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Shoreline change along Kerala, south-west coast of India, using geo-spatial techniques and field measurement

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Abstract
Coastal zone is a central attraction for coastal engineers, scientists and coastal community due to economic and developmental activities of the coast. Kerala has 593 km of coastline. More than 50% of the coast is occupied with artificial structures such as ripraps, groins, seawall, ports and fishing harbours. These coastal protection structures and developmental activities played a major role in altering the shoreline position significantly. Therefore, periodical analysis and monitoring of shoreline change is the primary requirement for effective planning and management of the coast. This paper provides the primary requirement of shoreline change rate for the past 26 years using geo-spatial technology and field investigation for proper management of the coast. Landsat 5 and 7, Resourcesat 1 and 2 and Cartosat-1 data set were used as primary data source. Long-term shoreline change rate (1990–2016) was calculated using weighted linear regression statistical method. The morphological study was carried out to substantiate the shoreline change pattern. For detailed investigation, the study area was divided into five sediment sub-cells. The analysis revealed that the maximum erosion of 54% was noticed in sediment sub-cells II, followed by IV (52%) and III (43%) respectively. The result also indicated that the accretion/erosion pattern of shoreline change on either side of breakwaters was varying from place to place. The effectiveness of the coastal protective seawall was very minimal. This indicates that proper planning of any artificial structures is the basic requirement for effective management of the coast. The overall shoreline change status of Kerala coast indicates that 45% of the coast is eroding and 34% of the coast is in stable condition. Only 21% of the coast is of accreting nature. The field survey was carried out to validate the analysed results for entire coast, specifically along the coastal structures. The study demonstrates that the combined effect of satellite data and field investigation can be a reliable approach for shoreline change analysis for these complex environments.

Keywords Shoreline change · Erosion · WLR method · Satellite data and sediment sub-cell

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1 Introduction

Shoreline, the boundary between land and sea water, keeps on changes its shape, orientation and position continuously due to dynamical environmental conditions. Shoreline changes are caused either by natural processes or by human activities. Coastal landforms and their orientation are mainly controlled by various oceanographic parameters such as waves, tides, currents, rainfall, storms and sea level change (Albert and Jorge 1998; Morton and Miller 2005). Due to the continuous growth of coastal populations and community, infrastructures are threatened by coastal erosion and other natural calamities. Therefore, the demand has increased for accurate assessment of shoreline changes and its effect on the coastal area for better coastal management. Artificial structures such as groins and seawalls were constructed to protect the coastal community from natural hazards such as erosion. Seawalls change the near-shore process, particularly the sediment dynamics of the shore and, to some extent, the longshore sediment transport. Beach sediment transports are influenced by this interaction which tends to change in morphology of the coast (Griggs and Tait 1988). Waves directly hit the seawall and reflected back due to which scouring at the toe of the seawall (Pilkey and Cooper 2012) takes place. Breakwater which is built close to the shoreline causes a serious consequence which rapidly increases the erosion behind the breakwater. Therefore, it becomes much more important to understand the behaviour of the artificial structures thoroughly.

Some of the shoreline detection methods include conventional ground survey, radar or laser altimeters, airborne and space-borne multi-spectral remote sensing satellites. According to Thieler and Danforth (1994), Smith and Zarillo (1990), remote sensing data are used for the extraction of shoreline positions for change detection study. Other remote sensing technologies, such as synthetic aperture radar (SAR), have also been used for shoreline mapping and change detection (Tuell 1998). Gibeaut et al. (2000) used LIDAR data and historical aerial photographs to study shoreline change along the Gulf of Mexico. Lee and Shan (2003) have combined the topographic data (LIDAR) and multi-spectral images (IKONOS) for coastal mapping. But, optical satellite data were found to be most successful data source, especially medium- to high-resolution sensors for shoreline change analysis. The optical images have the advantage as it has large aerial extent and easily obtainable. Even the tidal variation of the images remains the same for the entire scene. Hence, the tidal error of the image can be minimized to a certain extent. In the present study, an application of modern survey methods which includes both remote sensing data and field data was used to study the shoreline change pattern of the coast.

Visual interpretation of any geographic features in satellite imageries depends on interpreter skills (Anders and Byrnes 1991). Satellite imageries have certain limitation and hence cannot be used directly. Some of the possible uncertainties in satellite imageries are having cloud cover, rectification error, spatial resolution error, seasonal variation, pixel variation, tidal variation, etc. These limitations may impact the accuracy of extracted shoreline proxy. Therefore, these errors have to be taken into account before shoreline analysis. There are many statistical methods adapted to calculate the shoreline change rate (Maiti and Bhattacharya 2009; Kuleli et al. 2011; Ozturk et al. 2015).

Weighted linear regression rate method was best suited for calculating the shoreline change rate. This method has the advantage of taking the uncertainties and error values into consideration while calculating the shoreline change rate (Selvan et al. 2014; Kankara et al. 2015).

Eroding coast has been protected by hard structures like groins and seawalls. This approach may provide a short-term relief but on a longer run, the problems generally transfer from one geographical location to another. Erosion is one of the major coastal hazards along the Kerala coast for the past century due to which more than 50% of the coast was protected with artificial structures such as groins, seawall and breakwater. Noujas and Thomas (2015) have studied the hot spot eroding locations along Kerala coast and reported major erosion sites are downdrift side of artificial structures. Population along the coast has increased drastically, and therefore it becomes necessary to protect the coast from this natural phenomenon. For improvised coastal management system, shoreline change rates were studied on the basis of sediment sub-cell concept. Delineation of sediment sub-cells was based on the coastal processes (wave/wind/current, littoral drift pattern, sediment budget and bathymetry) prevailing along the coast (NCSCM 2014). The sediment transport rate plays vital roles in determining the stability of the coast. Coastal infrastructure development has become very vital for the economic progress of the state. This research work mainly focuses on the shoreline change study for the past 26 years and to determine the impact of artificial structures (groins, breakwater and seawall) on shoreline configuration of Kerala coast using remote sensing techniques in GIS environment.

2 Regional settings

Kerala is located in the south-west corner of the Indian subcontinent. The coast extends from Manjeshwar in the north to Pozhiyur in the south. It covers nine coastal districts. Kasaragod and Alappuzha districts are the longest coastal stretch, whereas Ernakulam and Kollam districts are the shortest coastal stretch. The total length of all nine coastal districts is shown in Table 1. The 593 km long coastline appears to be almost straight and oriented in NNW–SSE direction (Fig.1). The coastlines of Kerala have been originated as a result of faulting during the late Pliocene period (Krishnan 1968). Some of the prominent geomorphic features along the coast are sandy beaches, estuaries, bays, lagoons, rocky cliffs, headlands, sand dunes, barriers, spits, tombola, etc. The coastal belt of Kerala experiences both south-west and north-east monsoon seasons annually. But south-west monsoon has the severe affect and devastates the coast to the maximum extent (Shamji et al. 2010). During south-west monsoon, the intensity of wave increases along Kerala coast and thereby impacts the coastal region (Noujas and Thomas 2018), whereas during non-monsoon time, the coast experiences calm wave condition. According to Kumar et al. (2006), during south-west monsoon the waves approach from west and WSW direction. But during north-east monsoon, the waves approach from west and WNW direction. The Kerala coast is categorized as micro-tidal range, and in central Kerala, the tidal range is less than 1 m (Noujas et al. 2016). The direction of net sediment transport along Kerala coast varies from place to place due to change in wave parameters. Sheela Nair et al. (2015) has computed the net annual longshore sediment transport using Kamphuis (2002) formula and reported that net LST varies between 0.32×10^5 m^3 and 2.3×10^5 m^3 along the Kerala coast. The coast is dotted with one major port, 24 fishing harbours, 44 rivers, 27 estuaries and 7 lagoons or kayals. Some of the major rivers are Bharathapuzha, Pamba, Periyar and Chaliyar. Kerala coast has numbers of islets or islands. Dharmadam, a large island with mangroves, is situated on the northern coast of Kerala. About 40% of the people live in or near the coastal zone with a very high density of more than 2500 persons per sq km (Sachin Pavithran et al. 2014).
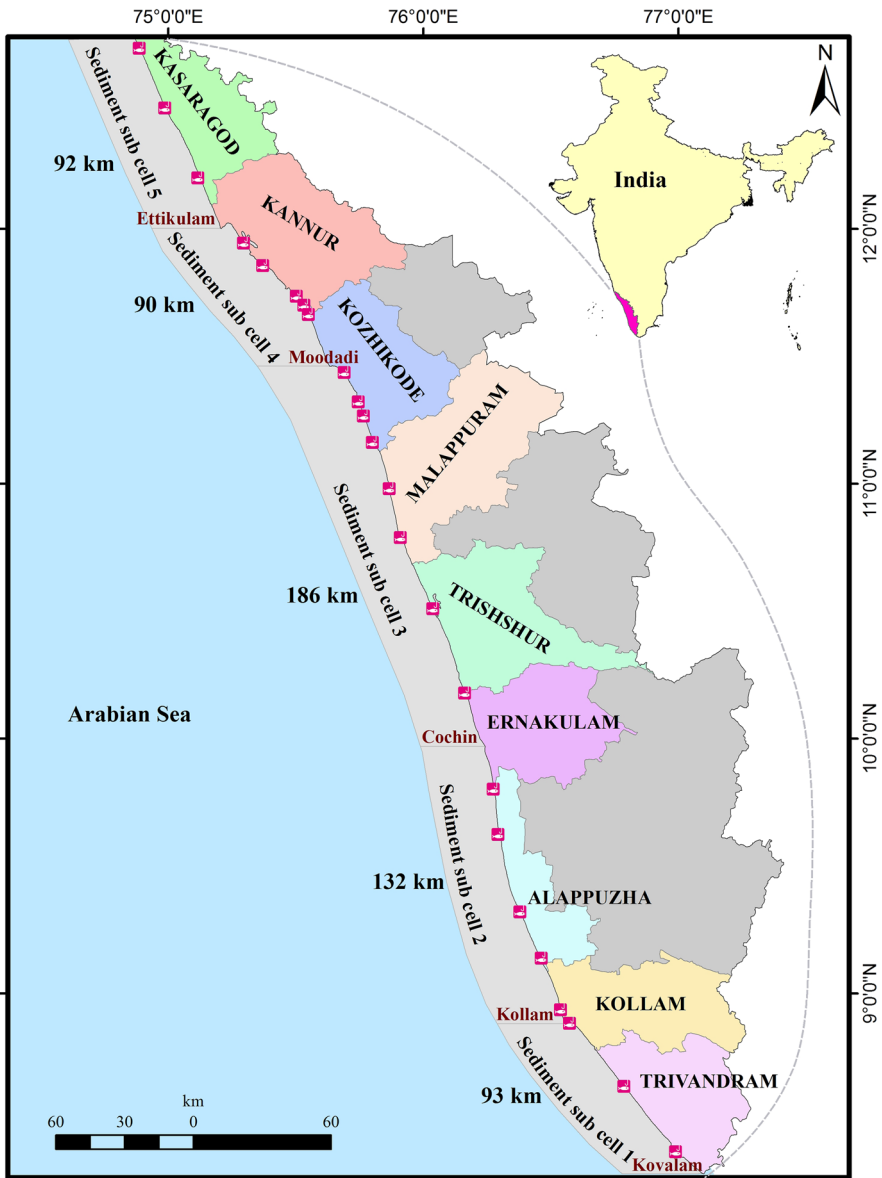
Fig. 1 Study area with five different sediment sub-cells

The coastal zone of Kerala is well known for its rich fisheries and placer mineral deposits. One of the most peculiar features seen in Kerala coast is mud banks. Mud banks are the region of calm and turbid water with high load of suspended sediments during south-west monsoon period. It forms near to the shore (Kurup 1977; CMFRI 1984). This is commonly observed in Thrikkunnapuzha to Alappuzha, Chellanam to Munambam and Calicut to Muzhappilangadi (Nair 1983).

Table 1 Coastal districts of Kerala

S. no.	District names	Coast length (in km)
1	Kasargode	83.51
2	Kannur	69.05
3	Calicut	78.05
4	Malappuram	50.86
5	Thrissur	61.55
6	Ernakulam	45.05
7	Alappuzha	83.55
8	Kollam	45.72
9	Thiruvananthapuram	75.62

Seasonal variation along the west coast was very prominent and played a significant role in altering the shoreline. Pre-monsoon (February–May), monsoon (June–September) and post-monsoon (October–January) are the major monsoon seasons which determine the activeness of coastal processes and wave climate along the west coast of India (kumar and Deo 2004). Therefore, the field survey was carried out in two different seasons. The hand-held GPS field survey was conducted during pre-monsoon season (February 2017) and during monsoon season (July 2017).

3 Materials and methods

The multi-temporal of multi-spectral satellite images such as Landsat (TM and ETM+), IRS-P5 (PAN) and IRS-P6 (LISS-III and LISS-IV) were used to calculate the shoreline change rate (Table 2). Due to non-availability of the homogeneous fine-resolution dataset, shoreline changes analysis has been carried with multi-resolution images. The handheld GPS field survey was undertaken for entire Kerala coast to collect ground control points (GCPs) with a 10-km buffer zone from the coast. About 100 GCPs collected from the field survey were evenly distributed all along the images for calculating the transformation. All

Table 2 Details of satellite data sets and uncertainty used in the study

List of image	Pixel size (m)	Date	Et (m)	Source
Landsat 5—(TM)	30	1989–1992	15.0	USGS
Landsat 7—(ETM+)	30	1999–2001	15.0	USGS
IRS P5 (Cartosat-1)—(PAN)	2.5	2005–2006	1.10	NRSC
IRS P6 (Resourcesat-1)—(LISS-III)	23.5	2008	15.0	NRSC
IRS P5 (Cartosat-1)—(PAN)	2.5	2009–2010	1.10	NRSC
Resourcesat 2—(LISS-IV)	5.8	2012	9.0	NRSC
Resourcesat 2—(LISS-IV)	5.8	2013	9.0	NRSC
Resourcesat 2—(LISS-IV)	5.8	2014	9.0	NRSC
Resourcesat 2—(LISS-IV)	5.8	2015	9.0	NRSC
Resourcesat 2—(LISS-IV)	5.8	2016	9.0	NRSC

the satellite images were georectified using GCPs with second-order polynomial transformation (Projection: UTM, Datum: WGS-84) in ERDAS IMAGINE 2013 software and maintained the root-mean-square error (RMSE) within a subpixel accuracy.

3.1 Shoreline extraction

Knowledge about the coast is very important to define the shoreline positions. Field survey helps in better understanding about the limitations and advantages of the coast. Identifying and defining the shoreline proxy has the potential to induce errors when estimating a shoreline position (Stockdon et al. 2002). The morphologic characters of the coast are changes from one geographic location to other. Hence, to extract a shoreline from a single feature class becomes a difficult task. Morton and Speed (1998) and Pajak and Leatherman (2002) explained various shoreline indicators such as bluff edges, vegetation lines, high water marks, beach crust, dune crust and beach scarp. Demarcation of a shoreline position from any satellite data is a subjective topic due to the different ranges of tidal variability, different meteorological conditions, inequalities in spatial resolution (pixel), seasonal setup, scaling factors and temporal data sets. In the present study, wet and dry line in sandy shore, vegetative line, rocky coast edge, cliff edge and seawalls with seashore facing are used as shoreline proxy (Kankara et al. 2014, 2015; Selvan et al. 2016). The shoreline positions were extracted from rectified satellite images of different years in ArcGIS 10.2 software.
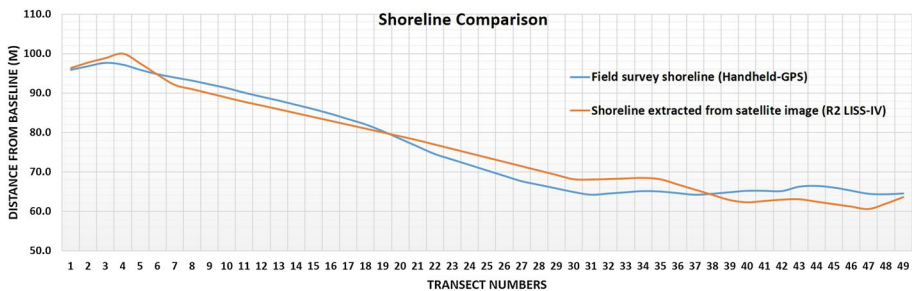
Fig. 2 Comparison of field-surveyed shoreline position with satellite-extracted shoreline along Punnapra beach, Kerala

Plate 1 Shoreline position tracking using handheld GPS along Punnapra beach, Kerala

Automated or semi-automated segmentation techniques were applied to extract the shoreline from various remote sensing data (White and El Asmar 1999; Dellepiane et al. 2004). According to Pal and Pal (1993), there is no single method which can be considered as good for all images. In the present study, after considering all the criteria and limitations, semi-automated method (includes both manual digitization with field inputs and automated extraction) was considered as a suitable method for extracting the shoreline position. Pixel misinterpretation is very common and important error in automatic method. Therefore, semi-automated method was best suited for shoreline extraction where this error can be minimized in the initial stage.

Field survey was conducted to track the shoreline positions during satellite pass time using handheld GPS (Trimble GEO XH 6000) at five different locations (Poovur, Punnapra beach, Paravanna beach, Mahe and Manjeshwar region). This handheld GPS (Trimble GEO XH 6000) provides the data with an accuracy of 1–3 m. 1 km coastal stretch was surveyed at each location separately. Shoreline positions were particularly tracked to compare and validate with the shoreline extracted from satellite images. Plate 1 shows the shoreline tracking using handheld GPS at Punnapra beach. The tracked shoreline is then compared with the shoreline extracted from 2016 LISS-IV (5.8 m) satellite images as shown in Fig. 2. Comparison shows that the field-surveyed shoreline positions were well matched with the shoreline extracted from images. The comparison shows that the maximum difference between two shoreline positions is within a pixel limit (5.8 m). The comparison of shorelines provides the higher confidence level with the extracted shoreline position.

3.2 Statistical methods for shoreline change calculation

The long-term shoreline changes for the past 26 years were computed with ten series of data set. Long-term shoreline change rate was generated using Digital Shoreline Analysis System (DSAS Version 4.1) which is an ArcGIS extension tool developed by the USGS (Thieler et al. 2009). WLR statistical method was used to calculate the rate of change. The shoreline change rates are calculated by taking the slope of the regression line (fitting a least-square regression line) for all transect along the coast. Further, a weightage value is attached to shoreline data considering the measurement and positional uncertainties involved in obtaining the data. Fine-resolution/quality data sets are given greater emphasis or weightage towards determining a best fit line in comparison with unreliable or poor data sets, i.e. the regression line can be placed in such a way so that the sum of the squared residuals is minimized. The weight (w) is defined as a function of the variance in the uncertainty of the measurement (e):

$$w = \frac{1}{e^2}, \tag{1}$$

where e = shoreline uncertainty value.

The shoreline positions were compiled in ArcGIS. A baseline was drawn parallel to the shoreline from where the starting point of all transects cast and intersect the shoreline position perpendicularly to calculate the rate (Leatherman and Clow 1983). In the present study, 20 m transect distance was maintained between each transect throughout the coast.

3.3 Uncertainty in shoreline position

The calculated shoreline change rate can be reliable only when the measurement errors are accounted which determines the accuracy of all the shoreline position. Several sources of errors were explained in detail which may affect the accuracy of historical shoreline positions (Anders and Byrnes 1991; Crowell et al. 1991; Thieler and Danforth 1994; Moore 2000; Morton et al. 2004). Hence, it is necessary to determine the errors and uncertainties associated with each shoreline position. In the study, five different errors were taken into account to calculate the final shoreline rate. Seasonal error (E_s) is the standard deviation of a randomly generated uniform distribution with minimum and maximum values equal to the mean plus two times the standard deviation of the difference in the seasonal shoreline positions. Tidal fluctuation error (E_{td}) is the standard deviation of a randomly generated uniform distribution with minimum and maximum values equal to two times the horizontal movement of the LWM. Digitizing error (E_d) is the error associated with digitizing the shoreline from satellite imagery. Interpretation of any features varies from person to person, and to minimize the digitizing error, only one analyst should digitize the shorelines positions for all satellite images. Pixel error (E_p) is the pixel size of the image. The pixel size in ortho-rectified images is 0.5 m, which means anything within 0.5 m cannot be resolved. Rectification error (E_r) is calculated from the ortho-rectification process. The RMS values calculated by the software are considered as rectification error. The total shoreline position error (E_t) includes all the measurement and positional errors by taking the square root of sum of the squares of seasonal error (E_s), tidal fluctuation error (E_{td}), digitizing error (E_d), pixel error (E_p) and rectification error (E_r) as shown in the following equation:

$$E_t = \pm\sqrt{E_s^2 + E_{td}^2 + E_d^2 + E_P^2 + E_r^2}. \tag{2}$$

For an example, 2016 data seasonal error = 7 m, tidal = 1.0 m, digitization error = 2.6 m pixel = 0.5 m, and rectification error = 4.9 m; hence, the total is error calculated as SQRT $(7^2 + 1.0^2 + 2.6^2 + 0.5^2 + 4.9^2) = 9.0$ m. Like this, the uncertainties values of each shoreline positions were calculated separately as shown in Table 2. Finally, the position errors are incorporated into the shorelines attribute to calculate the weighted regression rate.

4 Results and discussion

The Kerala coast was divided into five divisions based on sediment sub-cell criteria (NCSCM 2014) for detailed analysis. The sediment cell is defined as the length of the coastline and associated near-shore areas where movement of sediment is largely a self-contained. Distribution of these five sediment sub-cells from south to north is shown in Fig. 1, and the length of each sediment sub-cell is tabulated in Table 3. The sediment budget and the transport rate play a significant role in determining the stability of the coast which is primarily governed by the coastal processes prevailing in the area. The longshore sediment transport (LST) has significant influences in shoreline change pattern (Sheela Nair et al. 2015). Long-term shoreline study for five different cells was calculated for the past 26 years (1990–2016) using ten different datasets. The rate thus obtained from

Table 3 Details of long term shoreline change rate for 5 sediment sub cells and status of artificial structure(groins) mapped for year 2016 using Resourcesat-2 (LISS-IV) along Kerala coast

Class	Coastal length (km)	Erosion		Stable		Accretion		Number of groin structures as on 2016
		km	%	km	%	km	%	
Sub cell I	92.63	33.34	36	31.37	34	27.92	30	42
Sub cell II	131.96	70.8	54	36.52	28	24.64	19	93
Sub cell III	186.35	80.74	43	59.15	32	46.46	25	24
Sub cell IV	90.34	47.26	52	29.1	32	13.98	15	03
Sub cell V	91.68	33.08	36	43.2	47	15.4	17	00

analysis was classified into seven different categories. The classification scheme adopted to symbolize the long-term shoreline change rate pattern was taken from the work carried by Kankara et al. (2014). The range between −0.5 and +0.5 m was classified as stable condition. −0.5 to −3.0 m falls in low erosion, and −3.0 to −5.0 m falls in moderate erosion. Similarly, 0.5–3.0 m falls in low accretion category and 3.0–5.0 m falls in moderate accretion. The results thus obtained from the analysis are described below.

4.1 Sediment sub-cell I

Sediment sub-cell I stretches from Kovalam to Kollam with a length of 92.63 km. In general, the region between Karumkulam and Kazhivoor (5.8 km), Puthenthope to Muthalapozhi fishing harbour (7.0 km) and Anchuthengu to Varkala (7.0 km) is noticed with moderate-to-high accretion pattern, whereas 19-km stretch from Kazhivoor to Shangumugham is noticed with low erosion.

Vizhinjam fishing harbour is located between the rocky promontory on the north and rocky outcrop on the south. These outcrops play a significant role in controlling the hydrodynamic factor. The region between Poovar and Vizhinjam fishing harbour is seen with stable to low accretion. The rocky outcrop south of Vizhinjam fishing harbour acts as a barrier and traps the sediments flow. Due to this outcrop, the northern region was noticed with low erosion. The effect was clearly seen in places like Vazhamuttom and Pannatura where seawalls are placed to protect the coast. High-to-moderate erosion was noticed between Pannatura and Poothura. A similar observation was noticed by a recent study (Noujas and Thomas 2015). A stable pattern was noticed between Puthenthope and Shangumugham. Puthenthope to Muthalapozhi fishery harbour was noticed with moderate-to-high accreting pattern. This accretion is mainly due to the breakwaters at Muthalapozhi fishery harbour which trapped the sediments flow towards the north. About 350 m width of sediments was deposited on the southern side of the breakwater. But this harbour had the adverse effect on the northern side of the coast. This effect was seen till Thazhampally region due to which seawall was constructed to protect the coast. The effect of the breakwater and its impact on the adjacent coast along Thiruvananthapuram coast were documented by Neelima et al. (2018). Muthalapozhi fishing harbour (Fig. 3a) shows a familiar trend of accretion at the southern side and erosion at the northern side. Similar findings were documented by Noujas and Thomas (2018). This kind of sediment deposition along Muthalapozhi fishing harbour indicates that the net sediment transport is towards north direction. Recent study along this region also shows the similar trend (Thomas et al. 2013; Sheela Nair et al. 2015,
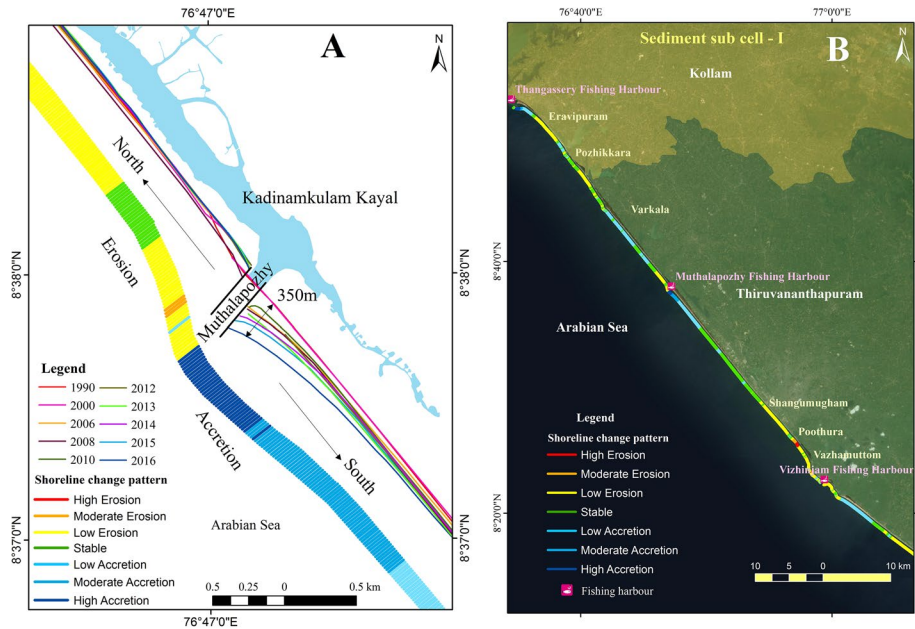
Fig. 3 **a** Shoreline change result on either side of Muthalapozhi fishing harbour. **b** Long-term shoreline rate for sediment cell I

b; Noujas and Thomas 2018). After Thazhampally, stable to low accretion was noticed till Varkala region. From field survey, it was noted that the seawall at Kayikkara was abandoned. Even the Rathickal region where series of groins (20 numbers) were filled with sediments is shown in plate 2a. This indicates that the coast is experiencing accretion at a faster rate. From the analysis, this particular coastal stretch was noticed with moderate accretion. 15-km stretch from Varkala to Eravipuram was seen with low erosion. Slumping of a lateritic cliff at Varkala was very prominent due to which even the cliff region was protected with seawall. Plate 2b shows the slumping of a lateritic cliff at Varkala region. South of Thangassery fishery harbour was noticed with a moderate-to-low accretion pattern. This may be due to the southern breakwater which traps the sediments, thereby making the region with sediment-rich coast. About 2.5 km south of southern breakwater, a broken dredger ship was trapped along the coast at Eravipuram. The vessel that washed ashore has become a matter of concern for the coastal people as it had the direct influence on the sediment transport, thereby altering the coast seasonally on either side of the broken ship. This broken ship acts as an asymmetric tombolo landform. Field survey was undertaken in both the pre-monsoon and monsoon seasons to understand the seasonal impact on the coast. Plate 2c shows the depletion of sand towards the north of broken vessel during pre-monsoon (Feb 2017). But, plate 2d shows the same location during monsoon (July 2017) with sand deposition. Analysis along sediment cell 1 clearly shows similar pattern of accretion along the southern side of the fishing harbour and erosion along the northern side. According to Noujas et al. (2014), the wave pattern along Thiruvananthapuram District is south–south-west (SSW) direction during fair season and west–south-west (WSW) direction during monsoon season. This trend indicates net sediment transport is towards north during most of the year. The overall pattern of the sediment sub-cell I shows 36% of

Plate 2 **a** Rathikkal location where groins were buried in sand. **b** Slumping of lateritic cliff at Varkala. **c** Field photograph showing depletion of sand towards the north of broken vessel during pre-monsoon (Feb 2017) at Eravipuram. **d** Field photograph showing sand deposition towards the north of broken vessel during monsoon (July 2017) season at Eravipuram

the coast was affected by erosion. 30% and 34% of the coast were under accretion and stable for the past 26 years. Figure 3b shows the shoreline change patterns for sub-cell I with seven different classes. The result of erosion/accretion is comparable to the recent study conducted by Noujas et al. (2017).

4.2 Sediment sub-cell II

Sediment sub-cell II is about 132 km from Thangassery fishery harbour at Kollam to Cochin port. Five fishing harbours (Neendakara, Kayamkulam, Thottappally, Chethi and Chellanam) are situated along this coast. The region between Thangassery and Neendakara fishing harbour is fully protected with seawall with few groins to arrest the sediments near the villages for traditional fishing work. The region between Neendakara and Kayamkulam fishing harbour which is about 24-km stretch was protected with seawall and groin series due to varying degree of erosion. At Neendakara fishing harbour, low erosion to stable condition was observed on either side of the breakwater (Fig. 4a). Sediment transport at this region shows irregular distribution due to which erosion was seen on both side of the fishing harbour. This defines the complication in the local morphology of the coast. Lack of sediment deposition on the southern side of Neendakara fishing harbour is mainly due to the Thangassery headland (Noujas and Thomas 2018). High erosion was noticed in Vellanathuruthu. The mining and processing of India Rare Earth Limited (IREL) and Kerala
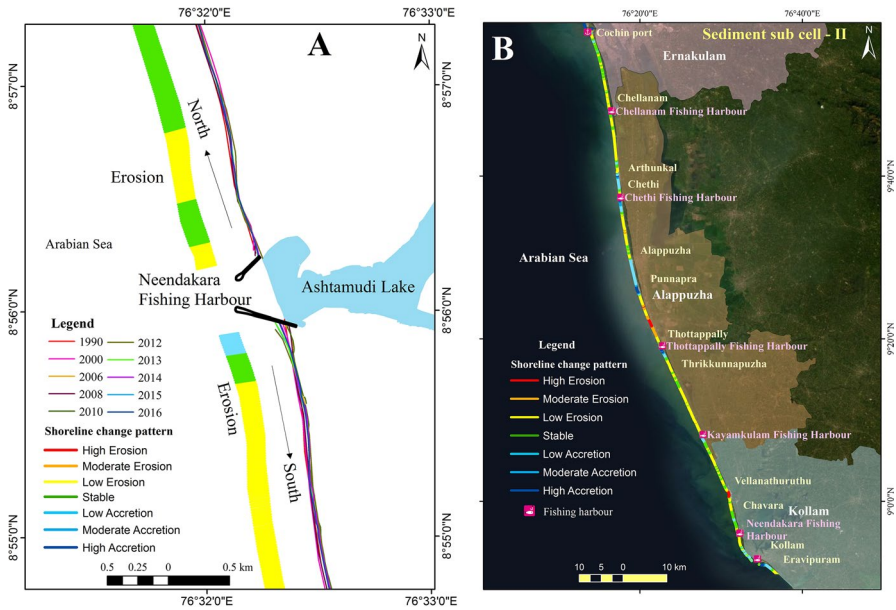
Fig. 4 **a** Shoreline change result on either side of Neendakara fishing harbour. **b** Long-term shoreline rate for sediment cell II

Mineral and Metal Limited (KMML) along the coastline of Chavara, Kollam, has played a significant role in altering the coastline. Noujas and Thomas (2015) reported Vellana-thuruthu mining site as one of the erosion hot spots based on their direct field measure-ments. Seawall can be seen on either side of the mining site to protect the coast. There is an open space of about 800 m between these seawalls. Due to high wave actions, the open coast at this region was altered as a bay-like structure (plate 3a). 22-km stretch from Kay-amkulam to Thottappally fishing harbour was seen with low erosion. This stretch too was protected with artificial structure (seawall and groins) to protect from erosion. About 3 km south of Thottappally fishing harbour was noticed with moderate-to-high accretion due to
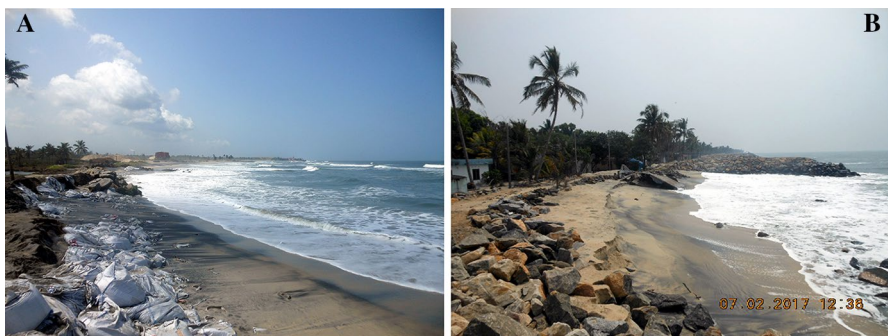
Plate 3 **a** Vellanathuruthu where the coast affected by sand mining process. **b** Slumping of seawall at Ambalapuzha

the southern breakwater which traps the sediments. This pattern clearly indicates that the net littoral sediment transport is towards north direction. Noujas and Thomas (2018) have accounted similar pattern of sediment transport. But the adverse effect was seen on the northern side of Thottappally fishing harbour where moderate-to-high erosion was noticed till Ambalapuzha. Field survey was carried out along the Ambalapuzha coast to substantiate the present condition of the coast. Field photograph shows slumping and scouring of seawall at Ambalapuzha region (plate 3b). A series of 42 numbers of groins with varying length was noticed along this entire stretch to protect the coast. This indicates that the particular stretch was severely affected by coastal erosion. About 8-km stretch from Punnapra to Alappuzha was noticed with moderate-to-high accretion. Noujas and Thomas (2015) have reported the mud bank at this particular region due to which the coast was seen with high sand deposition. Further north of Alappuzha, the shoreline pattern again recedes to low erosion pattern till Mararikulam. 3 km south of Chethi fishing harbour was noticed with moderate-to-high accretion pattern. Even the northern side of fishing harbour was noticed with moderate accretion till Arthunkal region. Noujas and Thomas (2018) have reported accretion pattern on the southern side of Chethi fishing harbour. This pattern of accretion and erosion indicates that the net sediment transport is northerly towards this region. No significant changes were noticed on either side of the Chellanam fishing harbour. In the entire stretch from Arthunkal to Cochin port, low erosion to stable pattern was noticed.

The result indicates that the erosion/accretion of shoreline change rate on either side of the breakwater was a peculiar phenomenon along this sub-cell. This may be due to the orientation of the coastline. This sediment cell covers entire coastal district of Alappuzha and few portions in Kollam district. According to Sheela Nair et al. (2015), the coastline orientation along Alappuzha District is 255° with respect to true north and the wave direction is 221°–250°. All three categories (stable, erosion and accretion) were noticed on both sides of fishing harbours. Chellanam fishing harbour in particular has not shown any significant alteration to the coast. This gives indirect evidence about the sediment transport and its local morphology which decides the erosion/accretion of the coast. But due to the coastal orientation, the net littoral sediment transport is towards north for entire year (Sheela Nair et al. 2015). Sheela Nair et al. (2015) has reported that the monthly average significant wave height along Alappuzha coastal district is between 0.68 and 2.52 m and wave direction is 221°–250°. Shoreline change indicates 54% of the coast was noticed with erosion. 19% and 28% of the coast fall in accretion and stable condition. The overall change pattern suggests that the coast was dominated with high per cent of erosion as shown in Fig. 4b.

4.3 Sediment sub-cell III

Sediment sub-cell III is about 186.4 km from Cochin port to Moodadi. Eight fishing harbours are located at this particular stretch (Munambam, Chettuva, Ponnani, Tanur, Beypore, Vellayil, Puthiyappa and Koyilandi). A coastal length of 6 km north of Cochin port to Elamkunnapuzha was noticed with moderate-to-high accretion. During field survey, local people (fishermen) were interviewed regarding the status of the coast for the past years and decades. According to fishermen, sand deposition at this particular stretch was due to the accumulation of dredged sediments from Cochin port. According to Dinesh et al. (2014), the shoreline position at Elamkunnapuzha (Malappuram) was receded by about 954 m. Field photograph clearly shows the sand deposition before the seawall base (plate 4a). A net shoreline movement of about 100 m width of sand deposition was noticed along
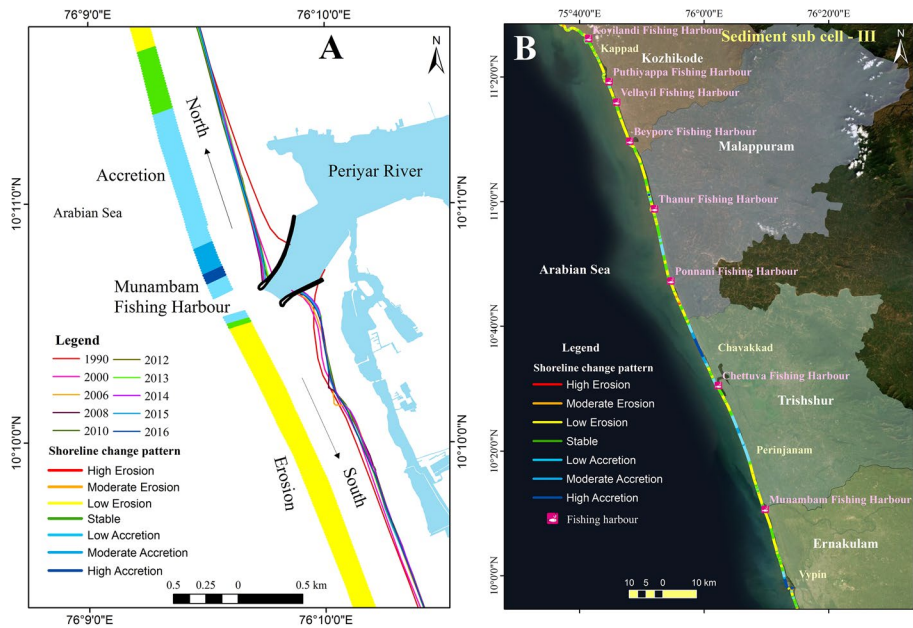
Fig. 5 **a** Shoreline change result on either side of Munambam Fishing Harbour. **b** Long-term shoreline rate for sediment cell III

Elamkunnapuzha region. 35 km coastal length from Elamkunnapuzha to Perinjanam was noticed with low erosion to stable condition. No significant changes have taken place from this particular stretch. Munambam fishing harbour shows low erosion on the southern side and low accretion at the northern side of the breakwater (Fig. 5a). This pattern of deposition indicates that the sediment transport is towards south along this stretch. Similar trend was observed by Noujas and Thomas (2018). According to him, the net sediment transport is −119,271 m^3/year along this coastal stretch. Low-to-moderate accretion was noticed between Perinjanam and Snehatheeram which is about 15-km-long coastal stretch. At Chettuva fishing harbour, low accretion was seen on the northern side of breakwater, whereas the southern side was seen with stable to low erosion. Similar trend of erosion
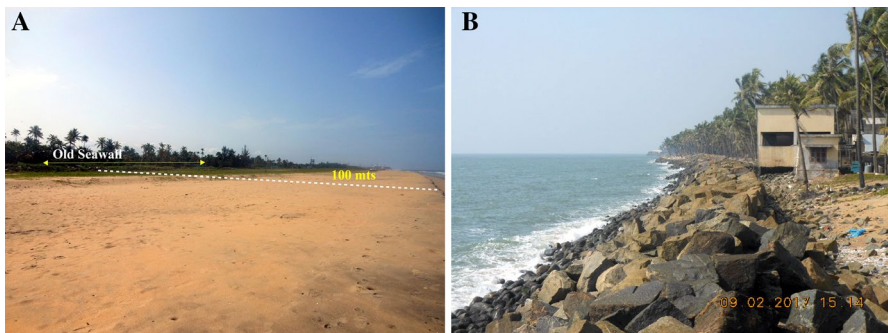

Plate 4 **a** 100 m width of sand deposition along Elamkunnapuzha region, Kerala **b** Erosion at Tannithura, Kerala, during pre-monsoon (February month)

and accretion was noticed along Munambam fishing harbour. Here too, the net sediment transport pattern is towards southern direction. From Chavakkad to Periyambalam which is about 14 km length was noticed with high accretion. Accretion at this region was mainly attributed due to the mud bank formation. Noujas and Thomas (2015) have explained about these mud banks and its role at Chavakkad region. 14 km south of Ponnani fishing harbour was seen with varying degree of erosion due to which the entire region was protected with seawall. Field survey shows that monsoon had very severe effect on this coast. Wave toppling is very common even during non-monsoon season. Plate 4b shows the field photograph of wave topping and hitting at Tannithura during February month. Stable to low accretion was noticed on the northern side of Ponnani harbour which indicates the net southerly transport at this region This accreting pattern was seen further north up to Tanur fishing harbour. Shoreline analysis indicates moderate accretion at places like Kuttayi Vakkad, Puthiya Kadappuram, Edakadappuram, Paravana and Unniyal. Abandoned seawall was seen at places like Paravana and Unniyal regions. Wide beach was measured before the old seawall and present shoreline position which indicates that the region was accreting for the past years. The remaining coast of about 60 km from Tanur fishing harbour to Moodadi was seen with stable to low eroding condition with few pockets of accretion. Low accretion was noticed on the southern side of Puthiyappa fishing harbour. But the northern side was noticed with stable to low eroding condition due to the presence of Elathur cliff. This pattern shows that net sediment transport is towards northern direction. This condition has been documented by Noujas and Thomas (2018). Koyilandi fishing harbour was seen with stable pattern on either side of the fishing harbour. Beypore and Vellayil are seen with similar pattern of low erosion to stable condition on either side of the breakwater.

The overall long-term shoreline analysis of sediment sub-cell III indicates that 43% of the coast was falling in erosion category followed by the stable with 32% and accretion with 25%. Accretion/erosion pattern varies for all fishing harbours. Munambam, Chettuva and Ponnani fishing harbours show similar pattern of shoreline change on either side of the breakwaters, which indicates that the net sediment transport is towards southern direction, whereas Puthiyappa, Koyilandi, Beypore and Vellayil fishing harbours show the opposite trend and hence indicates that the net sediment transport is towards northern direction. Change in sediment transport direction indicates that the longshore sediment transport is governed by the local condition and morphology of the coast. Figure 5b shows the shoreline change patterns for sub-cell III with seven different classes.

4.4 Sediment sub-cell IV

Sediment sub-cell IV is about 90 km from Moodadi to Ettikulam. It covers two coastal districts such as Kannur and northern part of Kozhikode. Five fishing harbours are located between these stretches (Chombala, Mahe, Thalai, Moplabay and Azhikkal). The entire coastal stretch from Moodadi to Chombala fishing harbour is about 26 km. Low erosion was noticed throughout the stretch, and therefore prior attention should be to given to arrest the erosion at this stretch. Stable to low eroding pattern was noticed on either side of the Chombala fishing harbour. Similar trend of low erosion was noticed till Mahe fishing harbour. The region between Mahe and Moplabay was bounded with many geomorphic features like long sandy beaches, pocket beaches, bays, rocky cliffs, sand dunes and headlands. Tombolo morphology was also noticed at Chera region. Mahe is about 3 km coastal length, which is one of the coastal districts of Union Territory of Puducherry. Stable to low erosion pattern was noticed along Mahe coast. Thalai
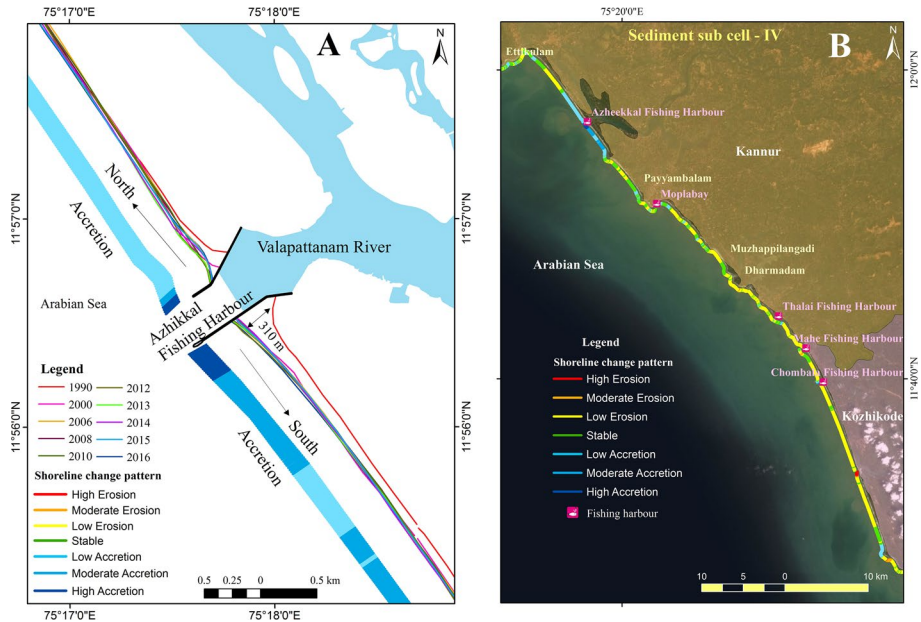
Fig. 6 **a** Shoreline change result on either side of Azheekkal Fishing Harbour. **b** Long-term shoreline rate for sediment cell IV

fishing harbour was located in Bay region due to which the northern side was naturally protected with the rocky coast. Low erosion pattern was noticed on either side of the fishing harbour. The Moplabay fishing harbour was also located in bay. The northern side of the bay was protected with the rocky coast, and the southern side was protected with a series of groins. Long-term analysis indicates low accretion on the southern side and low erosion on the northern side of the fishing harbour. 5-km-long stretch on either side of the Azhikkal fishing harbour was seen with moderate-to-high accretion. The Azhikkal fishing harbour was one of the peculiar locations where accretion was seen on either side of the breakwater (Fig. 6a). 310 m width of sandy beach was formed on the southern direction of the breakwater when compared to northern side.

From the long-term analysis, 52% of the coast was noticed with erosion. Remaining 15% and 32% of the coast falls in accretion and stable condition. Erosion and stable pattern were seemed to be more dominated in the sub-cell. This sediment cell has more significance as some of the fishing harbours such as Thalai fishing harbour and Moplabay fishing harbour were located at a bay region. Due to orientation of the coast, the headlands act as a natural barrier to these fishing harbours and form a bay-like structure. Sediment transport at this sediment cell is towards northern direction. Apart from Azhikkal where accretion was dominant, all other fishing harbours showed similar stable to low eroding pattern. Long-term shoreline change pattern for sub-cell IV is shown in Fig. 6b.

4.5 Sediment sub-cell V

Sediment sub-cell V is about 92 km from Ettikulam to Manjeshwar. Three fishing harbours (Cheruvathur, Kasaragod and Manjeshwar) were seen along this stretch.
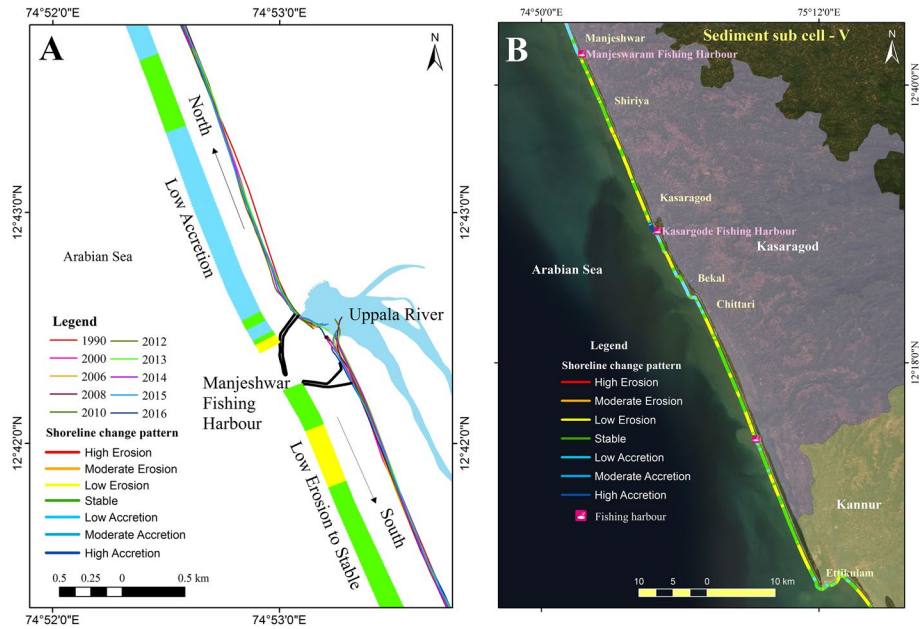
Fig. 7 **a** Shoreline change result on either side of Manjeshwar Fishing Harbour. **b** Long-term shoreline rate for sediment cell V

Long-term shoreline change status indicates low erosion to stable pattern. Cheruvathur fishing harbour shows low erosion on the northern side and low accretion on the southern side of the breakwater. In Kasaragod fishing harbour, moderate-to-high accretion pattern was noticed on either side of the breakwater. But in Manjeswar fishing harbour, accretion pattern was noticed on the northern side of a breakwater and low erosion pattern on the southern side (Fig 7 a). All three fishing harbours show different signatures of change patterns. Change in sediment transport direction indicates that the local condition and morphology of the coast govern the longshore sediment transport. About 4 km distance south of Bekal fort was noticed with low accretion to stable condition. A bay structure was noticed between Bekal fort and Bekal cliff region which suggests that the coast was in accreting nature. An abandoned seawall was noticed at Keezhur region. This indicates that the region is experiencing accretion for long period and there is no significance for these seawalls. About 5 km distance north of Manjeshwar fishing harbour was noticed with low accretion.

The shoreline status indicates 36% of the coast falls under erosion category. But, 47% of the coast was seen in stable condition. Only 17% of the coast was noticed with accretion pattern which was mainly at the north of Manjeswar, Kasaragod and near Bekal coast. Long-term shoreline change pattern for sub-cell V is shown in Fig. 7b.

5 Discussion

The overall long-term (1990–2016) shoreline analysis revealed that erosion was dominated by sediment sub-cells II(54%), III (43%) and IV(52%) respectively. Sediment sub-cell V was the only region where stable (47%) class was dominated. The overall percentage of

each class is shown in Table 3. 60 to 65% of the coast is protected with artificial structures such as seawall, groins and breakwater throughout the coast. About 162 numbers of groins were mapped using Resourcesat-2 LISS-IV (2016) satellite data. Sediment cells I, II and III are mostly dominated by these artificial structures to arrest the erosion all along the coast. Shoreline change result too reveals the importance of these artificial structures along these sediment cells. Details of all groins series in each sediment cells are shown in Table 3. These artificial structures (groins and breakwater) provide an indication to the littoral sediment transport direction throughout the coast. From the analysis, it was concluded that artificial structures played a significant role in altering the coastal processes, morphology and orientation of the coast. The erosion/accretion pattern along the fishing harbour does not remain the same which indicates that local parameter plays a vital role. Sediment cells I and II show similar pattern of accretion on the southern side and erosion on the northern side of the fishing harbour. This accretion/erosion trend indicates that the net sediment transport is towards northern direction. In sediment cell II, moderate-to-high erosion was noticed along Ambalapuzha region. In sediment cell III, Munambam, Chettuva and Ponnani fishing harbours show similar pattern of accretion on the northern side and erosion on the southern side of breakwaters which indicates that the net sediment transport is towards southern direction, whereas Puthiyappa, Koyilandi, Beypore and Vellayil fishing harbours show usual trend of deposition on the southern side and erosion on the northern side of breakwater. Hence, this trend indicates that the net sediment transport is towards northern direction. Sediment cell III shows peculiar pattern of accretion/erosion, and changes in sediment transport direction indicate that the longshore sediment transport is governed by the local condition and morphology of the coast. 14 km south of Ponnani fishing harbour is noticed with varying degree of erosion. In sediment cell IV, the coastal stretch between Moodadi and Chombala fishing harbour is noticed with eroding trend and prior attention is required to arrest the erosion along this particular stretch. The Azhikkal fishing harbour is the only location where moderate-to-high accretion was seen on either side of the breakwater, whereas remaining harbours show low erosion to stable condition on either side of the breakwater. In sediment cell V, all three fishing harbours show different signatures of accretion/erosion patterns. Change in sediment transport direction indicates that the local condition and morphology of the coast govern the longshore sediment transport. The overall shoreline change status on either side of the fishing harbour is shown in Table 4. This study provides a detailed description of erosion/accretion pattern and net sediment transport pattern throughout the coast. The historical shoreline change analysis along Kerala coast revealed the non-linear trend of shoreline changes. Further, the human interventions in the form of construction of various coastal structures has added the complexity in shoreline change pattern.

The field survey was carried out to validate the cumulative shoreline change pattern (1990-2016). Based on the long-term shoreline change results, 100 field locations were selected to validate the change patterns, particularly along the artificial structures. The validation in field is mainly based on daily, yearly and decadal observations by local fishermen and community members. Since local residents of the coastal region understand the natural dynamics of the beach erosion and sediment transport very well (Martinez et al. 2018). Local people (fishermen) were interviewed regarding the status of the coast for the past years/ decades (1, 5, 10, 20 and 25 years). The fishermen who are more than 40 years are particularly interviewed and should be born and brought at the same region. Twenty-five years of past details were collected from the fishermen and other local communities. Peoples residing in temples, churches, government industries, private industries, business owners and farmers were also interviewed.

Table 4 Status of shoreline change pattern on either side of fishing harbour

Id	Sediment cell	Fishing Harbours (FH)	Northern Side	Southern Side
1	Sub cell - I	Vizhinjam FH	Erosion	Erosion
2		Muthalapozhi FH	Erosion	Accretion
3		Thangassery FH	Accretion	Accretion
4	Sub cell - II	Neendakara FH	Erosion	Erosion
5		Kayamkulam FH	Erosion and stable	Accretion and stable
6		Thottappally FH	Erosion and stable	Accretion and stable
7		Chethi FH	Erosion and stable	Accretion
8		Chellanam FH	Erosion and stable	Erosion and stable
9	Sub cell - III	Munambam FH	Accretion	Erosion
10		Chettuva FH	Accretion and stable	Stable and erosion
11		Ponnani FH	Accretion and stable	Erosion
12		Thanur FH	Erosion	Erosion
13		Beypore FH	Erosion	Erosion
14		Vellayil FH	Erosion	Erosion
15		Puthiyappa FH	Erosion and stable	Erosion and stable
16		Koyilandi FH	Stable	Stable
17	Sub cell - IV	Chombala FH	Erosion	Erosion
18		Mahe FH	Erosion	Stable and erosion
19		Thalai FH	Erosion	Erosion
20		Moplabay FH	Stable and erosion	Stable and accretion
21		Azhikkal FH	Accretion	Accretion
22	Sub cell - V	Cheruvathur FH	Erosion	Stable and accretion
23		Kasaragod FH	Accretion	Stable and accretion
24		Manjeswaram FH	Accretion	Stable and erosion

The field information method includes beach width during the past decades, position of seawall and its impacts on the coast, groins and its impacts, impact of natural hazards with respect to shoreline position and position of shoreline during pre-monsoon and post-monsoon time. The information was well matched with the analysed result. In most of the locations, artificial structures had maximum effect on the coastline. Field photographs were also taken during both the monsoon periods to understand the wave behaviour and sediment transport along the coast. It was noted that buildings were seen collapsed during the monsoon period. The intensity of the waves is very high, and even the wave topping was very common during the monsoon period. The accretion/erosion pattern on either side of the fishing harbour indicates the net sediment transport direction (Noujas and Thomas 2018). Change in littoral drift direction by sediment deposition and erosion adjoining the breakwaters was clearly noticed in the field survey.

6 Conclusion

Shoreline change along Kerala coast was analysed for the past 26 years (1990–2016) using multi-temporal satellite data and comprehensive field surveys. The overall long-term shoreline change for entire Kerala coast shows that the coast was experiencing low

erosion to stable pattern. 45% of the coast falls under varying degree of erosion. 34% of the coast was in the stable condition, and remaining 21% of the coast was noticed with accretion. For detailed analysis, the study area has been divided into five sediment sub-cells. The result suggests that sediment sub-cells II, III and IV were dominated by erosion class, whereas sediment sub-cell V was dominated with stable (47%) class. 54% of sediment sub-cell II falls in erosion followed by sediment cell IV with 52%. Sediment sub-cell I have high percentage of accretion (30%). High attention has to be given to the coastal locations like Pannatura, Thazhampally, Eravipuram, Vallanathuruthu, Ambalapuzha, and south of Ponnani where the coast was affected by the high degree of erosion.

This study provides a detailed description of erosion/accretion pattern and net sediment transport direction all along the coast. Sediment cells I and II show accretion on the southern side and erosion on the northern side of the fishing harbour which indicates that the net sediment transport is towards the northern direction. Munambam, Chettuva and Ponnani fishing harbours in sediment cell III show accretion on the northern side and erosion on the southern side of breakwaters which indicates that the net sediment transport is towards southern direction, whereas in Puthiyappa, Koyilandi, Beypore and Vellayil fishing harbours, the net sediment transport is towards northern direction. Net sediment transport of sediment cell IV and V is towards northern direction. Analysis of shoreline change around the coastal structures supports that the rate of change is not uniform and varies from place to place which indicates the local hydrodynamic condition, coastline orientation and morphology of the coast play a significant role in altering the coast. Azhikkal fishing harbour shows accretion pattern on either side of the breakwater, whereas Neendakara, Vizhinjam, Vellayil, Tanur and Beypore fishing harbours are noticed with erosion on both sides of the breakwater. Muthalapozhi fishing harbour shows erosion at updrift side and accretion at downdrift side. Therefore, these protection effects required a careful understanding of the coastal system which has aggravated the erosion problem along the coast. The field survey was undertaken to validate the analysed results, and the information was well matched with the analysed result. Some of the regions like Vypin beaches, Puthiya beach, etc., have two or more layers of seawalls which indicate the complexity in understanding the erosion pattern using satellite data. For continuous monitoring, the information on human intervention becomes very vital to analyse the temporal satellite imageries in an effective way. The study demonstrates that combined effect of satellite imagery and field survey can be a reliable approach for shoreline change study in the complex environment for effective planning and management of the coast.

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