

Impacts of wave energy and littoral currents on shoreline erosion/accretion along the south-west coast of Kanyakumari, Tamil Nadu using DSAS and geospatial technology

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Received: 25 April 2013 / Accepted: 3 October 2013 / Published online: 20 October 2013
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Abstract The present study investigates the impact of wave energy and littoral current on shorelines along the south-west coast of Kanyakumari, Tamil Nadu, India. The multi-temporal Landsat TM, ETM+ images acquired from 1999 to 2011 were used to demarcate the rate of shoreline shift using GIS-based Digital Shoreline Analysis System. The statistical analysis such as net shoreline movement and end point rate were determined from the multi-temporal shoreline layers. Moreover, the wave energy and seasonal littoral current velocity were calculated for each coastal zone using mathematical equations. The results reveal that the coastal zones, which include Kanyakumari, Kovalam, Manavalakurichi and Thengapattinam coasts, consisting of maximum wave energy along with high velocity of littoral current, have faced continuous erosion processes. The estimated wave energy along these zones ranges from 6.5 to 8.5 kJ/km² and the observed current velocity varies from 0.22 to 0.32 m/s during south-west and north-east monsoons. The cumulative effect of these coastal processes in the study area leads to severe erosion that is estimated as 300.63, 69.92, 54.12 and 66.11 m, respectively. However, the coastal zones, namely Rajakkamangalam, Ganapathipuram, Muttam and Colachel, have experienced sediment deposits due to current movement during the north-east monsoon. However, the trend changes during the south-west monsoon as a result of sediment drift through

backwash. The spatial variation of shoreline and its impact on wave energy and the littoral current have been mapped using the geo-spatial technology. This study envisages the impact of coastal processes on site-specific shorelines. Hence, the study will be effective for sustainable coastal zone management.

Keywords Shoreline change · Coastal erosion · Wave energy · Littoral current · DSAS · Remote sensing and GIS · South-west coast · Kanyakumari · India

Introduction

The coastal landforms are complex, dynamic and delicate environment which interface both terrestrial and marine forces. Coastal hazards such as erosion, storm surge, sea water inundation and environment instability are the major problems concerned with this environment. According to UK Environment Agency (2009), the coastal landforms are dynamic systems that function over a range of temporal and spatial scales. Dominant physical factors such as wave height, wave energy, tidal range and littoral drift are responsible for shaping coastal landforms (Kaliraj and Chandrasekar 2012a). Multi-dated satellite images can be used to monitor shoreline changes by measuring sedimentation, erosion and accretion (White and El Asmar 1999). Smith and Zarillo (1990) have used Landsat images for multi-temporal shoreline mapping based on the spectral signature of land and water. The analyses of remote-sensing images include Landsat MSS, TM, ETM+ and Spot imagery have provided reliable results in the shoreline change assessment (El Asmar and Hereher 2011). The accurate demarcations of shoreline, littoral drift direction

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and erosion and accretion zones were estimated using remote-sensing and GIS techniques (Marfai et al. 2008; El-Banna and Hereher 2009; Sheikh Mujabar and Chandrasekar 2013). Many authors have used multi-temporal satellite images for the purpose of shoreline extraction, assessment of erosion and accretion, and coastal morphology change detection at local and regional scale (Dewidar and Frihy 2010; Hereher 2011). Moreover, (Kawakubo et al. 2011) have used a spectral linear mixing analysis to estimate the erosive and depositional features along the open coast. Also, the movement of suspended sediment particles along the offshore or near shore can be effectively demarcated from the false color composite image using principal component analysis (Short and Trembanis 2004; Kaliraj and Chandrasekar 2012b).

The shoreline layer, extracted from images acquired on different dates, is used to show the status of its changes. The statistical measurement of shoreline changes can be carried out using a predefined software. The Digital Shoreline Analysis System (DSAS) is a statistical software application used to compute the rate of change in multi-temporal shoreline data (Thieler et al. 2009). The shorelines extracted from the multi-temporal Landsat TM and ETM+ images were analyzed using DSAS software for measurement of erosion rate and retreating along the coastal area (Ryabchuk et al. 2012). The DSAS modules such as End point Rate, Linear Regression and Least Median Square were used to estimate the shoreline shift along the south-east coast of Tamil Nadu (Sheikh Mujabar and Chandrasekar 2011). The formation and dynamics of coastal landforms are mainly influenced by hydrodynamic forces of the marine environment (Vinayaraj et al. 2011). The nearshore zone is a highly energetic region characterized by a complex interaction of physical processes and seasonal variations of morphodynamic conditions, whereas the zone has influenced longshore immersed weight sediment transport rate (Kraus et al. 1988). The coastal dynamic change of an area is mainly influenced by the action of wave energy of the natural coast and amount of retreat along the coast. (Nafaa et al. 1991; Anil Cherian et al. 2012). Maktav et al. (2002) stated that the width of the natural land barrier such as sand dune, beach ridge and cliff decreased over time due to natural forces like wave energy, littoral current, longshore drift and anthropogenic activities including removal of coastal vegetation and unregulated mining activities. Seasonal variations in wave energy, wave height and wave direction have produced asymmetric shoreline erosion by changing the trends of sediment movement in the near shore area (Chauhan et al. 1996; Benumof et al. 2000; Georgiou and Schindler 2009; Saravanan et al. 2011).

The frequent erosion and accretion process along the coastal area within short-term periods is mainly due to unregulated coastal mining and natural hazards such as

storm surge, tsunami and cyclone (Chandrasekar et al. 2000). The headland features of the wider pattern coast have been affected by erosion in the downslope area by the waves and currents coming perpendicular to the shore (Frihy and Lotfy 1997). Artificial structures such as groins, seawalls, revetments and breakwaters along the coast disturb coastal natural processes such as wave direction and littoral current, causing shoreline changes by removing the sediment material from the coast (Masselink and Short 1993). The suspended sediment transport along the offshore or in the shallow water area (surf zone) is mainly controlled by wave action because the suspended materials reduce the force of the waves (Bassoullet et al. 2000; Lee et al. 2004). Besides, the offshore slope and bathymetry are important factors influencing the efficiency of deposition or detachment of sediments (Ridderinkhof et al. 2000). However, the sediment recharging processes are more effective in shallow water than in deep water (Trenhaile 1997). The mean suspended sediment concentration is inversely correlated with the depth of the wave propagation zone (Christie and Dyer 1998). Frihy et al. (2004) have reported that coastal erosion and accretion are highly influenced by the reversibility of longshore currents along the coast, which causes the formation of shoreline orientation and headland morphological structures. The wave propagation over a narrow shelf results in low frictional loss of energy, but expends much energy on the coastline and causes greater coastal erosion (Sunamura 1977; Lacey and Peck 1998; Manson et al. 2005). Also, man-made constructions such as groins, revetments and breakwaters divert the longshore current and cause removal of beach material from the downdrift side of the coast (Marghany et al. 2010; Mishra et al. 2011).

In this study, the shoreline changes in spatial and temporal aspect were analyzed in the study area using remote-sensing and DSAS-GIS techniques. Further, the impact of wave energy and seasonal littoral current on the erosion and accretion processes was also evaluated for better understanding of the coastal processes. Moreover, different geo-processing tool sets were used to analyze the multi-temporal images for accurate assessment of erosion and accretion rate.

Study area

The study area was located along the south-west coast of Kanyakumari District, Tamil Nadu, India. The geographical coordinates extend from 77°9'49.23"E to 77°34'14.99"E longitude and 8°6'32.63"N to 8°14'15.30"N latitude covering a total length of 58 km along the coastline (Fig. 1). The long narrow coastal stretch is characterized by numerous sandy pocket beaches, beach plains, shoreline terraces, sand dunes, rocky shore and estuaries. The rocky

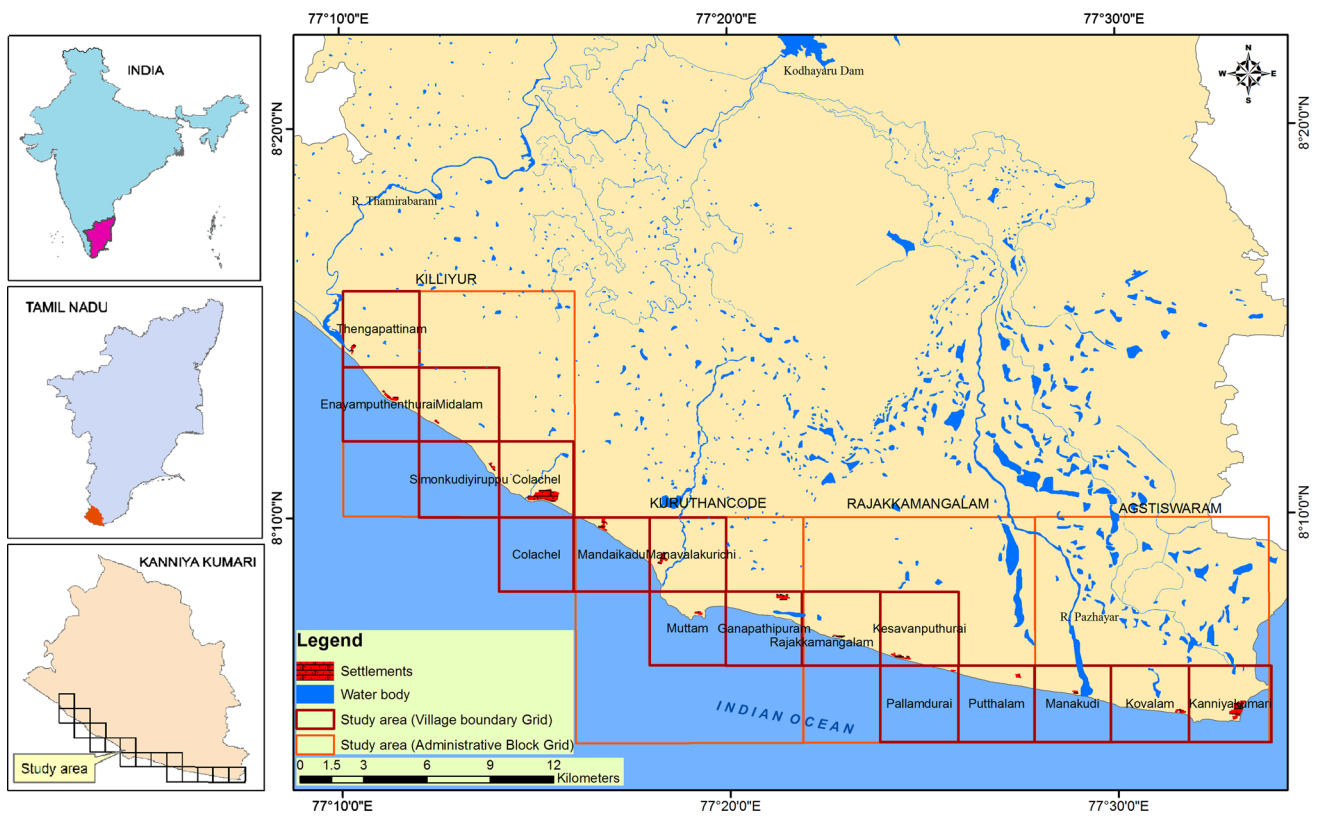


Fig. 1 Location of the study area

shoreline along with rocky outcrops in the offshore are located in the Kanyakumari and Muttam coastal stretches. The young formation of sandy beaches and beach ridges are found on the coasts of Ganapathipuram, Rajakkamangalam, Colachel and the eastern part of Inayamputhandurai. The landward margin of the coast (onshore) generally slopes toward the offshore and can be identified as thick Laterite rocky uplands, covered with settlements, habitats and vegetation, coconut plantation and shallow water bodies. Along the near shore area, the sand dunes are roughly parallel to the shore, although it is not continuously distributed along the coast. The coastline in the Kanyakumari coast is littered with evidence of erosion due to high-energy wave action. Moreover, irregular-shaped cliffs are formed between the Kovalam and Kanyakumari coastal stretch by direct wave action on the Terisand rocky shore. The major drainage networks of this area are R. Thamirabarani and R. Pazhayar and their tributaries flow in a south-westerly direction from the Western Ghats. These rivers flow through a gentle sloppy terrain and a large amount of sediment materials are carried to its estuary during both south-west and north-east monsoons. Sub-tropical climatic conditions prevail over the study area; the normal annual rainfall varies from 826 to 1456 mm and the annual mean minimum and maximum temperatures range from 23.78 to 33.95 °C. The coastal landform features

experience frequent erosion and accretion from Kanyakumari to Thengapattinam due to the prevailing marine and terrestrial factors. The intensity of wave energy is varied in different parts of the coast and the movement of littoral current also changes seasonally. From the last decade onward, the different parts of the coast have groins and revetments to divert the diffracted waves and decrease littoral drift. These structures intervene with natural coastal processes and induce shoreline changes and erosion and accretion. The study area consists of four administrative blocks with 15 coastal villages and one-third of the total population of the district. For systematic measurement of shoreline changes, the study area has been divided into four major grids of administrative block boundary (Agastiswaram, Rajakkamangalam, Kuruthancode and Killiyur) and further 15 smaller grids of coastal villages.

Geological structures

The study area is located in the southern tip of the Indian sub-continent which is composed of crystalline rocks of Late Quaternary deposits and sandy materials. The crystalline rock types such as Quaternary rocks, clay sand and sandy materials are predominantly found along the coast. Moreover, the coast stretching between Kanyakumari and Kovalam is mainly covered by thick laterite soil dotted

with a few rocky outcrops. The Teri sand dunes (reddish brown) are located along the coastal stretch from Kovalam to Manakudi; the thickness increases from 1.5 m in the coastal headlands to a maximum of 7.0 m in the interior terrestrial area. Rocky boulders and sea cliffs are found in the Muttam, Kanyakumari and Cape Comorin coasts. Sandstones found along the study area are made up of igneous rock and silt clay materials. Alluvium with intervening crystalline outcrops are noticed as patches in the west of Manakudi, Puththalam and Inayamputhandurai areas. Accumulations of charnockite, garnet and garnet–biotite gneiss are noticed between the coast of Manavalakurichi and Mandaikadu. Alluvial mixed clay is found at the mouth of the Thamirabarani estuary in Thengapattinam and Pazhayar estuary in Manakudi. Moreover, sandstone with clay intercalation structures is present along the eastern part of Thengapattinam coast (Fig. 2).

Coastal geomorphology

In the coastal area, morphological landforms have high erosion and accretion processes due to hydrodynamic fluctuation and anthropogenic activities. Morphologically, this coastal area has a combination of various types of land structures such as beach ridges, beach bar, sea cliffs, sand dunes, shallow weathered pediplain, meander scar, pediment inselberg, eolian plain, brackish water creek, deltaic plain, estuarine channel, alluvial plain and steep slope landforms. Among them, beach bars and beach ridges are

present in the coastal zones, namely Ganapathipuram, Colachel and the eastern part of Manakudi, Midalam and Simonkudiyiruppu. These linear features change in rhythmic beach forms and crescentic low water bar as the wave energy levels increase toward the south. The sand dunes are located between the coastal stretches of Pallam, Puththalam and Midalam with a height of up to 0.5–1.5 m and they are well protected by the vegetative covers. The coast of Thengapattinam has been well established with estuarine, deltaic plain and meander scar due to the course of the western Thamirabarani River. The fluvial depositional landforms such as flood basin, channel bars and terraces are laid along the east side of the Manakudi coast. Brackish water creek and eroded cliff landforms are dominant in Kanyakumari, Cape Comorin, Kovalam and Muttam. Fluvio-marine sediments are distributed parallel to the headlands and marine-barrier dunes are predominantly present in the middle part of the study area. The western part of the Manavalakurichi coast is replenished by large amounts of sediment deposits with valuable heavy minerals, which leads to intensive sand mining activity along the coastal stretches (Fig. 3).

Materials and methods

In the present study, the integrated remote-sensing, GIS and DSAS technology was used as an effective platform to evaluate the shoreline changes from 1999 to 2011. The

Fig. 2 Geological structures

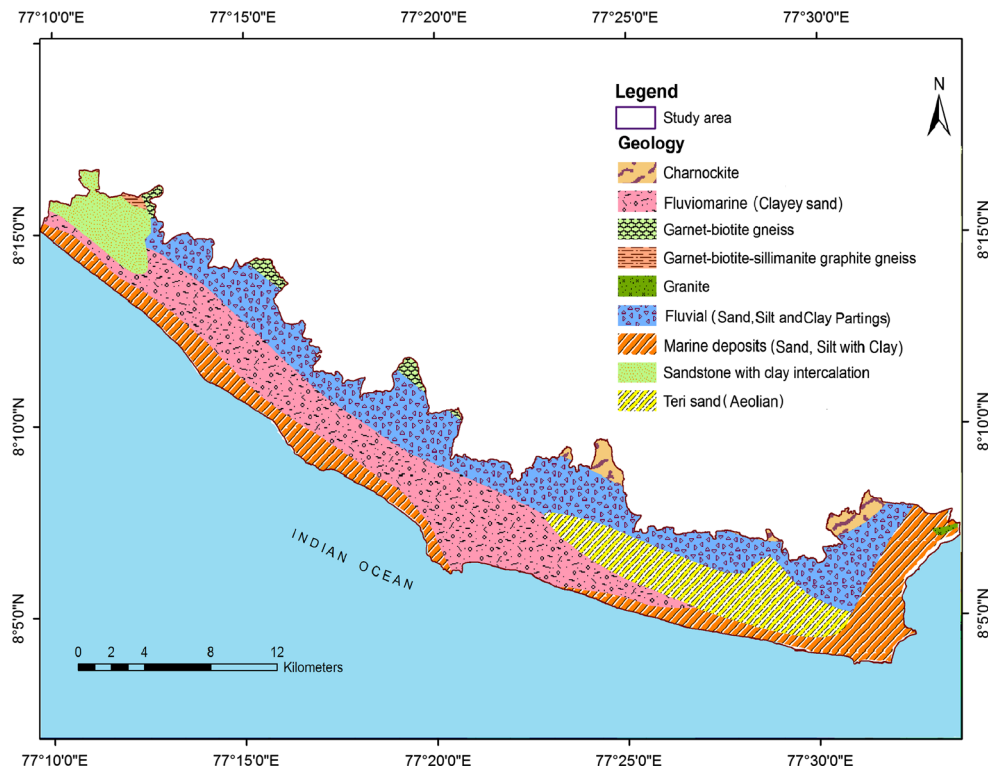
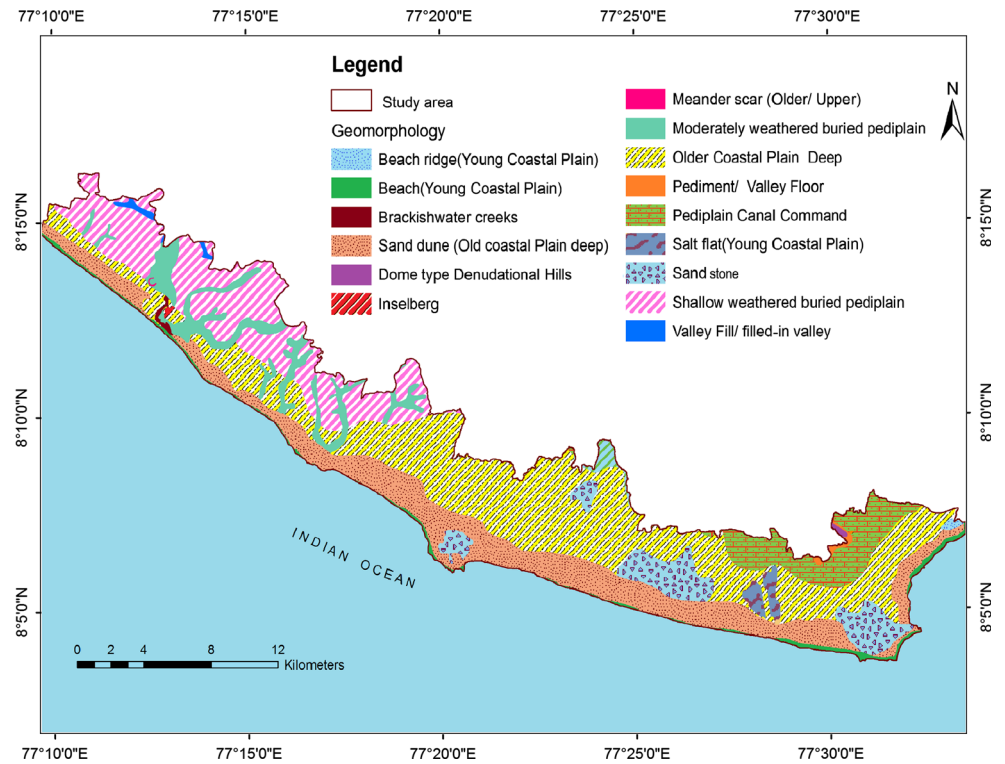


Fig. 3 Geomorphology



erosion and accretion rate and per year rate of shoreline change are estimated using the Net Shoreline Movement (NSM) and End Point Rate (EPR) statistical algorithms. Moreover, the wave energy and seasonal current velocity for the entire study area were analyzed to explore the influence of the shoreline change process.

Shoreline change analysis

The multi-temporal Landsat TM and ETM+ images acquired from 1999 to 2011 were used as the primary data source for shoreline extraction. To eliminate the influence of tidal variations, the images corresponding to low water level were used for clear demarcation of shorelines along the coast. Further, the images were processed by means of geometric correction using UTM-WGS 84 projection and coordinate system using ERDAS Imagine 9.2 software. Then the images were subjected to remove error and noise from pixels using non-linear edge enhancement techniques (Kawakubo et al. 2011). The image analysis techniques based on pixel values are used for shoreline extraction and erosion and accretion measurement (Mazian et al. 1989). The spatial and spectral properties of an image were enhanced using histogram equalization and convolution methods to improve the discrete line lying between the land and sea surface. The extraction of the discrete line between land and water surface was based on the spectral signature of the satellite image. The discrete shoreline was extracted

automatically by using binary classification techniques and exported into a personal geo-database file using Arc GIS software.

The extracted shoreline was divided into 526 transects with 100 m interval using DSAS 4.2 software. To measure the amount of shoreline shift along each transect, a buffer line (1 km) was created along the onshore side by assuming the 1999 shoreline as a baseline. Based on the position with reference to the baseline at each transect, the seaward shift of the shoreline along the transect is considered as a positive value (accretion), while landward shift is considered as negative (erosion). Among the various computational functions, two main statistical modules such as NSM and EPR are used to measure the rate of changes for a time series of shoreline layers. The NSM is used to calculate the rate of change between the shorelines of 1999 and 2011 at the intersecting point of each transect and the EPR is used to estimate the per year rate of change between the same periods. This is carried out by dividing the distance of NSM at particular transects by the time elapsed between the past and recent shorelines. The rate of change statistics of each transects is expressed in meters.

Mean wave energy calculation

The potential shoreline change varies from one site to another along the coast due to site-specific hydrodynamic

actions such as wave height, wave direction and gravity acceleration. The wave energy along the study area was calculated using the equation proposed by Dyer (1986) which is represented as,

$$E = \frac{1}{8} \rho g H^2 \quad (1)$$

where E is the wave energy (kJ/km^2), H is the mean significant wave height (m), ρ is the sea water density (g/m^3) and g is the acceleration due to gravity (m/s^2). In this equation, the mean significant wave height is used as a proxy for wave energy which drives the coastal sediment budget. The historical wave height and wave direction data sets have been derived from the Buoy Observation Center—Indian Ocean Forecast System (INDOFOS) and the sea water density data were derived from the National Institute of Ocean Technology (NIOT), India. The gravity due to acceleration data was extracted from the gravity anomaly map of India published by National Geophysical Research Institute (NGRI), India. These parameters were converted into raster layers and substituted into this equation using a raster calculator module in GIS environment.

Littoral current movements and velocity measurement

The seasonal littoral current movements were measured during the south-west monsoon (June–September), north-east monsoon (October–December) and summer (March–May) from wave (swell) atlas published by National Institute of Oceanography (NIO), India. The thematic layer of the current movement was extracted from the geo-referenced atlas map and exported into shape file using GIS software along with the attribute database information such as current velocity, direction of seasonal movement, bathymetry and the rip current point for each coast zone. Moreover, the bathymetry contours within 10 km of the offshore area were delineated from the bathymetry chart (2001) published by National Hydrographic Office (NHO), India. Finally, the shape file of the littoral current was overlaid on the offshore bathymetric layer for mapping spatial variation of depth and current movement along the study area.

The measurement of littoral current velocity along 15 coastal zones is performed by using the equation proposed by (Galvin 1963). Moreover, this has been also used by Higgins in 1970. The equation is represented as

$$V_{\text{LH}} = 20.7m(gH_b)^{1/2} \sin 2\alpha b \quad (2)$$

where V_{LH} is the littoral current velocity in the offshore (m/s), 20.7 is a constant value which represents the geometry of the breaking wave (Sanil Kumar et al. 2002), g is the acceleration due to gravity (m/s^2), m is the offshore slope, H_b

is the breaker height in m and αb is the breaker angle (angle between the breaking wave crest and the shoreline).

Field verification and data validation

The identified erosion zones along the study area were checked out to confirm its present status. Besides, the rate of erosion and accretion for the year 2011 obtained through DSAS analysis was verified with the field measurement using GPS (Garmin GPSMAP 76Cx) instrument. The static method of GPS survey was performed to assess the erosion rate by measuring the distance between high water line and selected landmarks. The net rate of erosion and accretion values obtained by both field measurement and DSAS analysis were compared together to verify the rate of variation in erosion and accretion.

Results and discussion

Investigation of the shoreline status from 1999 to 2011 reveals that severe erosion is noticed along the high wave energy zones which drive the coastal sediment budget. The significant shoreline change in different parts of the coastal area is driven by the process of swash and backwash of sediments due to seasonal current movements.

Rate of shoreline change: erosion and accretion

The variation of the net shoreline change rate is identical in different parts of the coastal zones. The measurements of NSM and the EPR at each coastal zone reflect the rate of erosion and accretion in the corresponding area. In this analysis, the shoreline change per year and the net rate of shoreline change are estimated zone-wise for the periods 1999–2011. The DSAS-processed shoreline status for different years of 15 coastal zones located within four administrative blocks are shown in Figs. 4, 5, 6 and 7. The Kanyakumari coast has faced severe erosion which is estimated as -300.63 m, whereas the net rate of shoreline change is -157.92 m. This is due to the impact of high-energy wave action on the coast that caused backwash of sediments from the downslope of the coastal headlands (Fig. 4a). The coastal landforms of this area such as sand dunes, sea cliffs and beach ridges are affected by severe erosion. Moreover, the north-east and western parts of the same coast have noted accretion rate up to 142.71 m. The sediment transportation induced by wave direction and seasonal change of littoral current has disclosed the processes of erosion and accretion in the narrow coast (Yang et al. 2007). As per their conclusion, the rates of erosion along the narrow coastal stretches between Kovalam and Manakudi are recorded as 69. 92

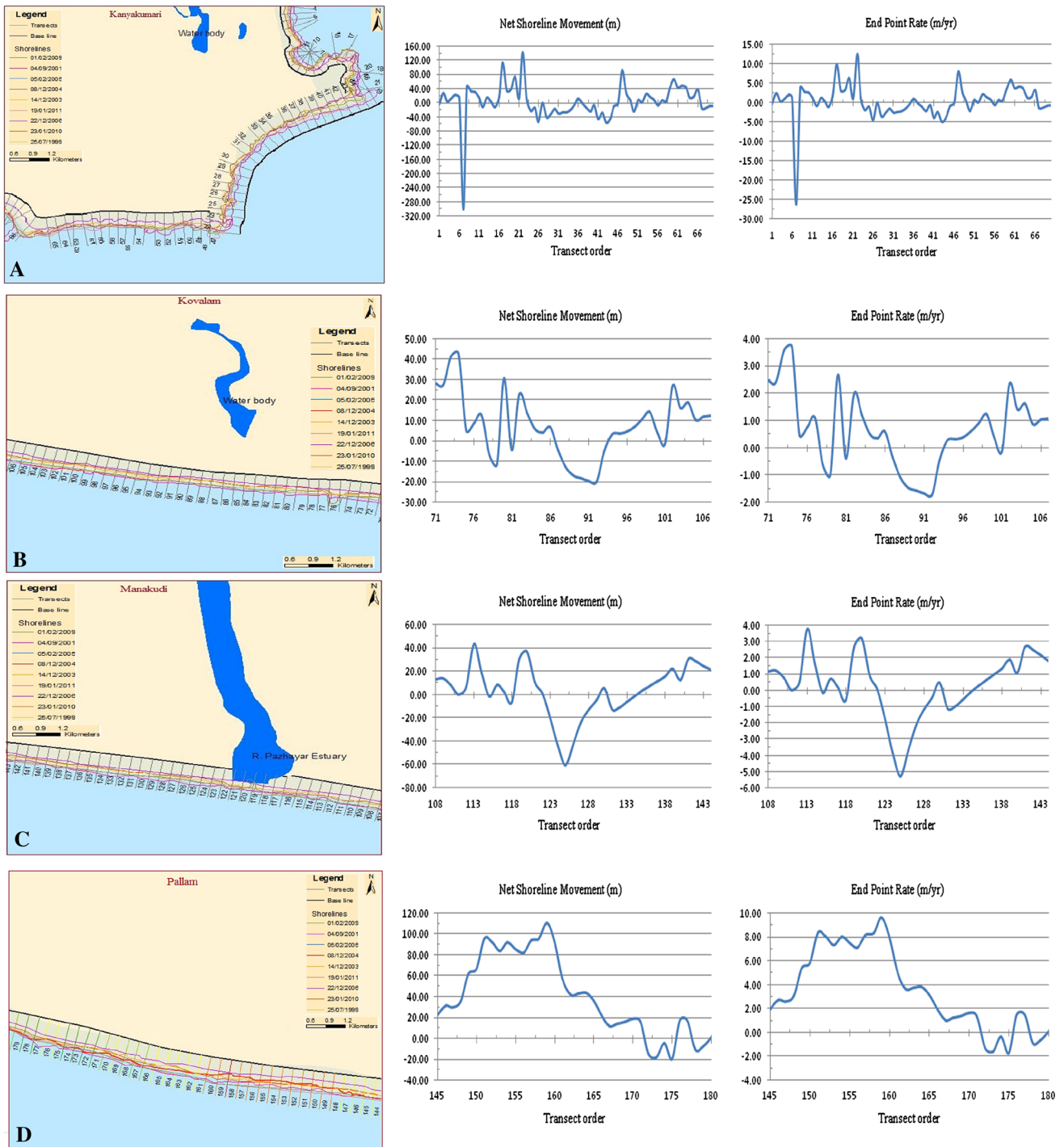


Fig. 4 a–d Shoreline change rates from Kanyakumari to Pallam (Agastiswaram block) during 1999–2011

and 60.61 m during 12 years, and the rate of change and per year change along these areas are 5.83 and 5.05 m, respectively (Fig. 4b). The coastal areas have man-made structures such as groins and revetments that intervened with the littoral sediments drift direction (Greenwood and Orford 2007; Mwakumanya et al. 2009). In the Kovalam coast, the Teri sand dunes are eroded at high rates due to

direct wave action on it. Wilcock et al. (1998) have pointed out that the wave propagation over the narrow coastal shelf results in low frictional loss of energy, but disburses much energy on the coastline which causes greater coastal erosion. However, the amount of sediment deposit is varied along the Manakudi estuary due to the addition of runoff materials that discharged from

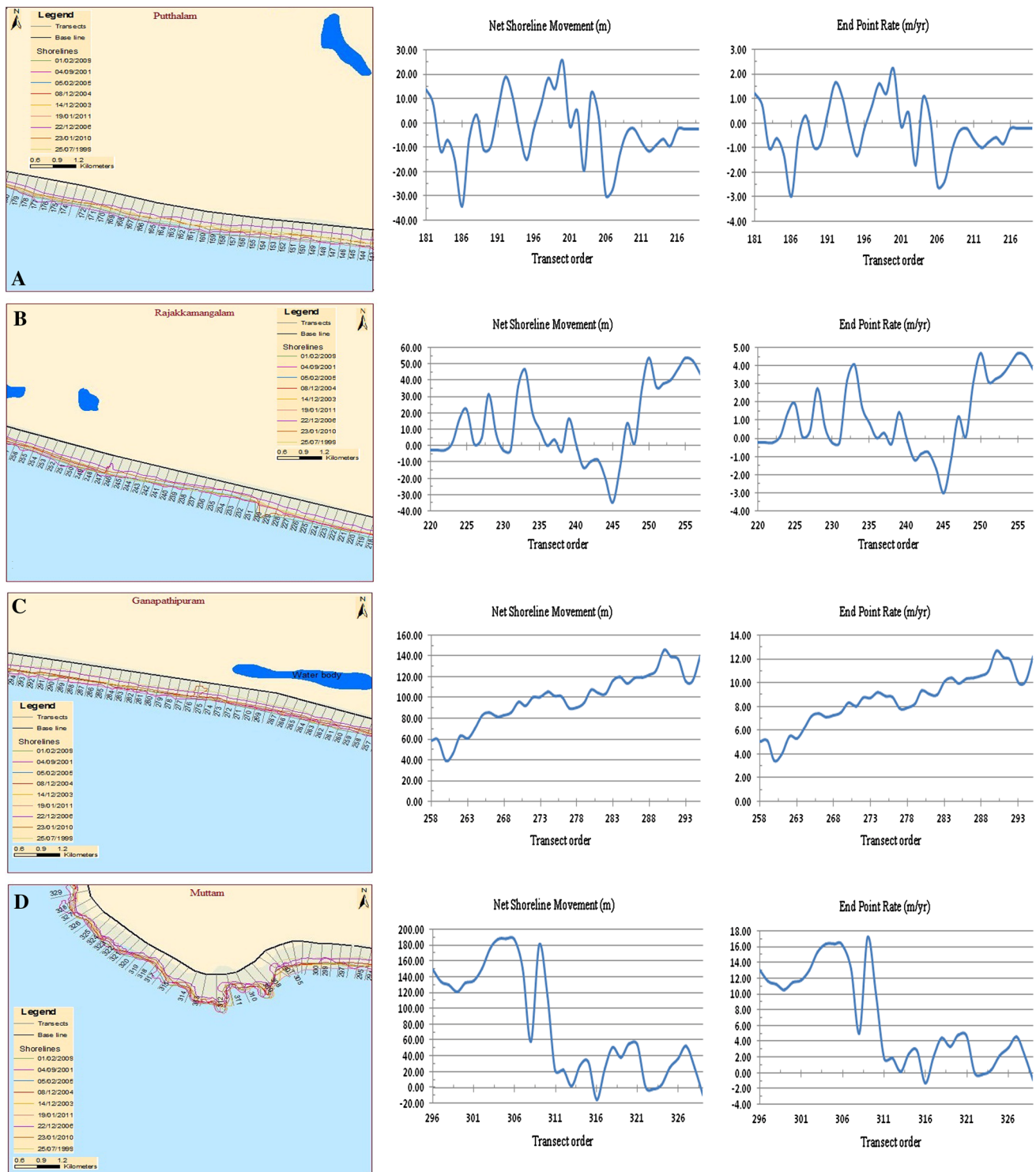


Fig. 5 a–d Shoreline change rates between Putthandurai and Muttam coastal stretch in Rajakkamangalam block

R. Pazhayar during SW and NE monsoons. During these periods, the Putthandurai and Rajakkamangalam coasts have high fluctuation in both erosion and accretion processes due to the dynamics of wave energy and littoral currents. Moreover, there is a simple pattern of beach

formation due to the effect of current flows along the offshore, parallel to coastal configuration structures. The rate of erosion along this area is measured as 34.1 and 34.56 m and the accretion rate is 53.85 and 25.66 m, respectively (Fig. 5a, b).

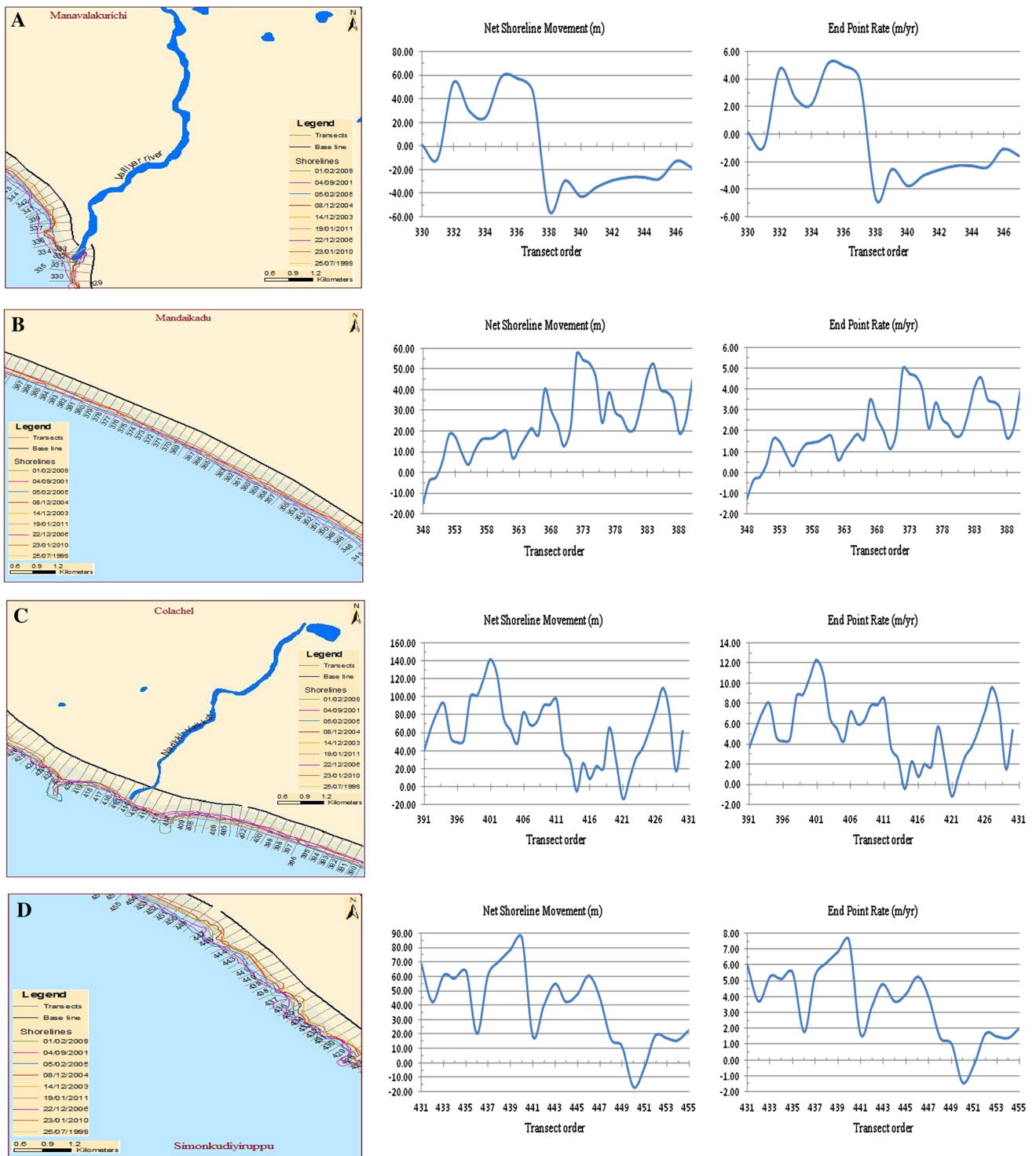


Fig. 6 a–d Shoreline change rates along the coastal area from Manavalakurichi to Simonkudiyiruppu in Kuruththancode block

In the Rajakkamangalam coast, a significant amount of sediments is deposited on the up-drift side of the groins; however a high amount of erosion was noted on the down-drift side due to the formation of rip current which induces backwash of sediments from the area continuously. The coastal zones, namely Ganapathipuram, Muttam and

Colachel, observed a high rate of accretion estimated as 145.48, 188.07 and 141.64 m, respectively (Figs. 5c, d and 6c). The sandy beaches are extensively developed along these coasts by the processes of constructive wave action, caused by continuous deposition of littoral sediment materials from the adjacent areas. According to Taaouati

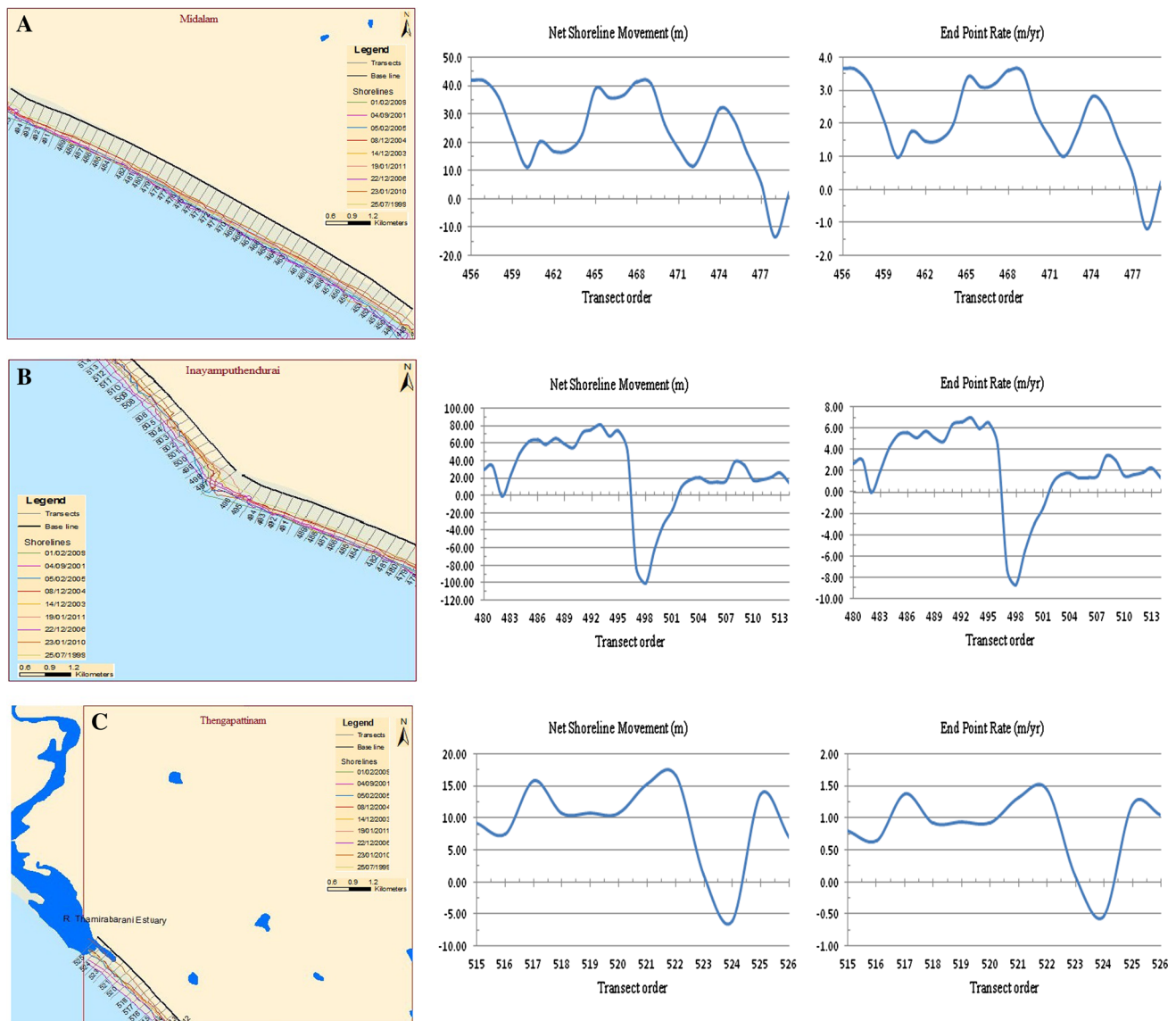


Fig. 7 a–c Shoreline change rates in the coasts between Midalam and Thengapattinam (Killiyur block) during 1999–2011

et al. (2011), frequent erosion and accretion processes along the coastal area within short-term periods are mainly due to unregulated coastal sand mining and natural hazards such as storm surge, tsunami and cyclone. The coastal area between Manavalakurichi and Mandaikadu is seriously depleted by high rates of erosion with an estimated value ranging from 44.75 to 54.12 m, whereas the per year rate of erosion is 3.73 and 4.51 m, respectively. This anomaly is also mainly due to unregulated mechanized mining activities in these areas (Fig. 6a, b). The estuary environment of the Thengapattinam coast has a morphologically different landscape such as estuarine, spit, sand beaches and mud flat. This coastal zone receives a large amount of runoff sediments released by R. Thamirabarani during SW and NE monsoons; however they are backwashed and

transported toward east by high wave energy action and littoral current (Jena et al. 2001). The erosion rate of this estuary is estimated as 66.11 m and per year rate of erosion is 5.51 m (Fig. 7c). Seasonal fluctuation of erosion and accretion processes is observed along the entire study area except for the coastal zones, namely Pallam Midalam and Inayamputhendurai where the hydrodynamic activities are intervened by revetments, sea walls and groins (Figs. 4d and 7a, b). The result of this process makes erosion in the down-drift side and accretion in the up-drift of the coast by disturbing shoaling action and wave refraction processes. The coastal configuration and the offshore bathymetry face direct interaction with littoral currents and waves which act as major controlling factors of seasonal longshore drift and formation of coastal landscapes at the local scale (Carter

et al. 1990). Here, the different coastal zones of this study area are also found as erosional landforms due to the influence of waves and currents on the coast which produce spatial variation in wave height and wave energy intensity. The rate of erosion and accretion and the characteristics of its influencing factors are given in Table 1.

Impact of wave energy on shoreline changes

The wave energy prevailing over the study area influences sediment budget according to wave height and wave direction, which determine accretion or erosion of the headland features. The intensity of wave energy depends on acceleration due to gravity which is one of Earth's forces that are influenced by wave height and propagation time. Figure 8 shows the spatial variation of wave energy and the erosion rate along the coastal area. For the entire coast, the calculated mean annual wave energy ranges from 0.5 to 8.5 kJ/km². Among them, the Kanyakumari coast is notified with very high wave energy (6.5–8.5 kJ/km²) because of the geographical location and its coastal configuration. The coast is located at the southernmost tip of the Indian sub-continent and with forces acting on the landforms from various directions. Moreover, the steep slopes of seabed along the offshore can decrease the discharges of littoral sediment by diverting the waves (Wang 1998). Due to these factors, the coastal landforms such as sea cliff, older sand dune, beach ridge and Teri sand deposits between Kanyakumari and Kovalam have faced a series of erosion throughout all seasons. Less wave energy prevails over the open coast, such as Ganapathipuram and Pallam, with the values varying between 0.5–2.5 kJ/km² and 1.5–3.5 kJ/km², respectively. This leads to deposition of littoral sediments which eventually form young beaches and other depositional landforms along these areas. The coastal zones, namely Manakudi, Rajakkamangalam, Colachel, Simonkudiyiruppu and Midalam, have found similar annual wave energy within the range of 2.5–3.5 kJ/km². Among them, the Manakudi coast has faced erosion (60.61 m) along the western side of the estuary and the net rate of change is –17.32 m. This is due to the impact of higher wave height acting on the gentle slope of this coast (Table 1). The waves are reduced in energy by hitting on the rocky outcrops present in the offshore and release sediments into adjacent areas (Sunamura 1977). Along the eastern part of Muttam coast, the young sandy beaches and beach bar landforms are formed by deposition of sediments due to waves and rocky outcrops interaction. The subsequent longshore drift is induced by littoral currents during SW and NE monsoons affecting the Simonkudiyiruppu coast with low intensity of wave energy, which eventually transports the sediments toward the east and get trapped down along the up-drift side of groins in the Colachel

coast. However, the rest of the above coastal zones are noted by a significant amount of accretion rate. At the location of the coast where direct to wave action is faced, more littoral sediment transportation leads to erosion. However, the adjacent zones are deposited with them by longshore drift and the headlands are formed as beaches or dunes (Van Wellen et al. 2000). In this study area, Thengapattinam coast experiences the same condition and the transported littoral sediments are deposited along the coastal stretches of Simonkudiyiruppu, Midalam and Colachel. Further, the overwash of sediments occurs along the Thengapattinam estuary and Inayamputhandurai coast due to high energy waves which force the ocean water flow to the onshore. The overwashing of sediments transport large volumes of sand onshore where it is deposited as young beaches and beach bars.

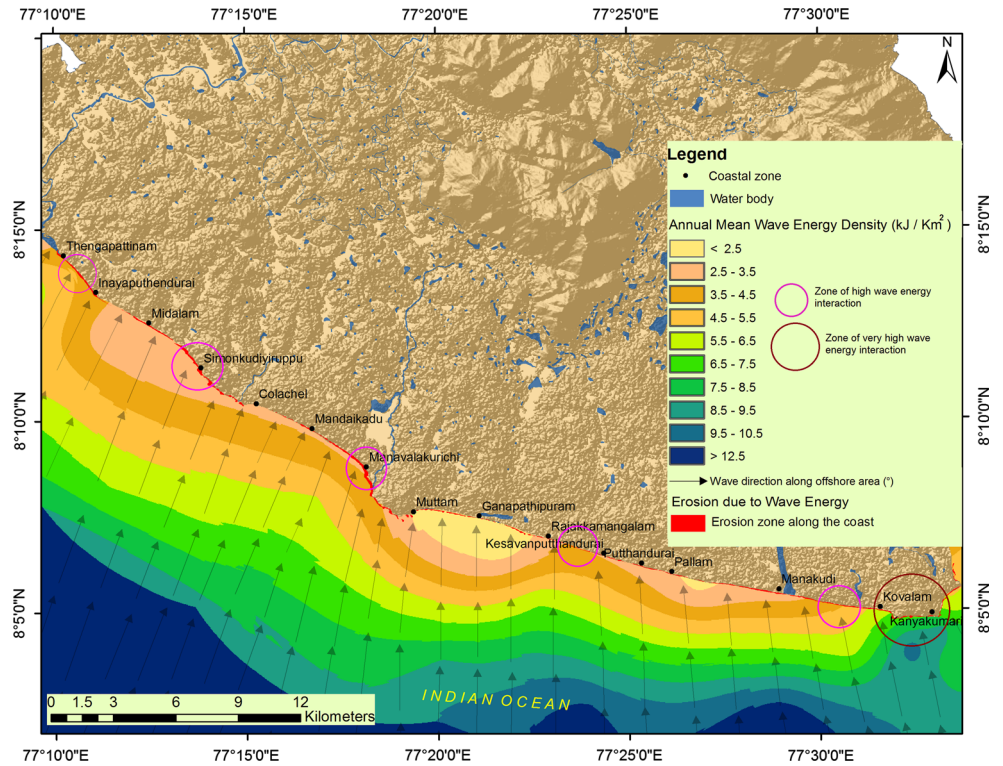
The Muttam coast is protected naturally from the wave action and other hydraulic forces due to the presence of rocky outcrops in the offshore that have reduced the intensity of wave energy. This phenomenon diverts the low-intensity waves toward east causing deposition of littoral sediment along the Ganapathipuram coast. The moderate wave energy condition (2.5–4.5 kJ/km²) endured along the coastal stretch of Manavalakurichi and Mandaikadu has produced large deposition of littoral sediments enriched with placer minerals. However, large amounts of sand have been evacuated from the coastal headlands due to unregulated mining activities, which have caused severe erosion, and the rate of erosion of these zones is estimated to be 54.12 and 44.75 m, respectively. Here, the groins are not completely effective in controlling the longshore sediment transport issue on the Manavalakurichi coast. The coast stretches between Manavalakurichi and Mandaikadu are noticed by permanent erosion due to man-made structures. The numerous coastal placer mineral mining events in the region have an effect on the wave regime. Further, in the open coast the revetment and groin intervene with the waves and act as breakers, causing long shore sediment transport and erosion (Robinson 1980). Moreover, the groins collect the down-drift sediment from the western part of Inayamputhandurai coast which results in continuous erosion between the Thengapattinam and Inayamputhandurai coastal stretch. Artificial structures like breakwaters, groins and seawalls divert the concentrating wave energy which results in erosion as well as accretion adjacent to these structures. A tremendous change in coastal landforms has been observed along the Thengapattinam estuary during summer due to the high intensity of wave energy (3.5–4.5 kJ/km²). The result reveals that the erosion and the accretion pattern along the coastal landforms is mainly controlled by the wave energy behavior which determines the sediment movement in the study area.

Table 1 Rate of coastal erosion and accretion in the coastal zones with wave energy and littoral current characteristics

Sl. no	Coastal zone	Net shoreline movement between 1999 and 2011 (m)		Net rate of change ($R = A - E$)	End point rate (m/year)		Wave energy (kJ/km^2)	Littoral current movement (direction from north)			Littoral current velocity (m/s) (source: NIO)	Erosional hazard ranking
		Erosion (E)	Accretion (A)		Erosion	Accretion		North-East monsoon (October–November)	South-West monsoon (June–September)	Summer (March–May)		
1	Kanyakumari	-300.63	142.71	-157.92	-25.05	11.89	6.5–8.5	NE–W	NW–SE	>–<SE–NW	0.32	Very high
2	Kovalam	-69.92	42.78	-27.14	-5.83	3.57	4.5–6.5	SE–NW	NW–SE	NW–SE	0.28	High
3	Manakudi	-60.61	43.29	-17.32	-5.05	3.61	2.5–3.5	SE–NW	NW–SE	NW–SE	0.22	Moderate
4	Pallam	-19.36	110.76	91.4	-1.61	9.23	1.5–3.5	SE–NW	NW–SE	NW–SE	0.16	Less
5	Putthandurai	-34.1	25.66	-8.44	-2.84	2.14	2.5–4.5	SE–NW	NW–SE	NW–SE	0.16	Moderate
6	Rajakkamangalam	-34.56	53.85	19.29	-2.88	4.49	2.5–3.5	SE–NW	N–S	NW–SE	0.20	Less
7	Ganapathipuram	-14.56	145.48	130.92	-1.21	12.12	0.5–2.5	SE–NW	NW–SE	NW–SE	0.14	Less
8	Muttam	-15.06	188.07	173.01	-1.26	15.67	1.5–3.5	NE–SW	N–S	>><<S–N	0.14	Less
9	Manavalakurichi	-54.12	18.78	-35.34	-4.511	1.57	4.5–5.5	S–NW	N–S	NW–SE	0.30	Very high
10	Mandaikadu	-44.75	17.57	-27.18	-3.73	1.46	2.5–4.5	S–N	NW–SE	NW–SE	0.22	High
11	Colachel	-13.01	141.64	128.63	-1.08	11.80	2.5–3.5	S–N	NW–SE	NW–SE	0.14	Less
12	Simonkudiyiruppu	-16.32	86.96	70.64	-1.36	7.25	2.5–3.5	S–N	NW–SE	NW–SE	0.14	Less
13	Midalam	-13.56	42.02	28.46	-1.13	3.50	2.5–3.5	S–N	>><<N–S	NW–SE	0.14	Less
14	Inayamputhandurai	-100.03	80.58	-19.45	-8.34	6.72	3.5–5.5	S–N	<<>>N–S	NW–SE	0.22	Moderate
15	Thengapattinam	-66.11	16.68	-49.23	-5.51	1.39	3.5–4.5	S–N	NW–SE	NW–SE<>SE–NW	0.28	Very high

The zone of rip current occurrence due to a) divergent (<<>>) and b) convergent (>><<) wave processes

Fig. 8 Spatial distribution of annual mean wave energy density in the study area



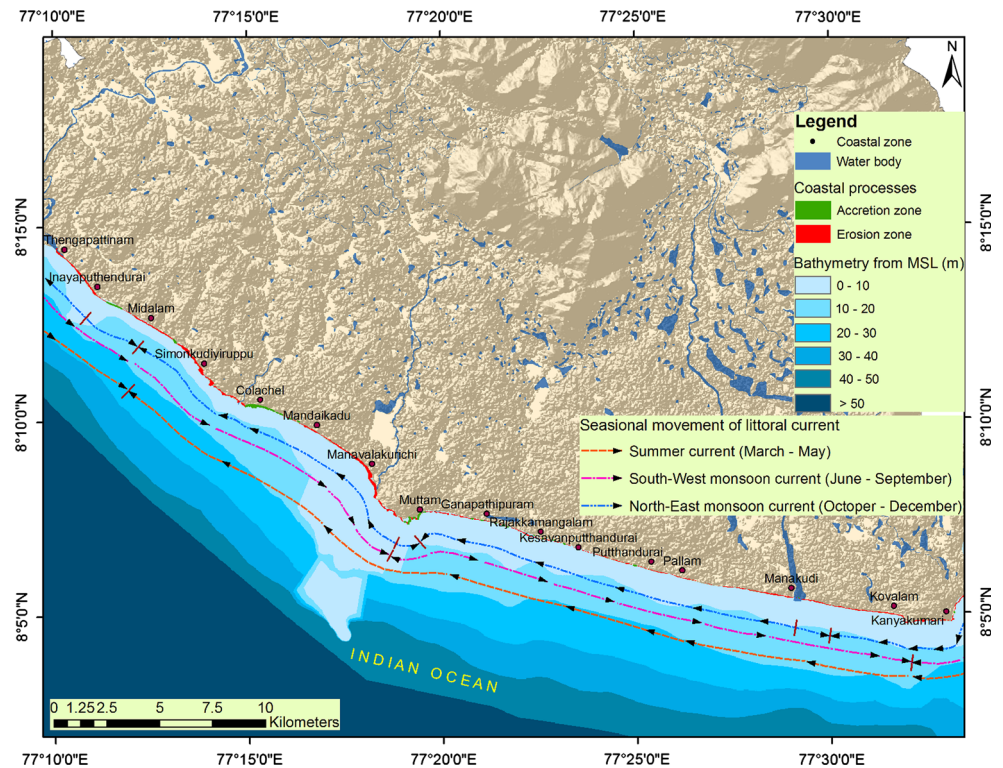
Impact of seasonal littoral current on shoreline changes

The movement of seasonal current varies in different parts of the study area causing shoreline changes by a deposit or withdrawal of littoral sediments. The study area experiences three types of littoral current system, such as south-west monsoon current (June–September), north-east monsoon current (October–December) and summer current (March–May) based on the wave direction and wind blow. The spatially interpolated current velocity, speed and angle of movement along with bathymetry of each coastal zone reflect the characteristics and its influence on erosion and accretion processes (Fig. 9). Besides, the littoral current flows from southeast to north-west during the NE monsoon and this phenomenon reverses during the SW monsoon and summer, and the reverse movement of current leads to dropping the sediments in different places of the study area (Table 1). Mohanty et al. (2011) have concluded that the shoaling wave effect propagates the concentration and direction of suspended sediments in the shallow region of the coast, whereas the suspended sediments are swashed by low current velocity along the low tide zones. In this study, it is noticed along the Pallam and Putthandurai coasts where the sandy pocket beaches have been identified. Moreover, the average current velocity along the coast is measured as 0.14 m/s, in which the fastest flow of its velocity is observed as 0.32 and 0.28 m/s in the Kanyakumari and Kovalam coasts during both SW and NE

monsoons. This coastal stretch has faced erosion due to the process of littoral sediment movement toward north during the NE monsoon, while it is reversed toward the southern direction during SW monsoon. The coast between Rajakkamangalam and Manakudi has been notified as low current velocity zones (0.14–0.22 m/s) and these areas have experienced accretion due to the presence of sea cliffs, eroded Teri sand dunes and very narrow patches of sandy beaches. The Manakudi and Ganapathipuram coasts have experienced accretion by SW current. Zhang (2011) has concluded that young formation of sandy beaches has the finest materials and is influenced by seasonal changes of hydrodynamic processes. The same phenomenon is applicable to the middle-west of Colachel coast, east part of Inayamputhandurai and Midalam coast. In these areas, the changes in littoral current movement produce accretion where the waves lead swash of sediments. But erosion is noticed in the backwash zones.

The rocky outcrops in the Muttam offshore restrict current velocity (0.14 m/s) and swash the sediments along these coasts, producing depositional landforms such as sandy beaches, beach ridges, beach berms, beach bars and dunes. However, a significant amount of beach materials was backwashed by the NE monsoon current from these areas during NE monsoon. The coastal configuration from Manavalakurichi to Thengapattinam extends toward south-east and north-west, where the summer and SW monsoon currents act on the headlands with high velocity

Fig. 9 Offshore bathymetry depth and seasonal movement of littoral currents in the study area



(0.28–0.30 m/s) from the north to south direction. This results in severe erosion along the coast by backwashing of the sediments. However, no significant changes occurred on the coast due to the effect of the NE monsoon current. Moreover, the coastal zones namely Cape Comorin in Kanyakumari and Muttam face rip current effect (0.3–0.5 m/s) in all seasons due to the presence of rocky outcrops and groins. These are often around the coastal structures because of narrow channels which allow the passage for water easily out to sea. The down-drift side has an obvious lack of supply of sediments. The beaches are depleted of habitat for plants and animals due to the loss of beach front or sediments (Walker et al. 2008). Manakudi, Putthandurai and Midalam also experienced the same condition due to the construction of groins and revetment, leading to backwashing of sediments on the down-drift side and then swashing on the up-drift side in the form of sandy beaches up to a length of 0.5–1.0 km. According to Dyer et al. (2000) the quantity of suspended sediment is more in turbulent waves along the surf zones that has discharged by surface runoff of the river system and significantly involved in changes of sediment regime in the estuary. This condition prevails in the Manakudi coast with high rates of sediments controlling the rate of coastal erosion. As the sediment supply is increased, the coastal zone is exposed to accretion in some parts, and the sediment supply is decreased in the eroded areas. Further, this analysis reveals that the current directs the longshore drift from north to

south during SW monsoon and summer periods. This produces a large amount of sediments along the coastal stretches in the western side of Muttam to Thengapattinam coast due to the process of constructive wave action, whereas during NE monsoon, this event occurs along the eastern side from Ganapathipuram to Kanyakumari coast.

Impacts of artificial coastal structures on shoreline changes

Man-made artificial structures such as groins, revetments and sea walls are built to protect shorelines and coastal landforms. This has modified the wave regime and depositional processes in the coastal zone. Groins are man-made structures designed to trap sand as it moves down the beach due to the longshore drift. The change in velocity of the longshore drift current causes deposition of suspended sand materials in the up-drift side of the groin. As the current continues around the groin, it becomes turbulent and actually contributes to erosion on the down-drift side (Daniel Martin et al. 2005). The eastern parts of Manakudi estuary, Simonkudiyiruppu and Colachel have experienced accretion on down-drift side. These structures have induced backwashing of sand materials from the down-drift side and caused beach erosion along the coast, namely Kovalam, Putthandurai, Mandaikadu and Inayamputhandurai coast. Butman (1987) has pointed out the effect of these artificial structures in intervening with coastal processes

such as wave direction and littoral current movement in offshore or surf zone and making changes in coastal landforms. In the Inayamputhandurai coast, erosion is induced due to high-energy wave action. The adjacent areas have large amount of accretion because of the groins that reduce the intensity of wave energy and increase retreat rates of sediments along the adjacent area (Fig. 10a–c). The both sides of R. Pazhayar mouth in Manakudi coast had linear-shaped groins perpendicular to the shoreline in 2007. After construction of these structures, severe erosion occurred on the long sandy beach on the down-drift side of the groins, but the beach width increased in the up-drift side (Fig. 10d–f). Moreover, the

Thengapattinam coast also has young beach formation in the eastern part of R. Thamirabharani estuarine (Fig. 10j–l). Unfortunately, the Colachel coast has normal erosion after the placement of four groins across the shoreline at a close distance (Fig. 10g–i). Coastal features such as beach, beach bar and sand dune have been stable or disappeared due to the structures.

Field verification and documentation

The shorelines of different years were extracted from multi-temporal satellite images to estimate the variation in distance at particular transects using a GIS platform. An

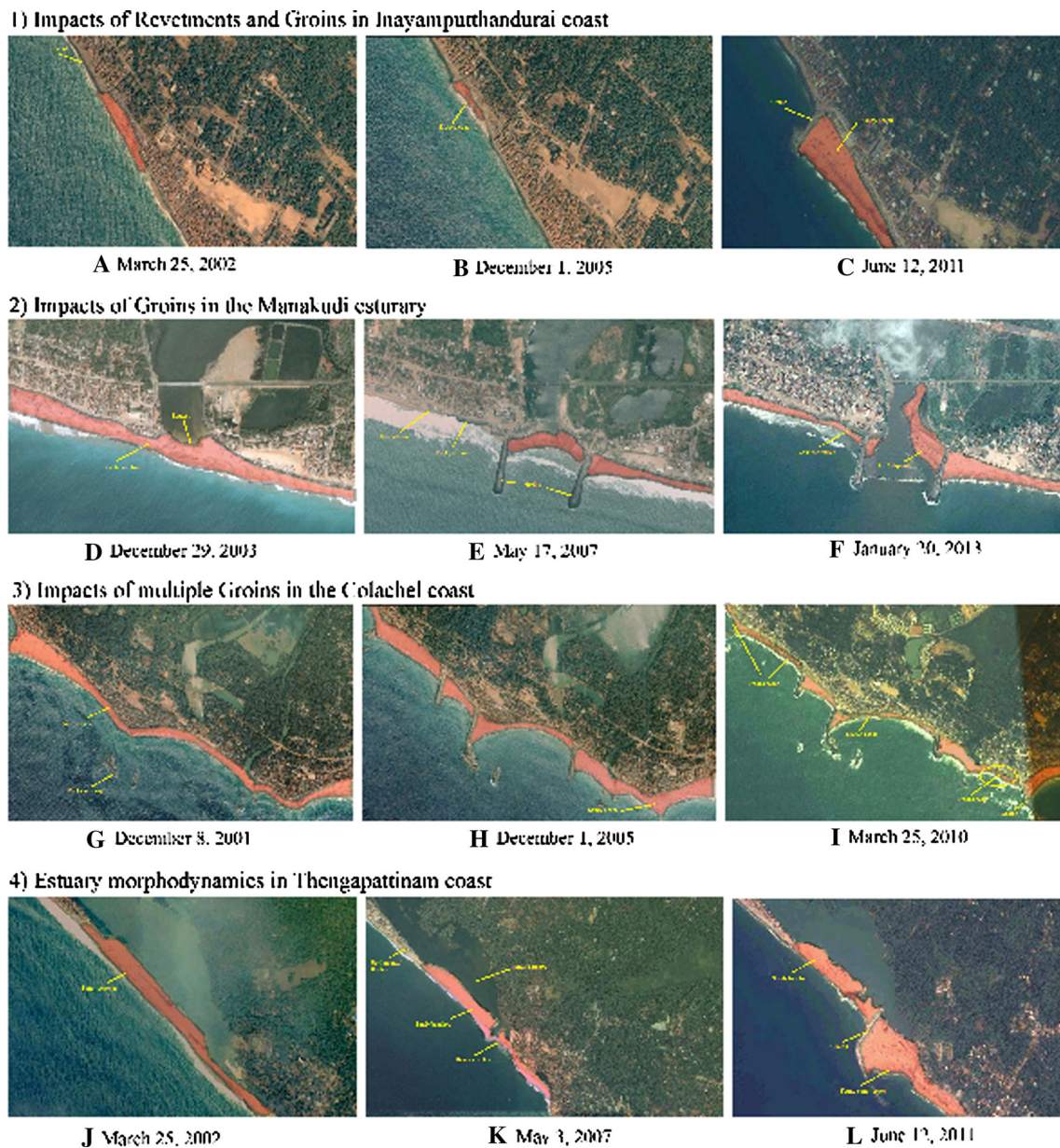


Fig. 10 Impacts of coastal artificial structures in different coastal zones (source: Google earth historical image data)

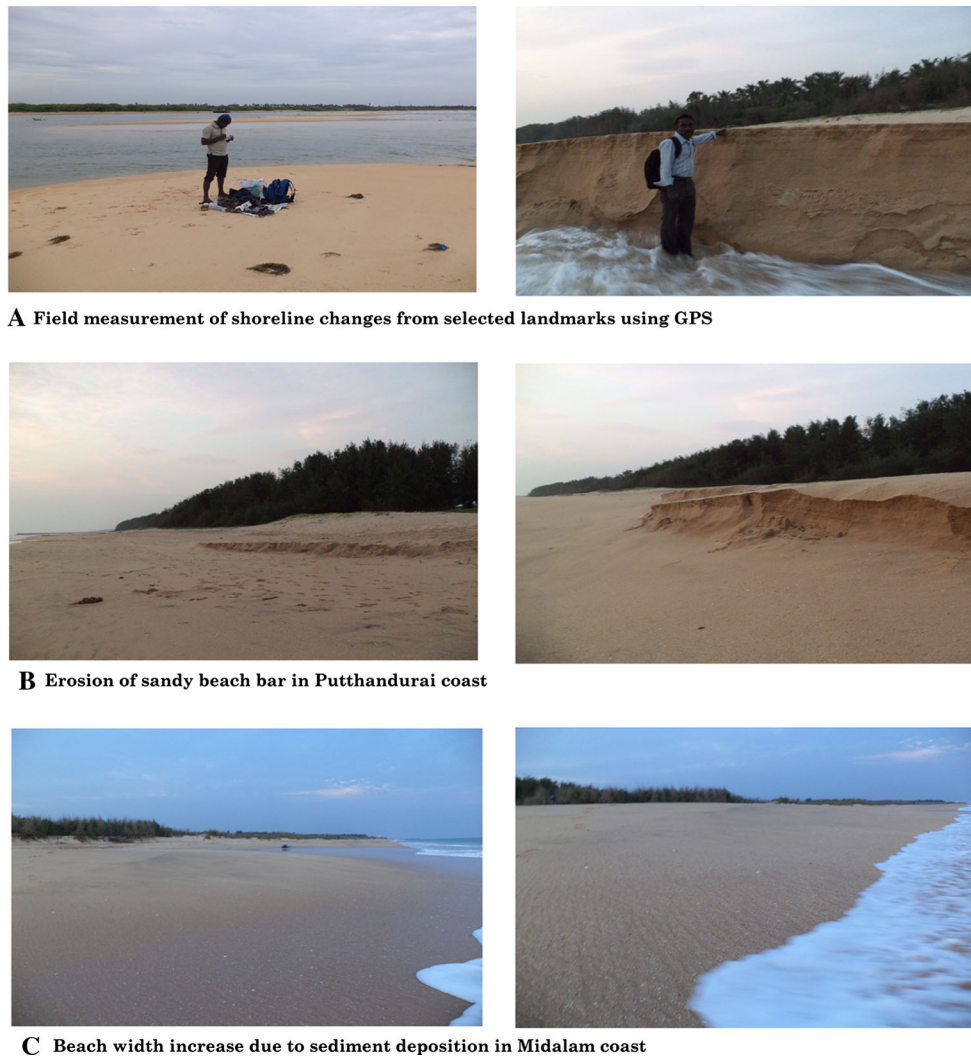


Fig. 11 Field measurement of shoreline changes using GPS and the erosion and accretion of coastal landforms

advantage of this technique is that it provides relatively accurate measurement of coastal erosion and accretion, though the area may be inaccessible or critical to manual survey. However, it is necessary to check the results of computerized assessment. For that purpose, the run-up measurement of erosion and accretion was carried out using a GPS (Garmin GPSMAP 76Cx) instrument. In this field verification, the GPS instrument is used to measure the linear distance between high water line and landmarks along the 15 coastal zones (Fig. 11). The field observed values are considered as the net rate of erosion and accretion (A) during 2011 and have been compared with the results (B) produced by the DSAS software system. The variations between these measurements clearly depict the shift of shoreline either landward or seaward that helps in understanding of the coast, either facing erosion or accretion. From this study, it is proved that the rates of erosion

and accretion are relatively accurate. Overall accuracy assessment reveals that the net rate of erosion and accretion obtained from both field survey and DSAS has relatively the same values and more reliability. However, some coastal zones namely Kanyakumari and Muttam have been identified with 0.8 % of the variations in measurement due to the presence of rocky outcrops along the surf zone, which makes it inaccessible during the survey. On the other hand, these areas have been highly influenced by the fluctuation of hydrodynamic processes. The rate of variation in erosion and accretion is about 0.29, 0.46 and 0.71 % in the Kovalam, Colachel and Simonkudiyiruppu coasts, respectively. It is due to the placement of artificial structures like groins, revetments and sea wall in the coastal headlands. The structures disturb the wave direction and littoral current movement and cause seasonal variation in shoreline shift throughout the year (Table 2).

Table 2 The accuracy assessment of coastal erosion and accretion using field-observed values

Sl. no.	Coastal zone	Net rate of erosion/ accretion (<i>A</i>) in meters (based on field estimation)	DSAS estimated net rate of erosion/ accretion (<i>B</i>) in meters	% of variation $P = (B - A) / \text{total area} \times 100$	Factors influencing rate of erosion and accretion
1	Kanyakumari	-155.5	-157.92	-0.81	Influences of high-energy waves from different directions induce severe erosion of Teri sand dunes
2	Kovalam	-28.0	-27.14	0.29	Wave diffraction and movement of seasonal littoral current cause erosion
3	Manakudi	-16.8	-17.32	-0.17	Diverting sediment supply to up-drift by groins causes erosion on the down-drift side
4	Pallam	90.5	91.4	0.30	Sediment deposition occurs by littoral drift
5	Putthandurai	-09.5	-8.44	0.35	Seaward flowing rip current induces seasonal erosion due to overwash of sediments from beaches
6	Rajakkamangalam	19.0	19.29	0.10	High wave action causes retreat of sediments, but is replaced during monsoon by littoral currents
7	Ganapathipuram	131.0	130.92	-0.03	Less energy waves produce swash of sand into the coast leading to formation of stable beach landforms
8	Muttam	175.5	173.01	-0.83	The recently constructed jetty causes accretion in the east and induces erosion in the western part.
9	Manavalakurichi	-35.6	-35.34	0.09	Erosion due to unregulated mining which induced removal of sand deposits
10	Mandaikadu	-27.0	-27.18	-0.06	Encroachment of coast for habitat and removal of coastal vegetation lead to older sand dune erosion
11	Colachel	130.0	128.63	-0.46	The presence of rocky outcrops acts as natural barrier to reduce wave intensity and cause sediment deposition along the east part of the zone
12	Simonkudiyiruppu	68.5	70.64	0.71	Trapping the littoral sediments transport from Thengapattinam estuary produces wide beaches
13	Midalam	28.5	28.46	-0.01	Accretion of transported sediments released by R. Thamirabarani
14	Inayamputthandurai	-20.0	-19.45	0.18	Placement of coastal configuration which directly faces high wave energy causes severe erosion. The revetments in the surf zone protects this zone
15	Thengapattinam	-48.2	-49.23	-0.34	The high wave energy action causes sediment transport in large quantities leading to erosion

Environmental impact assessment

The coastal environment is highly influenced by natural and anthropogenic activities which control the stability of coastal landforms and sedimentation. The coastal zone between Kanyakumari and Kovalam has severe erosion due to angle of wave approach and littoral current which divert the suspended sediments into the adjacent area. For the last decade, the study area has experienced up-normal changes due to the placement of artificial structures such as groins,

revetments and seawalls; they have disturbed the sediment movement by diverting the littoral current direction and wave and led to beach morphology changes in the Manakudi estuary in the eastern side as well as in Thengapattinam coast in the western part. These structures have produced erosion in the down-drift side and accretion in the up-drift side because some erosion of the beach front is still occurring. Shallow sand bar is noticed in the Thengapattinam estuary mouth. This is controlled by the angle of waves approaching the shoreline. The anthropogenic

impacts such as removal of vegetation and unregulated placer mining in the Manavalakurichi coast have caused loss of coastal headlands of sand dunes. Mining activities on this coast result in changes of beach morphology which affects the coastal aquifer, sea water intrusion and turbidity in the near shore regions. Further, the massive removal of sand dune complex has created a landscape with deep pits and steep slopes in the Mandaikadu coastal stretch. The inundation of sea water in the mined area is prominent. Also, it seems obvious that these areas are at risk and vulnerable to erosion, sea water intrusion, instability of settlements and changes of coastal landforms. Finally, the physical impact assessment of this study reveals that the SW coast has relatively increased vulnerability to natural and anthropogenic hazards that produce problems to coastal dune ecosystems.

Conclusions

The analysis of shoreline change assessment using Landsat images reveals that the study area has experienced high rates of erosion and accretion along the different coastal zones during 1999–2011. The net rate of shoreline change values of each coastal zone reflects its coastal dynamic characteristics. According to this study, the Kanyakumari, Kovalam, Manakudi, Mandaikadu, Inayamputhandurai and Thengapattinam coast fall under threatening condition due to erosion. In these areas, the morphology of the headland features such as young beaches, beach ridges, beach berms, sand dunes and sea cliffs are disturbed throughout the year due to the high intensity of wave energy and littoral currents. The rates of erosion and accretion of this coast have resulted from wave-induced longshore currents and other coastal dynamic processes. However, the hydrodynamic forces pose a favorable condition for significant amounts of littoral sediment deposited along the coastal zones, namely Rajakkamangalam, Ganapathipuram, Colachel and Midalam. This is due to the coastal configuration structure and less wave energy action prevailing in these areas. The sandy beaches along these zones are extensively developed by the processes of constructive wave action, which causes distribution of littoral sediment materials parallel to the shoreline. The R. Thamirabharani releases large amounts of runoff materials into the Thengapattinam estuary during the SW and NW monsoon periods. However, these sediments are shifted toward the southern side by the SW monsoon current and northward by the current movement during NE monsoon and summer and observed with erosion activities. The coastal defense structures are normally established to divert the diffracted waves and decrease littoral drift. In this coast, different coastal zones including

Kovalam, Rajakkamangalam, Muttam, Colachel and Inayamputhandurai are constructed with groins to reduce wave impacts on the area, but the long-term observation of these areas noted severe erosion on the down-drift side. The Manakudi estuary has deposited large amounts of sediments that is released by R. Pazhayar. However, the groins on either side of the river mouth induced backwashing of sediments and threatening loss of land forms. The nature of shoreline change in this area is mainly controlled by longshore drifting of sediments, convergence of wave refraction, unregulated coastal mining and other man-made activities. Moreover, the processes of beach, beach ridge, beach berms and sand dune formation, migration and relocation along this coastal area are mainly influenced by wave energy and reversing direction of littoral currents. The revetments are located in Manakudi, Putthandurai and Midalam coasts and produce rip current by disturbing the wave direction. The movement of rip currents seaward has eroded beach materials and caused loss of coastal landforms. These structures mainly disturb the shoaling, refraction and diffraction of wave processes and cause accretion on up-drift side and erosion on the down-drift side of the coast. For better management of the coastal environment, it is vital to monitor the coast continuously to understand the changes and its influencing factors. Hence, this study will be more useful to planners and decision makers for sustainable coastal management.

Acknowledgments The corresponding author S. Kaliraj is thankful to DST-INSPIRE Division, Department of Science and Technology (DST), Government of India for the award of INSPIRE Fellowship (DST/INSPIRE/2011/IF110366) for pursuing his Ph.D degree program. He also extends his gratitude to INCOIS, NIO, NIOT and Survey of India (SOI) for providing the necessary data source to carry out this research work.

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