uses a forward in time-central in space (FTCS) scheme to solve the continuity equation.

4.3.1 Model calibration and validation

The main tuning parameters used for the calibration of the LITPROF model setup for a particular location, are the scale parameter and maximum angle of the bed slope. The scale parameter is a calibration factor which reflects the cross-shore exchange of momentum, and it is proportional to the characteristic length scale over which the transport is smoothed. For the present study, the final values of the tuning parameters used are 30° for the maximum angle of the bed slope, 3 for the scale parameter, 0.78 and 0.8 for γ_1 and γ_2

(wave breaking factors), respectively, and 0.15 for the roller coefficient. The parameters are named according to the model interface. The calibration of the model is carried out by comparing the model results with that of the measured for various tuning parameters. For this commonly used statistical error estimation parameters such as the BIAS, correlation coefficient, root-mean-square error (RMSE), scatter index and standard deviation are computed. In addition to this, the Brier Skill Score (BSS) which is used to assess the skills of coastal morphological models (Sutherland et al. 2004; van Rijn et al. 2003; Pender and Karunarathna 2013) is also estimated. The BSS compares the mean square difference between the simulation and the measurement with the mean square difference between initial/baseline simulation and measurement and is defined as

$$\text{BSS} = 1 - \frac{\langle(|Z_{b,s} - Z_{b,m}| - \Delta Z_{b,m})^2\rangle}{\langle(Z_{b,0} - Z_{b,m})^2\rangle} \tag{8}$$

where $Z_{b,m}$ is the measured bed level, $Z_{b,s}$ is the simulated bed level, $Z_{b,0}$ is the initial bed level, $\Delta Z_{b,m}$ is the error of the measured bed level and $<..>$ denotes the averaging procedure over time series. Perfect agreement with the measured and simulated values gives a skill score of 1, whereas a lower value indicates a poor/bad performance. The classification of BSS by van Rijn et al. (2003) is shown in Table 1.

van der Wegen et al. (2011) expressed the same in terms of volumetric change and is defined as

$$\text{BSS} = 1 - \frac{\langle(\Delta \text{Vol}_{\text{simul}} - \Delta \text{Vol}_{\text{meas}})^2\rangle}{\langle(\Delta \text{Vol}_{\text{meas}})^2\rangle} \tag{9}$$

where ΔVol is the volumetric change compared to the initial bed in m^3, for simulated and measured quantity, $<..>$ denotes an arithmetic mean or a spatial average. The measurement error can be accounted by using the extended BSS$_{vr}$ proposed by van Rijn et al. (2003) and is defined as

$$\text{BSS}_{vr} = 1 - \frac{\langle(|\Delta \text{Vol}_{\text{simul}} - \Delta \text{Vol}_{\text{meas}}| - \delta)^2\rangle}{\langle(\Delta \text{Vol}_{\text{meas}})^2\rangle} \tag{10}$$

where δ denotes the volumetric measurement error in m^3.

For this work, both the BSS estimates as proposed by van Rijn et al. (2003) and van der Wegen et al. (2011) have been used as the study involves temporal comparison of cross-shore profile and volume changes.

**Table 1** Classification of BSS (van Rijn et al. 2003; van der Wegen et al. 2011)

BSS	BSSvr	Remarks
0.5–1.0	0.8–1.0	Excellent
0.2–0.5	0.6–0.8	Good
0.1–0.2	0.3–0.6	Fair
0.0–0.1	0.0–0.3	Poor
<0.0	<0.0	Bad

BSS Brier Skill Score, *BSSvr* Brier Skill Score extended by van Rijn et al. (2003)

### 4.4 Data analysis and interpretation

4.4.1 Wind

The 1-year wind data collected from the AWS shows a maximum wind speed of 10 m/s recorded during August, with an average magnitude and standard deviation of 3 and 1.5 m/s, respectively. From the monthly Wind Rose plots presented in Fig. 2, it can be seen that westerly and northwesterly winds dominate except during the months of February, March and December. Scattering is low during the months of June and July. The measured data being from a coastal station daily reversal of wind due to the influence of sea and land breeze could be observed.

Figures 3 and 4 show the percentage occurrence plots for the wind speed and direction recorded for 2014. The wind speeds are in the range of 0–5 m/s for 86 % of the observation period. The remaining 14 % of the wind speed falls in the range 5–9 m/s. The predominant
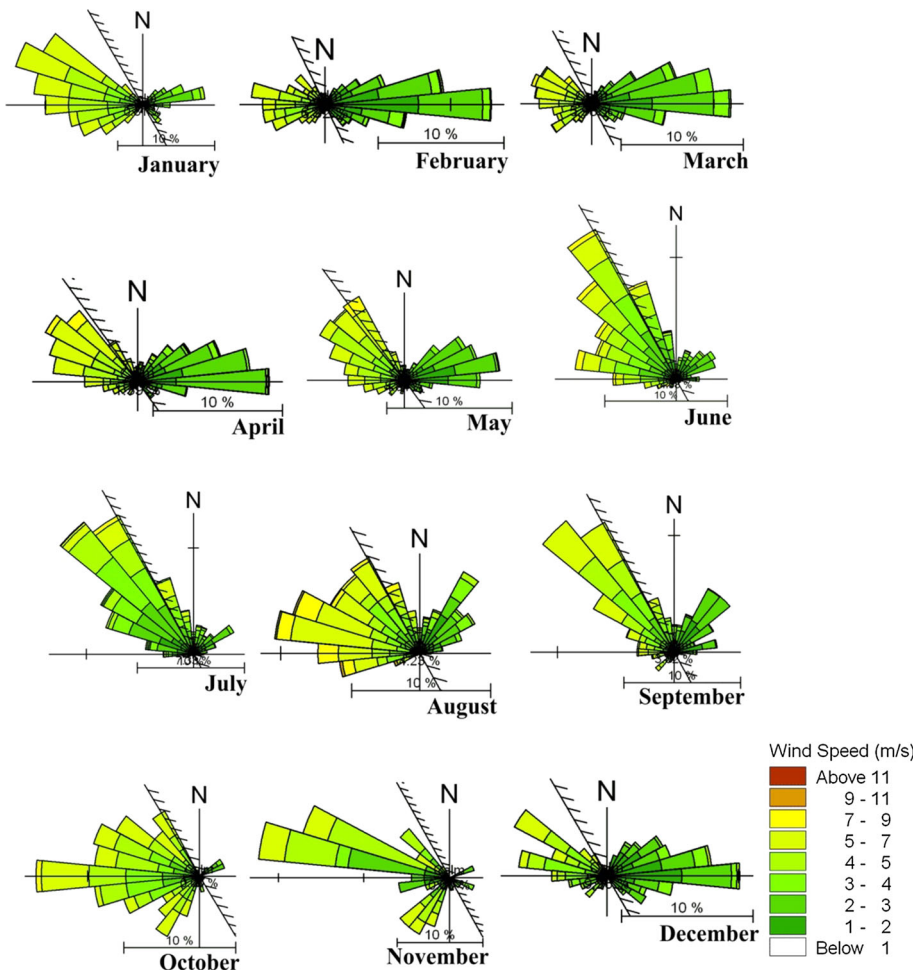
Fig. 2 Monthly wind roses for Chavara during January–December 2014
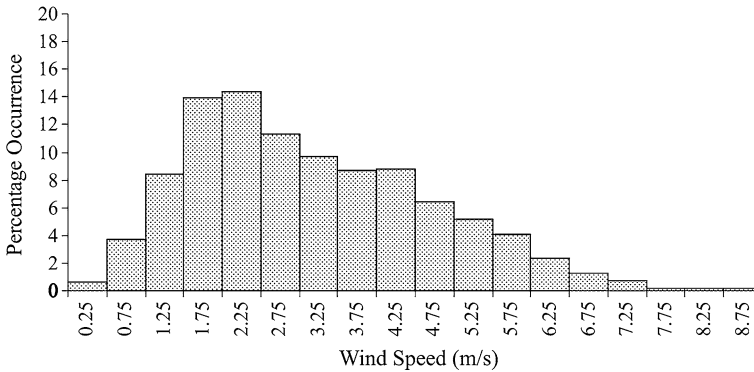
Fig. 3 Percentage occurrence of wind speed measured from the Automatic Weather Station installed at Chavara during January–December 2014
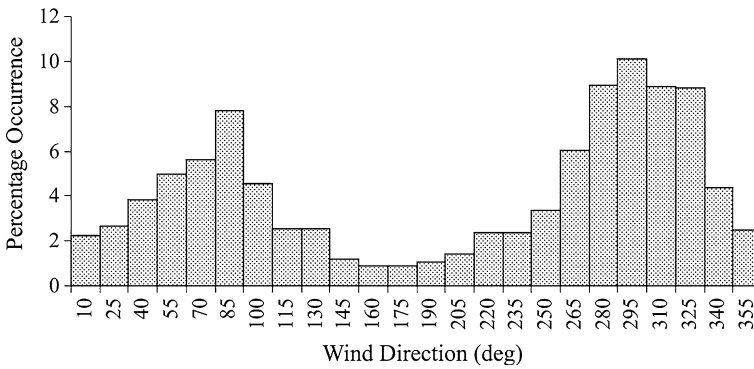

Fig. 4 Percentage occurrence of wind direction measured from the Automatic Weather Station installed at Chavara during January–December 2014

wind directions are northwesterly to north-northwesterly with a combined percentage occurrence of 50 %. The northeasterly winds constitute about 27 % and the remaining 23 % of the total observations comprises of southeasterlies to southwesterlies.

4.4.2 Waves

Analysis of the yearlong innershelf wave data collected shows dominance of south-southwesterly waves with peak periods around 11 s during the months of January–May and September–December and 9 s during the monsoon. This indicates that the coast is under the influence of swell waves during major part of the year. From the monthly wave rose plots (Fig. 5), it can be seen that the south westerlies and westerlies dominate the peak monsoon period of June–August due to the influence of the monsoon waves generated in the Arabian Sea.

Figures 6, 7 and 8 show the percentage occurrence plots for the various wave parameters for the whole year. The significant wave height (H_s) is in the range of 0.29–3.2 m. Of these about 55 % of the H_s are in the range of 0–1.0 m and it is mostly during the non-
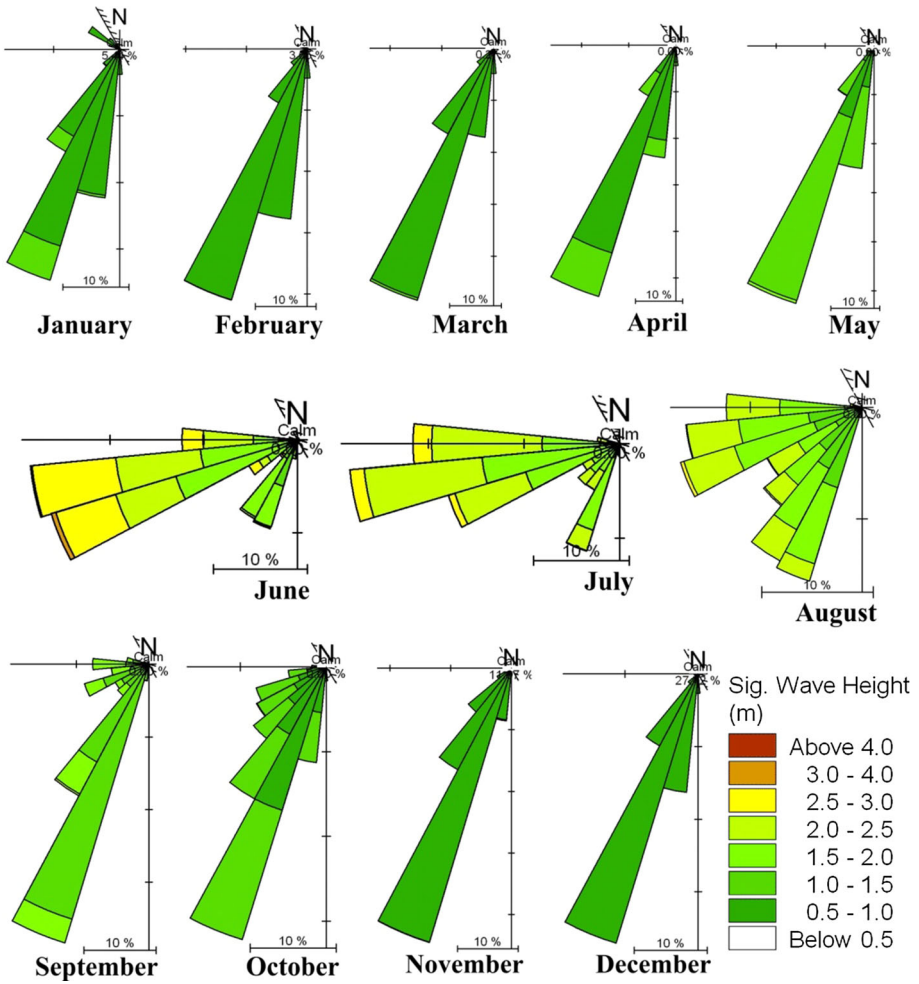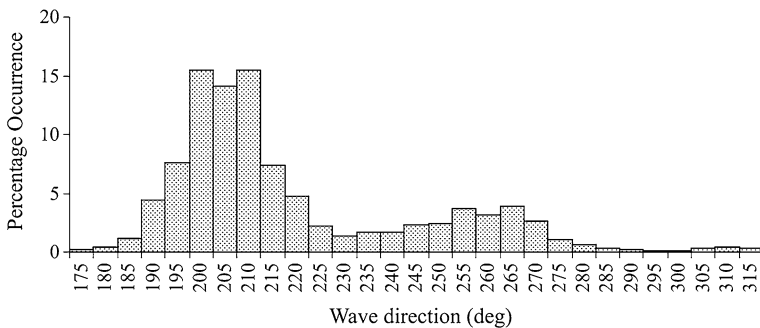
Fig. 5 Monthly wave roses for Chavara during January–December 2014
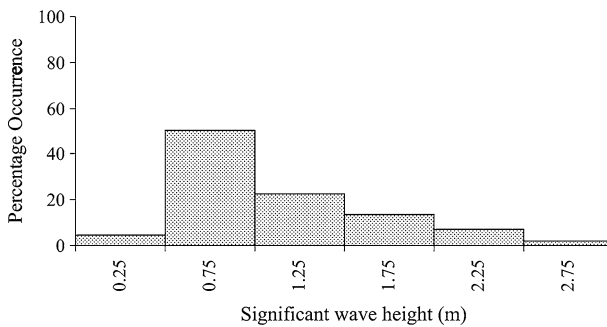
Fig. 6 Percentage occurrence of significant wave height measured off Chavara during January–December 2014
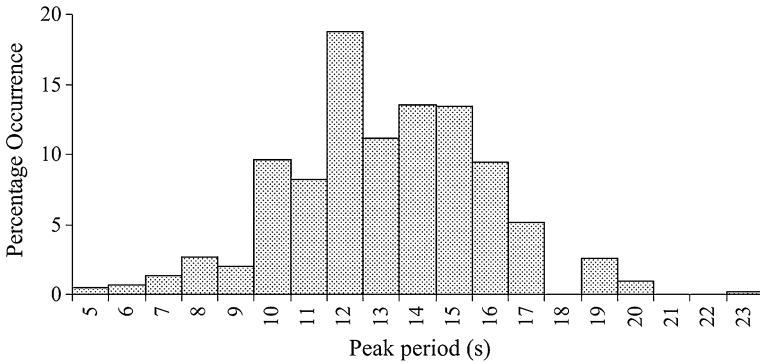
Fig. 7 Percentage occurrence of peak wave period measured off Chavara during January–December 2014

Fig. 8 Percentage occurrence of wave direction measured off Chavara during January–December 2014

monsoon periods. The percentage occurrences of H_s in the range of 1–2 m and >2 m are 36 and 9 %, respectively. High wave activity is normally during the monsoon season, and hence, the percentage occurrence in a year is relatively low.

The peak wave period (T_p) is found to vary between 3 and 23 s. The percentage occurrence of T_p in the range of 3–10 s is only 16.7 %, and this indicates the influence of local wind waves is less. In general swell waves with $T_p > 10$ s dominate with a percentage occurrence of 83.2 %.

The wave direction varies between 105 and 357°N. About 73.3 % of the waves are from the southerly to south-southwesterly direction, and this happens during the non-monsoon period which clearly shows the dominance of southerly swell waves. For the rest of the period, southwesterly to northwesterly directions dominate, indicating the influence of sea waves which are more common during the monsoon. In a nutshell, the analysis of the percentage occurrence of the measured wave parameters decipher that the coast is dominated by the influence of swell waves during the major part of the year and steep waves for a short period during the monsoon.

4.4.3 Beach profiles

Figure 9 gives the seasonal variations in the beach profiles at Srayikkadu. The maximum beach width is observed during January and minimum in December. During the months of
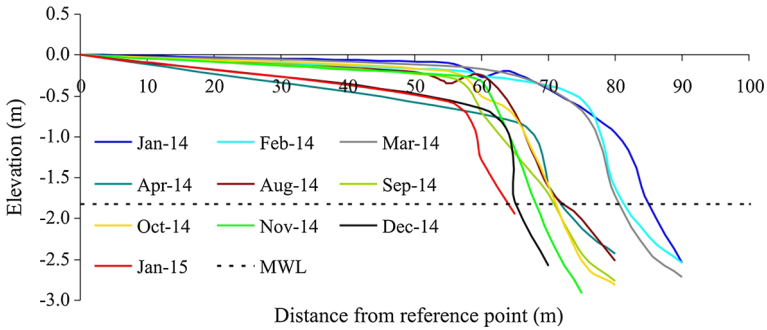
Fig. 9 Measured beach profile at Srayikkadu during January 2014–January 2015
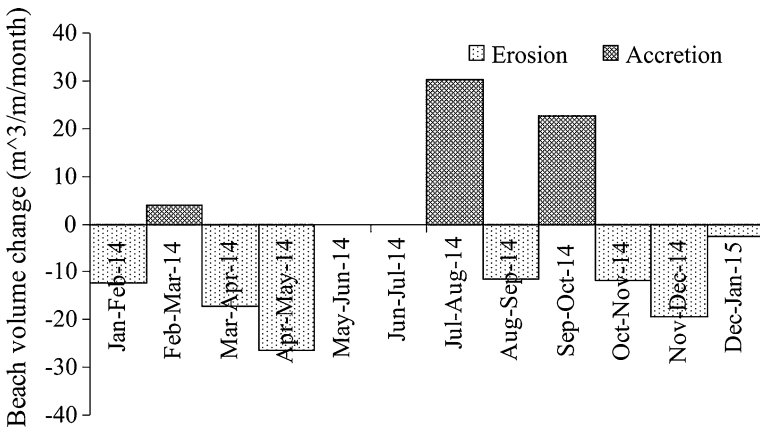

Fig. 10 Calculated beach volume change from the measured beach profiles at Srayikkadu during January 2014–January 2015

May, June and July, the beach was more or less completely eroded and hence no profile data are available. From the volume change (Figs. 10, 11), it can be seen that significant accretion occurs during the months of July–August and September–October. However, erosion in the subsequent period of October–January has offset the accretion made earlier and at the completion of 1 year (i.e. in January 2015) the beach has not regained its original profile. In general the observation is that the coastal stretch is not dynamically stable and has a negative cumulative beach volume change indicating net eroding tendency.

4.4.4 Shoreline orientation

Shoreline orientation which is defined as the normal to the shoreline with respect to North has been derived from the GPS measured shoreline data. The monthly shoreline orientation presented in Fig. 12 varies between 234°N and 244°N. The computed average value during the 1-year observation period of January–December 2014 is around 240° with a standard deviation of 3°.
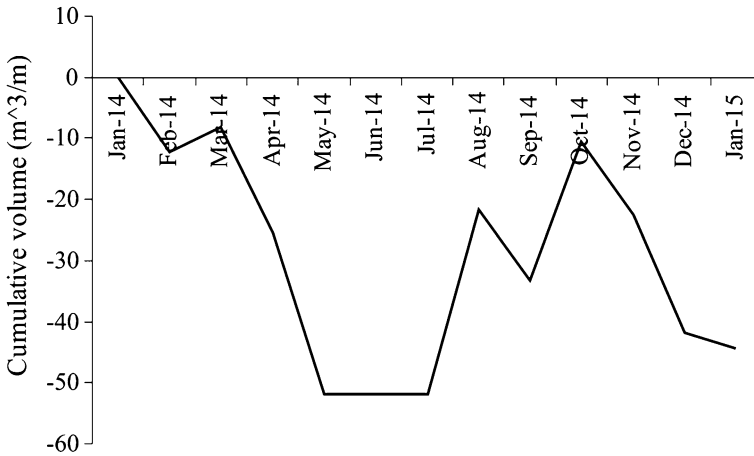
Fig. 11 Cumulative volume change at Srayikkadu during January 2014–January 2015
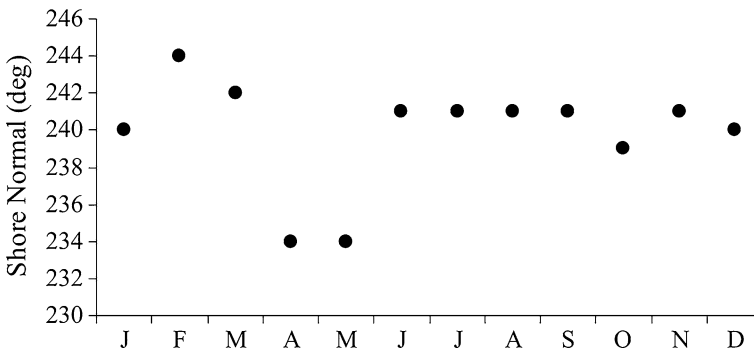
Fig. 12 Measured monthly shore normal at Srayikkadu during January–December 2014

4.4.5 Sediment size

Sediment samples were collected during the field measurements and were analysed for their textural characteristics. The details are given in the accompanying paper (Part-II, Prakash et al. 2016).

5 Results

The shore normal is an important parameter in deciding the quantum and direction of longshore transport (Kurian et al. 2002, 2012). When the waves approach from a direction north of the shore normal, the direction of transport is southerly and vice versa. The quantum of transport is directly proportional to the obliqueness of the wave with respect to the shore normal. The entire coastal stretch extending from Neendakara to Kayamkulam is mostly protected by seawalls except at a few locations which are maintained as mining sites or fishing gaps. The presence of seawall keeps the shoreline intact during the monsoon

season where the wave activity is at its peak. The shoreline in this case coincides with the seawall as there is hardly any beach. However, during the non-monsoon season the wave conditions are favourable for beach building initially and subsequent stabilization. Hence the orientation of the shoreline keeps changing with season. Here in the present study, the monthly shore normal was derived from the GPS measured shoreline data and the same was used for computation of the sediment transport rates. The limiting depth for longshore sediment transport was taken as 10 m in order to compare with the earlier work of Black et al. (2008).

5.1 Wave breaking and breaker type estimation

Breaking of waves is the most important wave transformation phenomenon that takes place in the surf zone region and it is considered to be very complex as it depends on various parameters like the water depth, offshore wave steepness (H_0/L_0), deep water wave approach angle (α_0) and the beach slope ($\tan\beta$). To study the temporal variation in the breaker parameters viz. the breaker wave height, breaker wave direction and the breaker depth off the Chavara coast, the data from the offshore WRB were utilised. The breaker parameters were derived from the offshore wave data adopting standard procedures (U.S. Army Corps of Engineers, Coastal Engineering Manual 2002) and the variation of these parameters during the observation period of January–December 2014 are plotted in Fig. 13. The breaker wave angle is southwesterly to westerly during the monsoon months of June to August. Since the wave breaker angle during this period oscillates on either side of the shore normal, the wave induced longshore currents are also oscillatory. However, an overall domination of southerly current and sediment transport can be seen. During the remaining months, the breaker wave angle is on the southern side of the shore normal, resulting in northerly wave induced longshore currents and northerly sediment transport.

   Waves as they approach very shallow waters can break in four different ways—plunging, spilling, collapsing and surging–depending on the offshore wave steepness, beach slope and breaker wave height. The condition under which a particular type of breaking occurs is attributed to the dimensionless breaker parameter ξ_0 (surf similarity parameter) (Galvin 1968; Battjes 1974) which is defined as given below.
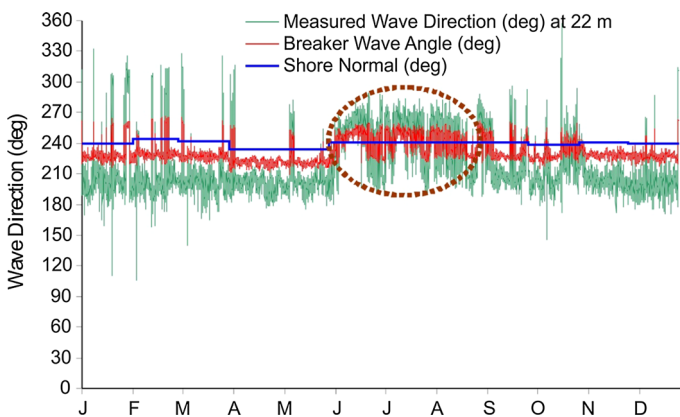
Fig. 13 Comparison between measured offshore wave direction, shore normal and calculated breaker wave angle off Srayikkadu during January–December 2014

$$\xi_0 = \frac{\tan \beta}{\sqrt{\frac{H_0}{L_0}}} \tag{11}$$

where $\tan \beta$ is the beach slope, H_0 is the deep water wave height, and L_0 is the deep water wave length. Surging/collapsing, plunging and spilling will occur for $\xi_0 > 3.3$, $0.5 < \xi_0 < 3.3$ and $\xi_0 < 0.5$, respectively.

For studying the wave breaking phenomenon along the Chavara coast the data from the offshore WRB described earlier is used. For determination of the breaker type, the wave steepness (H_0/L_0) obtained from the 1 year wave data as shown in Fig. 5 and the beach slope from the monthly field measurements are used. The surf similarity parameter for the 1-year observation period was computed using the offshore wave parameters and beach slope estimated from the field, and is presented in Fig. 14. From the figure it is observed that plunging type of wave breaking dominates during the entire period of observation. Spilling and surging breakers are of rare occurrences in this coastal sector.

5.2 Longshore current

The monthly longshore current (LSC) computed by the LITDRIFT module is presented in Fig. 15. For validation of the LSC, monthly LEO taken at field which includes the longshore current data in addition to the wave parameters was used. The result from LITDRIFT corroborates well with the field observation. Since continuous measured data were not available, the comparison was made with the LEO observations made at the location for the respective period for which the simulation was carried out. The simulated LSC for the months of May, June and July have not been validated as the monthly LEO data could not be collected because of high wave activity. The LSC computed using the LITDRIFT module shows southerly current during the monsoon months of June and July with magnitudes of 0.12 and 0.21 m/s, respectively. Because of the southerly current, the sediment transport during the monsoon is also towards south. During the remaining 9 months, the
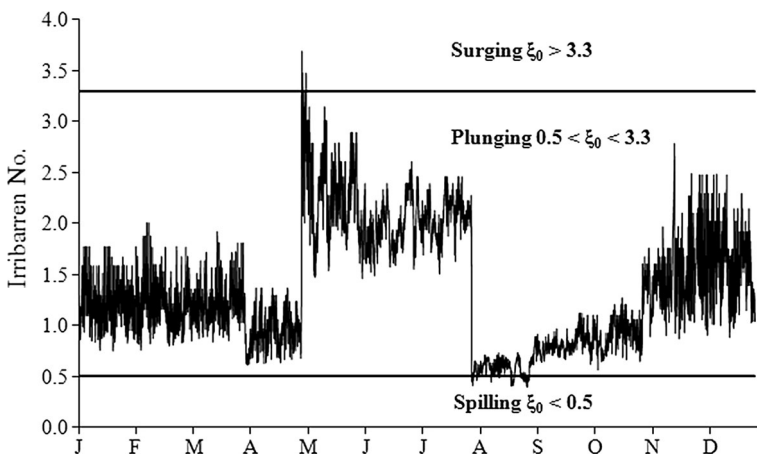
Fig. 14 Estimated surf similarity parameter (ξ_0) (after Galvin 1968) off Srayikkadu during January–December 2014
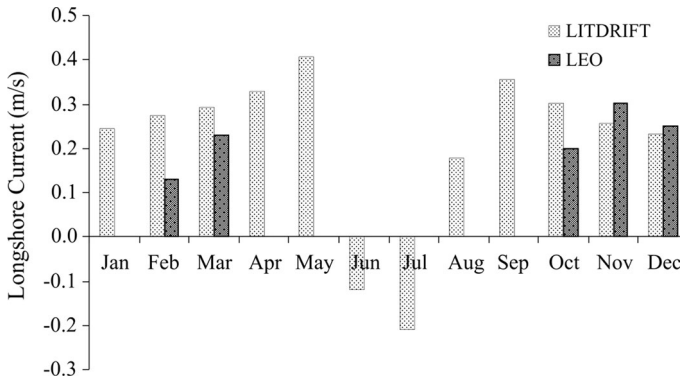
Fig. 15 Monthly maximum longshore current at Srayikkadu estimated by using LITDRIFT module of LITPACK and by LEO

LSC is northerly indicating a net annual northerly transport. The computed maximum LSC of 0.41 m/s is during May.

5.3 Surf zone longshore transport

For estimation of the surf zone longshore transport (LST) as described in Sect. 4.2, three different methods viz. CERC formula, Kamphuis formula and LITDRIFT module of LITPACK were adopted. The results obtained using the three methods (Fig. 16; Table 2) were compared among themselves as well as with field signatures/observations to assess/ascertain the applicability of the adopted method for the Chavara coast. It is observed that the directions of the annual net transport obtained using all the three methods are northerly.

As regards the magnitude, it can be seen from the results that the monthly LST rates computed using the LITDRIFT are less than that obtained by the Kamphuis and CERC formulae. In general the LITDIFT computed LST is higher during the months of April,
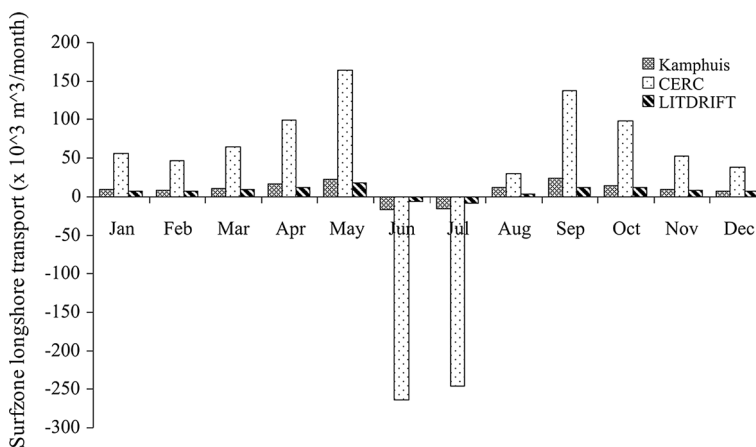
Fig. 16 Monthly LST in the surf zone at Srayikkadu computed using Kamphuis formula, CERC formula and LITDRIFT module of LITPACK
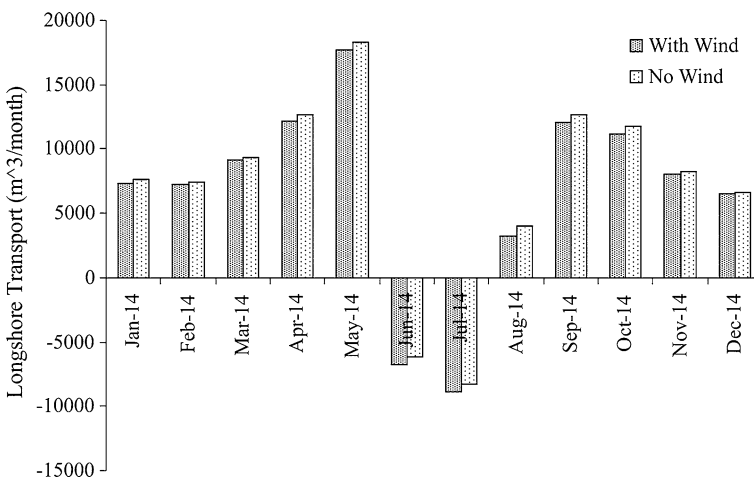
Table 2 Annual longshore sediment transport in the surf zone at Srayikkadu estimated by using Kamphuis formula, CERC formula and LITDRIFT module of LITPACK

Annual surf zone longshore transport Q (m³/year)				
Direction	Kamphuis formula	CERC formula	LITDRIFT	
			With wind	No wind
Northerly transport	134,085	785,737	94,521	98,641
Southerly transport	−32,716	−510,224	−15,560	−14,437
Gross transport	166,801	1,295,961	110,081	113,078
Net transport	101,369	275,513	78,961	84,205

−ve sign indicates southerly transport and vice versa

May, September and October, while the CERC and Kamphuis outputs show comparatively higher transport rates during April–October. Another interesting thing that can be noticed from the monthly drift values is that the LST computed by the LITDRIFT during the monsoon months of June–August is much less (varies between 3000 and 9000 m³/month) compared to that calculated using the other methods (varies between 12,000 and 17,000 m³/month for Kamphuis; between 29,600 and 264,000 m³/month for CERC).

The results computed adopting the Kamphuis formula and the LITDRIFT shows reasonably good comparison with values of 101,369 and 78,961 m³/year respectively, whereas the CERC formula gives exorbitantly higher values. The values arrived at on the basis of numerical model studies using LITDRIFT are more realistic compared to the Kamphuis method (which uses an empirical formula) as the model output is based on simulation of the site-specific field processes and the effects of coastal wind and tide also have been included. Figure 17 shows that the inclusion of wind in the input parameters will bring about only marginal changes in the quantum of LST. The estimation of LST using the Kamphuis formula gives better results compared to that of the CERC mainly because

Fig. 17 Comparison of computed longshore sediment transport in the surf zone with and without wind using LITDRIFT module at Srayikkadu

the effect of swells, the sediment gain size and the bed slope have been considered in the sediment transport computation.

5.4 Innershelf longshore transport

The longshore transport computed for the innershelf between isobaths of 3 and 10 m using the LITDRIFT module shows net southerly transport throughout the year unlike in the surf zone where the northerly transport dominates except during monsoon. The magnitude of the transport is generally high during the peak monsoon period (June–July). Also a strong correlation between the innershelf transport and the local wind conditions has been noticed as is evident from the results presented in Fig. 18. The computed annual innershelf longshore transport (Table 3) is predominantly southerly with a net magnitude 43,172 m^3.

5.5 Cross-shore transport

The temporal variation in cross-shore transport across the innershelf and surf zone for a period of 1 year has been computed using the LITPROF module of the LITPACK modelling suite of programmes and the results are presented in Fig. 19. For validation of the LITPROF results, the simulated monthly cross-shore profiles were compared with the
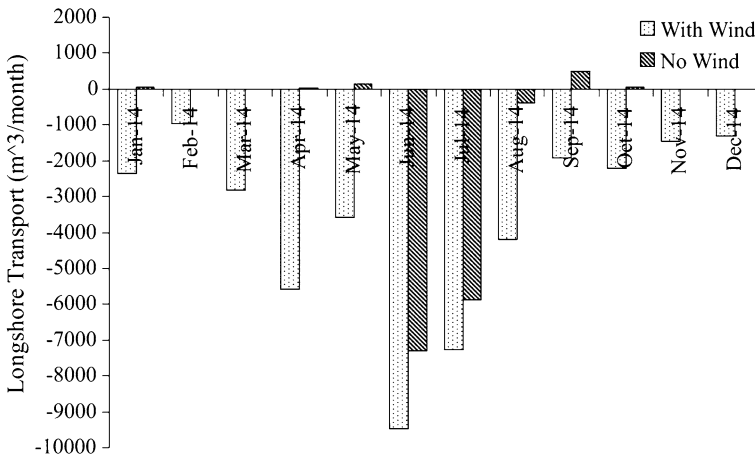
Fig. 18 Monthly LST in the innershelf at Srayikkadu estimated by using LITDRIFT module of LITPACK. The case for 'no wind' is also presented to highlight the significant influence of wind in the LST in the innershelf

| Table 3 Annual LST in the innershelf at Srayikkadu estimated by using LITDRIFT module of LITPACK	Annual innershelf longshore transport Q (m^3/year)		
	Direction	With wind	No wind
	Northerly transport	0	745
	Southerly transport	−43,172	−13,551
	Gross transport	43,172	14,296
	Net transport	−43,172	−12,806
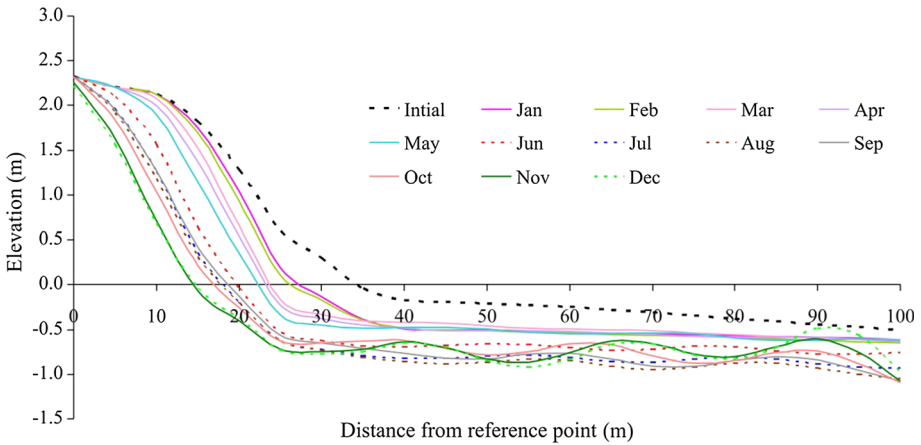
Fig. 19 Beach profiles at Srayikkadu simulated using LITPROF for 1 year

monthly measured beach profile. Since the measured monthly profile measurements were limited to the portion above the Still Water Line (SWL), the validation was limited to the sub-aerial portion of the profile. The computed beach volume results are in close agreement with the computed volume from the beach profiles during non-monsoon and monsoon months except during October and November. The comparison for the months of May to July is not possible since the beach is completely eroded at this station due to the rough monsoon wave conditions. The measured beach profiles indicate an overall eroding tendency without any significant recovery even towards the end of the year (i.e. during December), and this corroborates well with the simulated beach volume computation (Fig. 20).

Statistical error estimates of the results for each month have been calculated from the monthly beach and simulated cross-shore profiles and are presented in Table 4. In addition
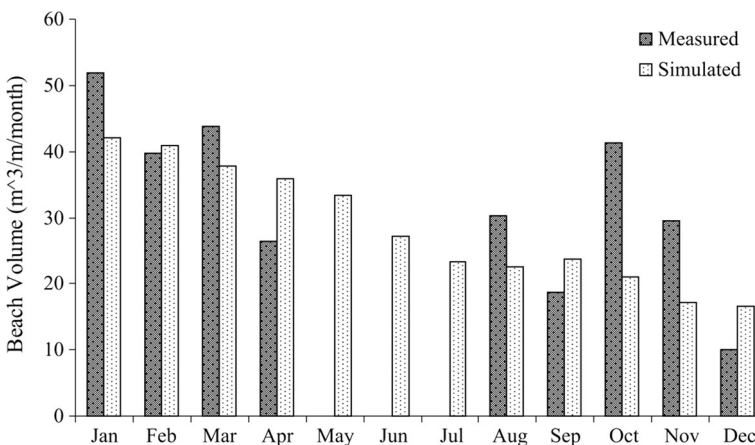
Fig. 20 Validation of the cross-shore transport using the beach volume from the measured beach profile and simulated beach volume from the LITPROF cross-shore profile during January–December 2014 for Srayikkadu (*Note* No beach during May–July)

Table 4 Error estimation for the beach profiles using the measured beach profile and simulated cross-shore profile (from LITPROF) during January–December 2014

Month	RMSE	BIAS	SI	SD	CC	BSS	Remarks from BSS (van Rijn et al. 2003)
Jan-2014	0.79	−0.22	0.67	1.04	0.73	−0.31	Bad
Feb-2014	0.63	0.12	0.79	1.07	0.83	0.24	Poor
Mar-2014	0.67	−0.07	0.74	1.14	0.82	−0.29	Bad
Apr-2014	0.47	0.43	0.68	1.12	0.99	0.83	Good
May-2014	#	#	#	#	#	#	–
Jun-2014	#	#	#	#	#	#	–
Jul-2014	#	#	#	#	#	#	–
Aug-2014	0.60	−0.33	0.65	1.07	0.91	0.34	Fair
Sep-2014	0.38	0.26	0.96	1.09	0.97	0.93	Excellent
Oct-2014	0.89	−0.77	0.67	1.19	0.92	−3.79	Bad
Nov-2014	0.69	−0.47	0.67	1.15	0.89	0.45	Fair
Dec-2014	0.59	0.57	1.00	1.03	1.00	0.92	Excellent

RMSE root-mean-square error, *SI* scatter index, *SD* standard deviation, *CC* correlation coefficient, *BSS* Brier Skill Score, [#] no beach

to this, the Brier Skill Scores estimated from the computed beach volume change are presented in the Table 5. The results show a good correlation during the entire period of observation even though the root-mean-square error value is a bit high. Also the bias is within the acceptable limit except for the months of April, October, November and December. The scatter index and standard deviation values are also reasonably good during the entire period of observation.

The Brier Skill Scores (BSS) have been estimated from the measured beach profiles and from the simulated cross-shore profile for each month during January to December 2014.

Table 5 Estimation of BSS from the measured and simulated beach volume (from the LITPROF cross-shore profile) during January–December 2014

Month	BSS	Remarks from BSS (van der Wegen et al. 2011)
Jan-2014	0.19	Fair
Feb-2014	0.78	Excellent
Mar-2014	0.97	Excellent
Apr-2014	0.70	Excellent
May-2014	#	#
Jun-2014	#	#
Jul-2014	#	#
Aug-2014	0.98	Excellent
Sep-2014	0.92	Excellent
Oct-2014	−1.22	Bad
Nov-2014	0.88	Excellent
Dec-2014	0.93	Excellent

BSS Brier Skill Score, [#] no beach

As per the classification of the BSS (proposed by van Rijn et al. 2003; Sutherland et al. 2004; van der Wegen et al. 2011) Scores <0; 0–0.1; 0.21–0.2; 0.2–0.5; and 0.5–1.0 represent 'bad', 'poor', 'fair', 'good' and 'excellent' validation of the model results, respectively. Also an additional error factor was introduced in the BSS estimation by van Rijn et al. (2003), and the Scores were reclassified as BSS < 0, 'bad'; 0–0.3, 'poor'; 0.3–0.6, 'fair'; 0.6–0.8, 'good'; and 0.8–1.0, 'excellent'. In this simulation the highest BS Scores of 0.93 and 0.92 are observed during the months of September and December, respectively, and the scores are considered as excellent according to van Rijn et al. (2003). The BSS estimates for the remaining months indicate mixed response as is evident from the scores of 0.24 (February), 0.34 (August) and 0.45 (November) which denotes 'poor' and 'fair' validation. The negative values obtained for the BSS estimates for January, March and October show poor comparison between the measured and simulated values. This probably could be due to the changing environmental conditions that prevail during the transition periods between the high and low wave activity period (i.e. the monsoon, monsoon breaks, and non-monsoon period). It is expected that by increasing the frequency of measurements during these periods better tuning of the model results is possible during the calibration stage and the BS scores can be improved considerably.

For validation of numerical models, the estimation of BS Scores considering the measured and simulated volume has been adopted widely by many researchers for similar studies. In the present study, the BSS estimates have been made from the measured and simulated beach volume for each individual month from January to December 2014. A similar study has been performed by van der Wegen et al. (2011) using the measured and modelled depositional volume. Maximum BSS indicating 'excellent' performance is observed during the months of February, March, April, August, September, November and December. The BSS score shows 'fair' estimate for January (0.19), and the validation is bad during the month of October.

The BSS estimates using the measured and simulated profile and beach volume, in general, confirms the acceptability of the model. The monthly cross-shore sediment transports across the surf zone and innershelf for Srayikkadu computed using the model are presented in Fig. 21, and the annual cross-shore sediment transports are presented in Table 6.
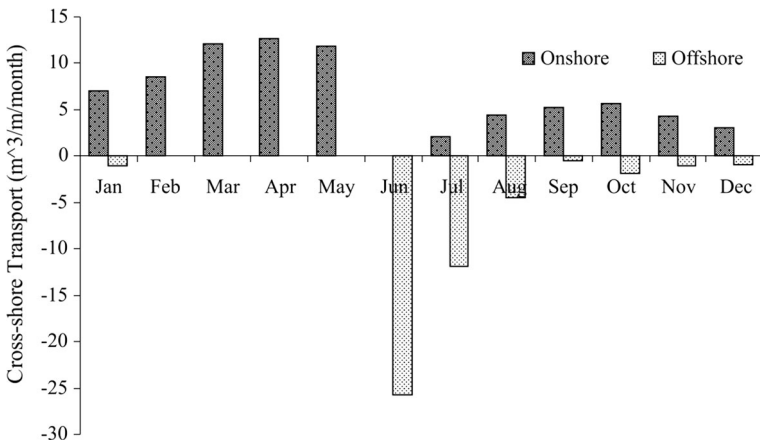
Fig. 21 Monthly cross-shore sediment transport at Srayikkadu estimated by using LITPROF module of LITPACK during January–December 2014

Table 6 Annual cross-shore sediment transport at Srayikkadu estimated by using LITPROF module of LITPACK during January–December 2014

Annual cross-shore transport (m³/m/year)	
Onshore transport	77
Offshore transport	−47
Gross transport	124
Net transport	30

The computed values show an annual onshore and offshore transport of 77 and 47 m³/m, respectively with a net annual cross-shore transport of 30 m³/m in the onshore direction. It can be seen that the onshore transport dominates during the 1-year simulation period.

6 Discussion

The study has brought out the nearshore sediment transport regime for a location of the Chavara coast. The LST in the surf zone has a net yearly value of about 79,000 m³ in the northerly direction, whereas the transport in the innershelf is consistently southerly with a value of about 43,000 m³. While LST in the surf zone has been estimated by various researchers for this coast (Chandramohan and Nayak 1991; Sajeev et al. 1997; Jose et al. 1997; Sanil Kumar et al. 2006; Black et al. 2008; Sheela Nair et al. 2015), the LST in the innershelf is estimated only by Black et al. (2008). Barring the recent works of Black et al. (2008) and Sheela Nair et al. (2015), the earlier authors have used empirical methods and the computations are based on wave data available only for short duration (seasonal observations for few days, monthly/weekly LEO observations). Thus, the exceptionally high quantities and contrasting direction obtained by them (Chandramohan and Nayak (1991)—950,000 m³/year towards south; Sajeev et al. (1997)—380,000 m³/year towards south; Jose et al. (1997)—360,000 m³/year towards south; Sanil Kumar et al. (2006)—380,000 m³/year towards south) may not be realistic. The present estimate of the LST in the surf zone works out to be very close to the net northerly longshore transport of 74,000 m³/year computed by Black et al. (2008). That the net surf zone longshore transport is northerly is amply clear from the huge accretion on the southern side of the breakwater at Kayamkulam inlet and the critical erosion observed on the northern side of the inlet (Kurian et al. 2012).

As regards the LST in the innershelf, the only other work available is that of Black et al. (2008). For a 2 km width of the innershelf, they have estimated a value of 1,72,000 ± 50 % m³/year which can be considered as high. The wide difference in the computed results may have to do with the models used. Moreover, the lower value of 43,000 m³/year appears to be agreeing to the field signatures which do not support the high quantum of transport obtained by Black et al. (2008).

Except for the study by Black et al. (2008), estimates on cross-shore sediment transport are lacking for this coast. They obtained onshore and offshore fluxes of 0.201 and 0.437 m³/m/day, respectively. Based on the assumption that onshore and offshore fluxes are predominant for 8 and 4 months, respectively in a year, they arrived at yearly values of 49 and 53 m³/m/year in the onshore and offshore directions, respectively. The assumption of offshore flux for 4 months in a year appears to be on the higher side. Thus there is every possibility that the onshore flux estimated by them could be on the higher side when

compared to the offshore flux. The higher onshore flux obtained in the present study when compared to offshore flux appear to conform to their results.

Black et al. (2008) based on their study for the Chavara coast has concluded that the system is a closed, dynamic, and finely balanced one. They have coined the term 'step ladder' for the observed dynamic equilibrium on a regional scale. However, the dynamic equilibrium which was proposed by them based on their field data pertaining to the period 1999–2001 is no more applicable to this coast. The physiographic setup of the coast has undergone tremendous change since then starting with the construction of two breakwaters at the Kayamkulam inlet in 2000 having lengths of 720 and 485 m on the south and north of the inlet, respectively. Groins numbering 26 that were constructed during the past 5 years also have brought in localised shoreline changes. The results of the present study confirm the absence of this dynamic equilibrium which is evident from the field data as well as the computed results. The monthly beach profiles for the year 2014 shows that the profile has not regained its original shape on completion of 1 year. To put it in terms of volume change, on completion of 1 year, the beach is in short of 44 m^3/m of sand to regain its original position. While 101 m^3/m is the offshore transport (volume of erosion), the onshore transport (volume of accretion) is only 57 m^3/m. Considering the fact that the beach profile station (Sraikkadu) could be under the influence of excessive sand mining in the neighbourhood some amount of sand loss is expected from that account. The actual quantity of sand available for onshore transport could be reduced due to this. Hence, the onshore transport observed in the field is found to be considerably less than the computed one.

The computed and observed sediment fluxes have a bearing on the mining volumes. As per the beach profile data, the yearly onshore transport is 57 m^3/m. Thus the maximum sustainable mining volume from a 1 km stretch of beach can be 57,000 m^3. As per the computed onshore sediment flux, the mining can be a much higher figure of 77,000 m^3 over a 1 km stretch of mining site. However, it should not be expected that the actual replenishment from offshore will be in tune with the computed one due to the reasons already mentioned. Excessive mining over the annual replenishment will have far reaching consequences as will be seen in the accompanying paper (Part III, Prasad et al. 2016).

7 Conclusions

A study of the nearshore sediment transport regime of a placer mining coast has been carried out combining field measurements with computations using different mathematical formulations. The longshore and cross-shore sediment fluxes in the beach and innershelf were estimated using the validated LITDRIFT and LITPROF models of LITPACK modelling system. The model results indicate dominance of annual onshore transport over offshore transport. The longshore transport in the surf zone is northerly, while it is consistently southerly in the innershelf. The two counter directional pathways are linked through the cross-shore transport. The domination of the computed onshore flux is actually not reflected in the observed beach volume change, probably due to the influence of excessive sand mining by the industries.

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