

Shoreline change analysis along the coast between Kanyakumari and Tuticorin of India using remote sensing and GIS

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Received: 21 February 2011 / Accepted: 24 August 2011 / Published online: 18 September 2011
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Abstract Shoreline is one of the rapidly changing landform in coastal area. So, accurate detection and frequent monitoring of shorelines are very essential to understand the coastal processes and dynamics of various coastal features. The present study is to investigate the shoreline changes along the coast between Kanyakumari and Tuticorin of south India, where hydrodynamic and morphologic changes occur continuously after the December 2004 tsunami. Multi-date satellite data of Indian Remote Sensing (IRS) satellites (1999, 2000, 2003, 2005, and 2006) are used to extract the shorelines. The satellite data is processed by using the ERDAS IMAGINE 9.1 software and analyzed by ArcGIS 9.2 workstation. The different shoreline change maps are developed and the changes are analyzed with the shoreline obtained from the Survey of India Toposheets (1969). The present study indicates that accretion was predominant along the study area during the period 1969–1999. But recently (from 1999 onwards), most of the coastal areas have experienced erosion. The study also indicates the reversal of shoreline modifications in some coastal zones. The coastal areas along the headlands have experienced both erosion and accretion. Though the coastal erosion is due to both natural and anthropogenic activities, the coastal zones where sand is mined have more impacts and relatively more rate of erosion than that of other zones. Improper and in-sustainable sand mining leads to severe erosion problem along this area. So the concept of sustainable

management should be interpreted in the management of the near-shore coastal sand mining industry.

Keywords Coastal zone management · Erosion · Accretion · Hazards · Beach nourishment

Introduction

Coastal areas are very important for human being since the beginning of time. Most of the big cities in the world are situated along the coastal area. About one third of the human populations are living in and around the coastal area. Due to abundant natural resources, the urbanization and population rapidly increases on the coastal area. Various developmental projects are made around the coastal areas. They put high pressure on it and lead to various coastal hazards like sea erosion, sea water intrusion, coral bleaching, shoreline change etc. The coastal landforms are highly dynamic in nature. They are continuously modified by natural and other man-made processes.

Li et al. (2001) reported that the shoreline is one of the most unique features of earth surface. It is one of the twenty-seven features recognized by the International Geographic Data Committee. A shoreline is defined as the line of contact between land and water body. It is easy to define but difficult to capture since it is always changing. Nayak (2002) implied that the accurate demarcation and monitoring of shorelines (seasonal, short-term, and long-term) are necessary for understanding various coastal processes. Remotely sensed satellite data is widely used to analyze the shoreline changes. It can provide more information within a short span of time. Several studies using satellite data have proved its efficiency in understanding various coastal processes (Anderson et al. 1973;

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Carter and Schubert 1974; Cracknell et al. 1982; Nayak and Sahai 1985; Loveson and Rajamanickam 1988; Gupta et al. 1989; Nasir et al. 1990; Nath et al. 1991; Wagner et al. 1991; Hill et al. 1994; Ahmed and Neil 1994; Ramalingam and Renganathan 1998; Anbarasu et al. 1999).

Chandrasekar et al. (2000) reported that the space technology by virtue of its capability to provide information over a large area in a repetitive basis has proved to be very useful in identifying and monitoring various coastal features towards a suitable action plan in order to achieve the development in any coastal area. Desai et al. (2000) have reported the advantages of GIS for the integration of various thematic information derived from satellite data with other collateral data such as socioeconomic and cultural data are significant in arriving at integrated coastal zone management practices. Champati (2000) insisted that the information given in digital format is easily accessible to users and policy-makers for various applications and decision-making purposes. Charatkar et al. (2004) reported that the IRS 1C/1D imagery is well suited for generating land–water boundary because of the strong contrast between land and water in the infra-red portion of the electromagnetic spectrum.

After the Indian Ocean tsunami (26 December 2004), different morphological changes and variations in sea level were frequently observed along this coastal area. Chandrasekar and Immanuel (2005) insisted that the recent Indian Ocean tsunami induced sudden erosion unlike seasonal variations along the southeast coast of India. Mujabar et al. (2007) reported that the tsunami induced large amount of beach erosion along the study area. Recently, various developmental projects are started along this area. So the present study by using remote sensing and GIS will be very useful to assess the impact of hydrological and morphologic factors on modifying the shorelines along this area.

Study area

The study area is the coast between Kanyakumari and Tuticorin which extends over a distance of 160 km with different morphological features along the southern coast of Tamilnadu state, India (Fig. 1). For effective spatial data modeling and analysis of shorelines, it is very essential to segment the entire shoreline in to several zones or grids. Kairu and Nyandwi (2000) also state that the effective coastal classification is a fundamental precursor to any study of shoreline change. So based on the geological and hydrological aspects, the entire study area has been divided in to four coastal zones namely Kanyakumari (KAN), Ovari (OVA), Tiruchendur (TRU), and Tuticorin (TUT) on the basis of coastal geomorphology, drainage pattern, and

diverse energy conditions which are stated in Table 1. Each zone has further been sub-divided in to three grids of aerial size about 100 km² (Fig. 1). The Kanyakumari zone is influenced with tourism and developments. The grids of Manappad, Tiruchendur, and Kayalpatinam have head lands. Sand mining is actively pursued along the coasts of Idinthakarai, Navaladi, Ovari, and Periathalai. Breakwater has been constructed in Kanyakumari, Koottapuli, and Perumanal coasts. The Tuticorin is one of major ports in India. Recently various developmental projects like Koodankulam nuclear power plant and Sethu-samuthiram ship canal are also started along the study area.

The southern coastal Tamilnadu is replenished with valuable deposits of heavy minerals. The occurrence of black sands has been reported by Jacob (1956), Rao (1957), Siddique and Rajamanickam (1978), and Loveson and Rajamanickam (1989). Moderate to high wave energy condition prevail along the study area, and it is an enriched zone of placer mineral deposits (Angusamy and Rajamanickam 2000). Loveson et al. (1996) found that the reason for the heavy minerals along the study area is not due to the presence of rivers, but the basinal structure of the coastal configuration which acts as a trap to accumulate heavy minerals transported northwards by long-shore current.

The drainage pattern along the study area is controlled by a major river, Tambraparni; minor streams like Palaiyar, Nambiyar, and Hanuman Nadhi; and seasonal streams like Nilapparai and Puttanar channels. Cliffs are along the Kanyakumari coast which projects towards the Indian Ocean forming promontory. Most of the coastal areas have sandy beaches and some areas are rocky in nature. Oceanography of the Indian east coastal region is mainly controlled by northeast monsoon. In addition to northeast monsoon, the Tamilnadu coast has the effect of southwest monsoon. Along the study area, the wind speed during the southwest monsoon ranges from 36 to 50 km/h and during northeast monsoon it ranges from 20 to 80 km/h. Plunging breakers were mostly observed in the coasts of Koottapuli, Idinthakarai, and Ovari and spilling breakers were mostly observed in other coasts.

Materials and methods

In this present study, the multi-date satellite data (IRS data) is used as primary data for extracting the shorelines. The Survey of India (SOI) Topographical maps (1:50,000 scale) are used as base map. Nayak (2002) insists the importance of the low tide satellite data for shoreline mapping. So in order to eliminate the influence of tidal variations and to get a clear demarcation of both low and high water levels, satellite data during low tide with same period is used.

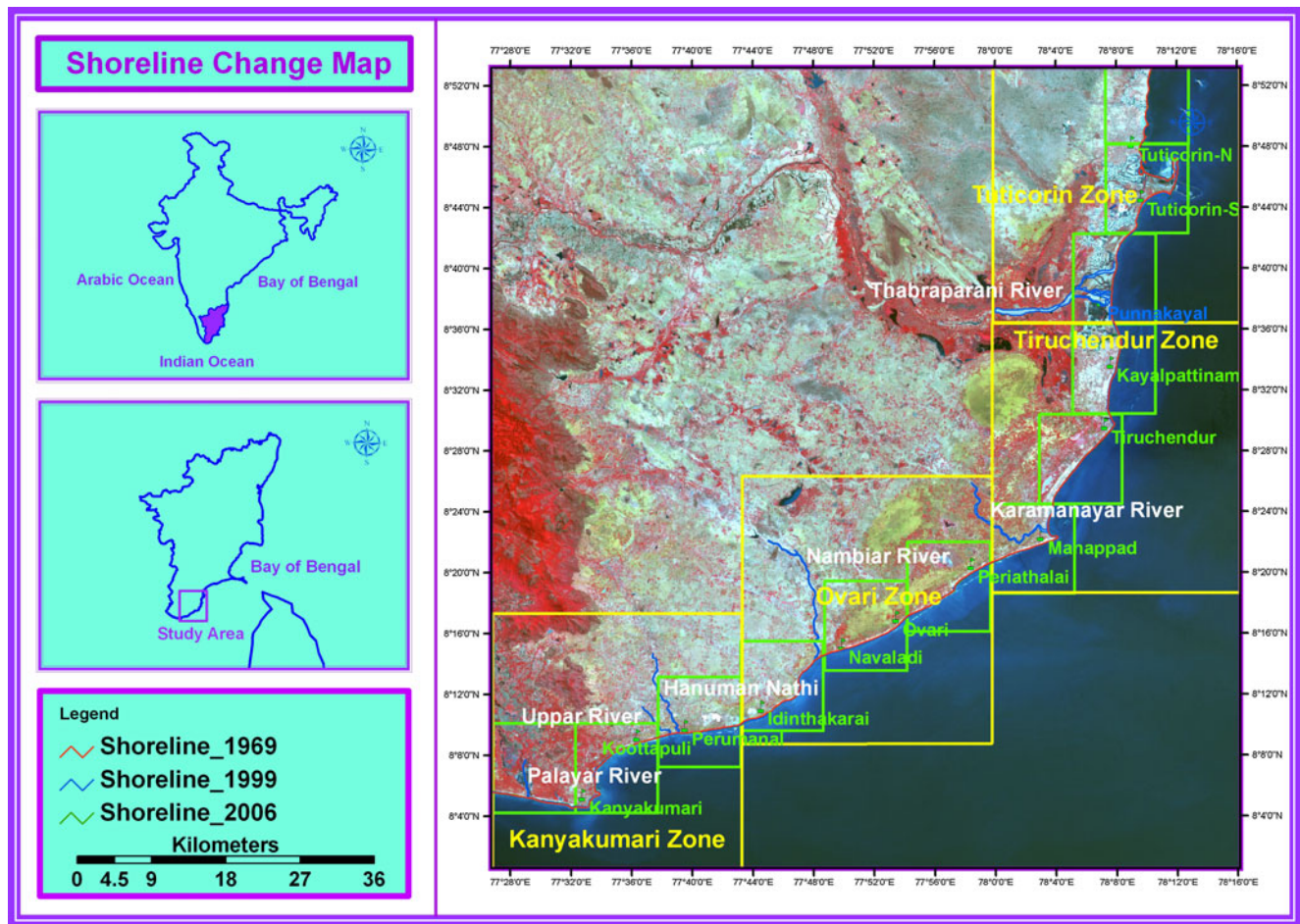


Fig. 1 Study area map

District maps and other information obtained during the GPS field survey are also utilized as secondary data.

The raw satellite images usually contain many defects like radiometric distortion, geometric distortion, presence of

noise, etc. due to variations in the altitude, attitude, and velocity of the sensor platform. So they cannot be used as map base without corrections (Lillisand and Kiefer 2000). After performing preprocessing operations, the satellite

Table 1 Classification of study area in to four coastal zones

| Parameter | Name of the coastal zones | | | |
|-----------------------------|---|--|--|--|
| | Kanyakumari | Ovari | Tiruchendur | Tuticorin |
| Coastal geology | Crystalline rocks | Crystalline rocks | Marine calcareous, siliceous sand | Coralline rocks |
| Coastal geomorphology | Cliff rocks, beach ridges, marine terrace | Dune complex, wave cut platform | Headlands and bays | Spits, bays, mud flats |
| Shore configuration | E–W | NE–SW | NNE–SSW | N–S |
| Beach gradient | 3–6° | 2–4° | 3–5° | 1–3° |
| Beach composition | Moderate heavy mineral | Rich heavy mineral | Calcareous | Siliceous, muddy |
| Breaking wave height | 0.6–0.8 m | 0.5–1.2 m | 0.3–0.7 m | 0.2–0.5 m |
| Wave energy | High wave energy | High wave energy | Medium wave energy | Low wave energy |
| Width of beaches | 50–80 m | 50–130 m | 70–100 m | 50–110 |
| Drainages/estuaries | Minor/Manakkudy | Nil | Nil | Major/Thambraparani |
| Net littoral sediment drift | 20–180 × 10 ³ cm ³ | 80–440 × 10 ³ cm ³ | 50–250 × 10 ³ cm ³ | 75–320 × 10 ³ cm ³ |

image is geo-referenced and projected with polygonic projection and WGS 84 as datum by using ERDAS IMAGINE 9.1 software. More than 25 ground control points (GCP) collected from toposheets are used during this geometric correction process with third-order polynomial geometrical model. The obtained GCP's are also verified by using the GPS survey and the root mean square error is kept less than 0.005 of a pixel. The image is then re-sampled by nearest neighbor method. The geometric correction is very essential for applications such as change detection, resolution merge, mosaic, and layer stacking purposes and should be highly accurate, because the misalignment of features at the same location leads to large errors. The current process of manual point measurement can be prohibitively labor intensive for large applications, and it does not enforce sub-pixel level correlation between images due to the limitation of human visual interpretation.

IMAGINE Auto-Sync workstation uses an automatic point matching algorithm to generate thousands of tie points, and produces a mathematical model to tie the images together. The resulting workflows significantly reduce or sometimes completely eliminate manual point collection. However, for near-shore areas where shoreline changes occur, it is potentially possible that the Auto-Sync function forces two laterally displaced shoreline features as the same ground control points (i.e., they are interpreted by the function as the same geographic location) and Auto-Sync function leads mistakenly geo-reference the two images. In order to eliminate this problem, all automatically generated GCP's are carefully verified and the points which present along the shorelines are removed. The control points only from the stable ground features are taken and processed by using IMAGINE Auto-Sync workstation. Thus the remaining images are geo-referenced and a better output is made with high accuracy in comparison to the previous methodology.

The imageries are then subjected to noise reduction technique to segregate the noise from the data. Many semi-automatic or automatic segmentation techniques were applied to extract the shoreline from variety of remote sensing data (White and El Asmar 1999; Dellepiane et al. 2004), but there is no single method which can be considered good for all images (Pal and Pal 1993). In this present study, the exact land–water boundary is obtained by using non-linear edge-enhancement technique with Sobel operator (3×3 kernel matrix). The operations are being implemented to image data to get an enhanced output of the image for subsequent visual interpretations. The enhancement techniques provide better feature exhibition to increase the visual distinction between features contained in a scene. This technique gives a clear demarcation of land–water boundary and the shoreline is carefully digitized and exported as shapefiles to ArcGIS 9.2 for further

analysis. The extracted shorelines are then overlaid to produce the shoreline change map. The erosion and accretion are measured and analyzed.

Results and discussion

Different shoreline change maps are created by using ArcGIS and shown in Fig. 2a–l. In order to investigate the long- and short-term changes, the shoreline data of 1969, 1999, and 2006 are utilized. The shoreline lengths during different periods and their linear changes are estimated and shown in Table 2.

Linear shoreline changes

The length of shoreline and their linear change detection (Table 2) provide useful information on the dynamics of shorelines. It helps to predict whether a particular coastal zone is undergoing uniform or irregular changes. The length of shorelines and their linear changes are calculated based on the modeling of coastal dynamic segmentation (Van Dusen 1997). The multi-temporal shoreline vectors (during 1999 and 2006) along with the reference dataset of SOI topo-maps (1969) are segmented in to multiple homogeneous subunits based on the coastal zones. Based on the coastal zones along the study area, the individual shoreline lengths are calculated for different years. Figure 3a–d shows the dynamics of linear shoreline changes along the different coastal zones.

The linear shoreline change study reveals that the entire shoreline has been modified. During the period 1969–1999, the linear shoreline change is more in Tiruchendur and Tuticorin zones (Table 2). The Tiruchendur zone has experienced a high linear shoreline change of +530 m. This zone has headlands and bays along the coast of Manappad and Tiruchendur. These headlands and bays are found together on the same stretch of coastline. A bay is surrounded by land on three sides, whereas a headland is surrounded by water on three sides. Headlands are characterized by high, breaking waves, rocky shores, intense erosion, and steep sea cliffs. Bays are typically quiet with sandy beaches. Headlands and bays form on discordant coastlines, where bands of rock of alternating resistance run perpendicular to the coast. Bays form where weak (less resistant) rocks (such as sands and clays) are eroded, leaving bands of stronger (more resistant) rocks (such as chalk, limestone, and granite) forming a headland, or peninsula. This difference in the rate of erosion is caused by differential erosion and it enhances the linear change in the length of the shoreline.

The Tuticorin has also comparatively higher linear shoreline change of +170 m. The zone has mud flats

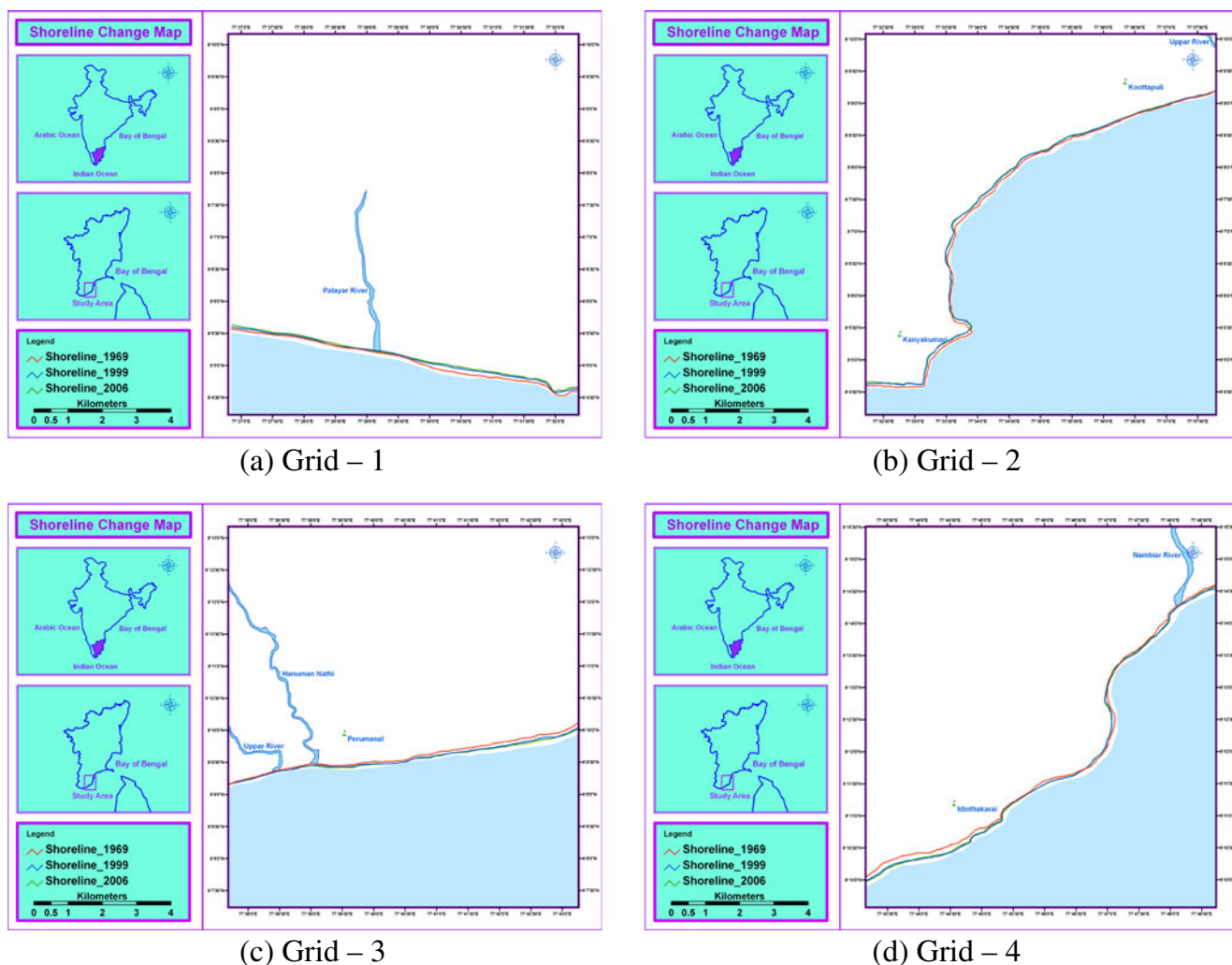


Fig. 2 a–d Shoreline change map, e–h shoreline change map, i–l shoreline change map

along the coast of Punnakayal estuary and Tuticorin which eventually modifies the dynamics of the coast and enhances the length of the shoreline. The coast of Kanyakumari and Ovari have less (–60 m and –70 m) linear shoreline changes (Table 2). During this period (1969–1999), the Kanyakumari zone has faced a uniform rate of erosion and Ovari zone has experienced a uniform rate of accretion. This uniform changes in erosion and accretion does not modify the trend and configuration of shoreline and thereby results in low linear shoreline change.

During the period of 1999–2006, the Tiruchendur zone has more linear shoreline change and the remaining coastal zones have experienced comparatively less changes. The shoreline length of the Tiruchendur coast is decreased by 200 m. This indicates the accretion of sediment along the bays of this coastal zone and thereby reduces the length of the shoreline. From the satellite images, it has also been observed that refraction of waves occurs along the

Manappad coast in the Tiruchendur zone. Refraction of waves occurs on headlands concentrating wave energy on them, so many other landforms, such as caves, natural arches, and stacks, form on headlands. Wave energy is directed at right angles to the wave crest and lines drawn at right angles to the wave crest (orthogonal) represent the direction of energy expenditure.

Easterbrook (1999) emphasizes that the orthogonal converge on headlands and diverge in bays which concentrate wave energy on the headlands and dissipating wave energy in the bays. In the formation of sea cliffs, wave erosion undercuts the slopes at the shoreline and they retreat landward. This increases the shear stress in the cliff-forming material and accelerates mass movement. The debris from these landslides collects at the base of the cliff and is removed by the waves, usually during storms where wave energy is greatest. This debris provides sediment, transported through long-shore current for the nearby bay.

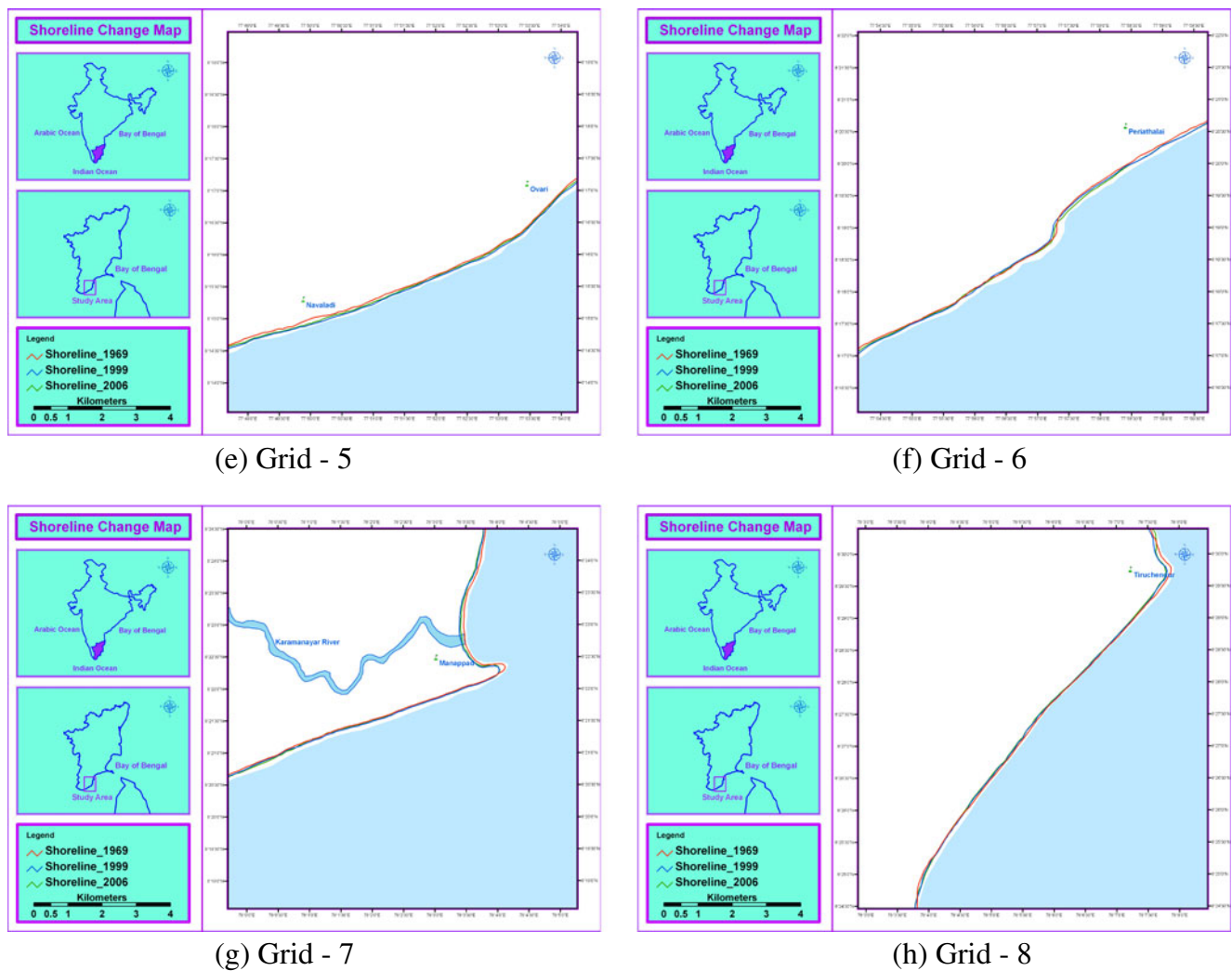


Fig. 2 (continued)

Long-term shoreline changes

1. Kanyakumari zone: The coastal erosion and accretion made along the different grids are in Tables 3 and 4. The long-term erosion and accretion in different grids are shown in Fig. 4. The Kanyakumari coastal zone includes three grids (nos. 1, 2, and 3). During 1969–1999, the grid 1 has an erosion of 0.675 km^2 ha and no accretion is noted during this period. The sand dunes along this grid have experienced more erosion due to both natural and man-induced activities. The southeast monsoon also enhanced the erosion along this grid. The net growth observed along this grid is -0.675 km^2 with a rate of $-22,500 \text{ m}^2/\text{year}$. The grid 2 has experienced more erosion of 0.838 km^2 and an accretion of 0.05 km^2 . The net growth observed along this grid is -0.788 km^2 . This grid was eroded at a rate of $26,267 \text{ m}^2/\text{year}$. No erosion is noticed in grid 3, but it experienced a heavy accretion of 0.657 km^2 . The

- sediment discharged from the rivers Hanuman Nathi and Uppar are deposited along this grid 3. In addition to that the sediment eroded from the western part of the Kanyakumari coastal zone are drifted along east side by littoral currents and deposited along the eastern side of zone. Similar effect has been observed along many coasts of the world. Frihy and Komar (1993) also states that long-shore patterns wherein erosion along a stretch of coast gives way to accretion in an adjacent stretch of the coast of Egypt.
2. Ovari zone: The Ovari coastal zone includes three grids (nos. 4, 5, and 6). Even though this coastal zone is presently eroding at higher rates, heavy accretion is noted along this coast during 1969–1999. All the grids of this zone are accreted at very high rates. The fourth and fifth grids of this zone experienced more accretion and no erosion is noted in fifth grid.

The grid 4 has an accretion of 0.932 km^2 and an erosion of 0.155 km^2 . The sediments discharged from

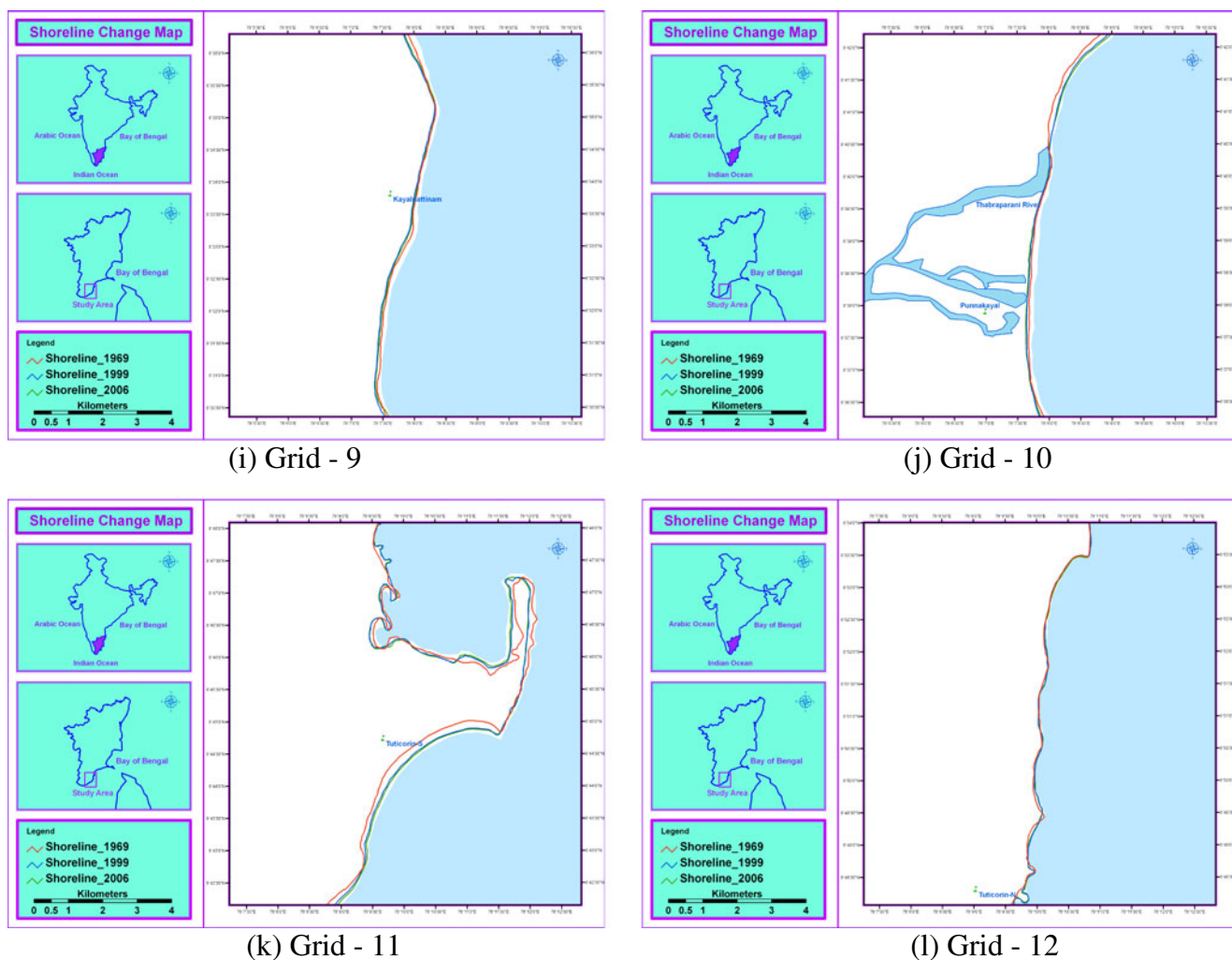


Fig. 2 (continued)

the rivers of Hanuman Nathi and Uppar deposited along the grid. The net growth observed along this grid is 0.778 km² with a rate of 25,933 m²/year. The grid 5 also has more accretion (0.957 km²) and no erosion is noticed along the grid. In addition to the sediments discharge from the rivers Hanuman Nathi and Uppar, the Nambiar River also supplies sediment for the accretion along this grid. The net growth observed

along this grid is 0.957 km² and the coast was accreted at a rate of 31,900 m²/year. The grid 6 has an accretion of 0.497 km² and an erosion of 0.135 km². Even though accretion dominated in this grid, the shoreline along the south of Periathalai coast had experienced severe erosion problem which is mainly due to beach placer mining by the private industries. A breakwater has been constructed in Periathalai coast to save local fisherman from severe threat of submerged reefs along the coast (Fig. 7). But after the construction of breakwater, the grid 6 experiences accretion. The offshore breakwaters reduce the intensity of wave action in inshore waters and thereby reduce coastal erosion. The net growth observed along this grid is 0.362 km² with a rate of 12,067 m²/year which favors the replenishment of placers in this grid.

3. Tiruchendur zone: The Tiruchendur coastal zone includes three grids (nos. 7, 8, and 9). During the period 1969–1999, this zone undergoes heavy erosion.

Table 2 Linear changes of shorelines

| Coastal zone | Shore length (km) | | | Linear shoreline change (m) | |
|--------------|-------------------|-------|-------|-----------------------------|-----------|
| | 1969 | 1999 | 2006 | 1969–1999 | 1999–2006 |
| Kanyakumari | 36.82 | 36.76 | 36.75 | −60 | −10 |
| Ovari | 38.08 | 38.01 | 37.99 | −70 | −20 |
| Tiruchendur | 38.62 | 39.15 | 38.95 | +530 | −200 |
| Tuticorin | 51.15 | 51.32 | 51.27 | +170 | −50 |

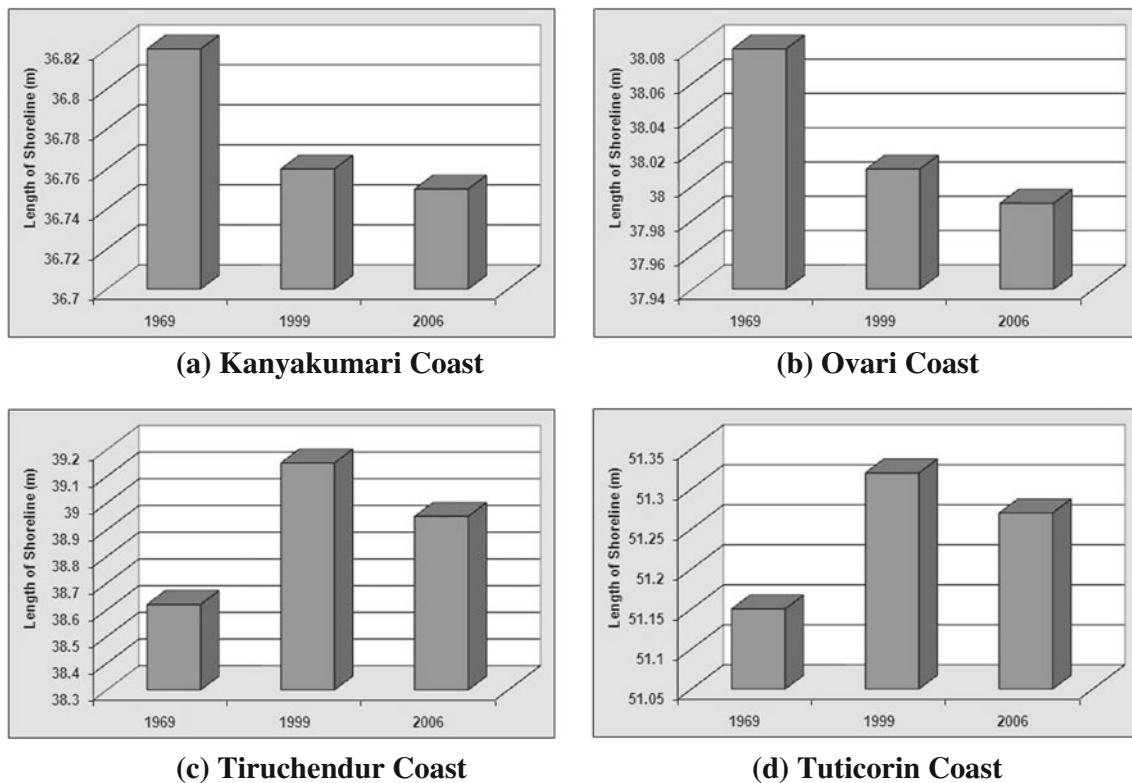


Fig. 3 a–d Linear shoreline changes along the different coastal zones

The headlands at Manappad and Tiruchendur have faced severe erosion. The seventh grid which includes the Manappad headland has experienced an erosion of 0.432 km^2 . The northern part of the Manappad headland has experienced this erosion whereas the southern part of headland was accreted (0.301 km^2).

Table 3 Long-term erosion and accretion along the different grids

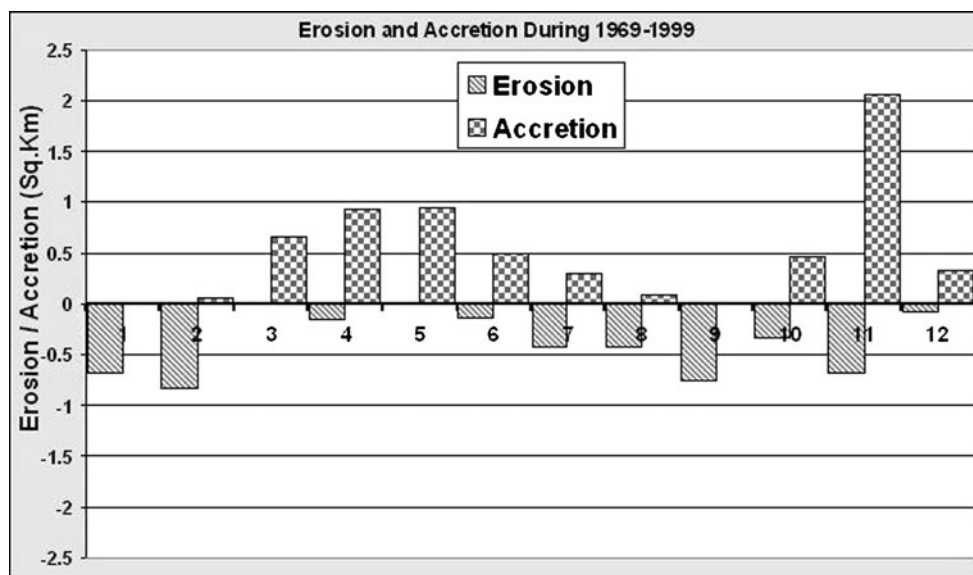
| Coastal zone | Grid no. | Erosion and accretion during 1969–1999 | | | |
|--------------|----------|--|-----------------------------|------------------------------|--|
| | | Erosion (km^2) | Accretion (km^2) | Net growth (km^2) | Growth rate (m^2/year) |
| Kanyakumari | 1 | 0.675 | 0.000 | -0.675 | -22,500 |
| | 2 | 0.838 | 0.050 | -0.788 | -26,267 |
| | 3 | 0.000 | 0.657 | 0.657 | 21,900 |
| Ovari | 4 | 0.154 | 0.932 | 0.778 | 25,933 |
| | 5 | 0.000 | 0.957 | 0.957 | 31,900 |
| | 6 | 0.135 | 0.497 | 0.362 | 12,067 |
| Tiruchendur | 7 | 0.432 | 0.301 | -0.131 | -4,367 |
| | 8 | 0.421 | 0.089 | -0.332 | -11,067 |
| | 9 | 0.765 | 0.000 | -0.765 | -25,500 |
| Tuticorin | 10 | 0.334 | 0.455 | 0.121 | 4,033 |
| | 11 | 0.681 | 2.050 | 1.370 | 45,667 |
| | 12 | 0.072 | 0.331 | 0.259 | 8,633 |

The coast along Manappad to Tiruchendur has sand dunes. This coastal sand dune along northern part of the headland was eroded heavily. This grid has bands of rocks with different resistances, so that the weak (less resistant) rocks (such as sands and clays) are eroded more and forming curved bays and leaving the bands of stronger (more resistant) rocks (such as chalk, limestone, and granite) forming headlands and bays. Due to more or less equal accretion and erosion, the net growth is low (-0.131 km^2) and the coast is eroding at a rate of $-4,367 \text{ m}^2/\text{year}$. The grid 8 has an erosion of 0.421 km^2 and an accretion 0.089 km^2 is noted during this period. This grid has also headland (Fig. 8). The entire stretch of the headland was eroded. The net

Table 4 Net erosion and accretion made during 1969–1999

| Coastal zone | Erosion and accretion during 1969–1999 | | | |
|--------------|--|-----------------------------|------------------------------|--|
| | Erosion (km^2) | Accretion (km^2) | Net growth (km^2) | Growth rate (m^2/year) |
| Kanyakumari | 1.530 | 0.707 | -0.823 | -27,433 |
| Ovari | 0.289 | 2.389 | +2.100 | +70,000 |
| Tiruchendur | 1.618 | 0.390 | -1.228 | -40,933 |
| Tuticorin | 1.087 | 2.836 | +1.749 | +58,300 |

Fig. 4 Variations of erosion and accretion (long-term) along the grids



erosion made in the grid was -0.332 km^2 at a rate of $-11,067 \text{ m}^2/\text{year}$. The grid 9 has experienced severe erosion (0.765 km^2) and no accretion has been noted. The net erosion made in the grid was -0.765 km^2 and eroding at a rate of $-25,500 \text{ m}^2/\text{year}$.

4. Tuticorin zone: The Tuticorin coastal zone includes three grids (nos. 10, 11, and 12). During the period 1969–1999, this coastal zone experienced more accretion. The grid 10 has an erosion of 0.334 ha and an accretion of 0.455 ha . The southern part of the grid along the Punnakayal area had experienced erosion, whereas the northern part of the Punnakayal area has been noted for accretion. The net accretion made in the grid was 0.121 km^2 with a rate of $4,033 \text{ m}^2/\text{year}$. The grid 11 has experienced heavy accretion. This grid has experienced the maximum accretion (2.05 km^2) among all other grids of the study area. Erosion was also observed (0.681 km^2) along this grid. The net accretion made in the grid was 1.37 km^2 with a rate of $45,667 \text{ m}^2/\text{year}$. The grid 12 had an erosion of 0.720 km^2 and an accretion of 0.331 km^2 . The urban coast of Tuticorin (grid 12) was accreted by 0.259 km^2 with a rate of $8,633 \text{ m}^2/\text{year}$.

During the period 1969–1999, the Kanyakumari coastal zone has an erosion of -1.53 km^2 and a net accretion of 0.707 km^2 (Table 4). This coast has a net growth of -0.823 km^2 and it undergoes erosion at a rate of $-27,433 \text{ m}^2/\text{year}$. The Ovari zone has experienced an accretion of 0.289 km^2 and an accretion of 2.389 km^2 . This coastal zone has reclaimed a land of 2.1 km^2 with a rate of $+70,000 \text{ m}^2/\text{year}$. The Tiruchendur coastal zone experiences an erosion of 1.617 km^2 and an accretion 0.39 km^2 . This zone has a net growth of -1.228 km^2 with a rate of $-40,933 \text{ m}^2/\text{year}$. The Tuticorin coastal

zone has experienced more accretion and light erosion. The erosion made along this zone is 1.087 km^2 and an accretion made is 2.836 km^2 . This zone has a net accretion of 1.749 km^2 with rate of $+58,300 \text{ m}^2/\text{year}$. The study reveals that the accretion process is more dominant than the erosion process during 1969–1999. The study area has more accretion along Tuticorin and Ovari coastal zones. But erosion is also noted along the coast of Kanyakumari and Tiruchendur due to both natural and man-induced activities. Erosion is noticed on both sides of headlands present in the Manappad and Tiruchendur coast. The Ovari and Tuticorin coastal zones have more accretion rates. The Rivers Hanuman Nathi, Uppar, and Nambiar supplied sediment for the accretion along the coast of Ovari. The sediments eroded from the sand dune complex also supplies sediment for this process. The displaced sediments are deposited along the coast of Ovari.

The Tuticorin coastal zone also has more accretion. The sediment transported from the Thambraparani River is discharged along the Punnakayal Estuary. These sediments are drifted by littoral current and deposited along the coast of Tuticorin. During the northeast monsoon the sediments are transported through the Thambraparani River and are discharged along the Punnakayal estuary. But during the southwest monsoon these sediments are drifted in the northerly direction by the littoral drift and are deposited along the coast. The curved shape of the southern part of Tuticorin coast traps these sediments. Selvavinayagam (2009) also states that the long-shore sedimentation from south to north resulting accretion along the coast of Tuticorin coast is mainly due to the discharge of sediment through the Thambraparani River.

Emery and Aubrey (1991) insists that an entirely independent method of assessing the rate of coastal erosion or accretion is to consider the long-term (geologic) sea level change, which is the major factor determining the coastal evolution. During the field visits, it has been observed that the Tuticorin coast has beach ridges. These ridges have been recognized as representing successive still-stand position of sea of an advancing shoreline from satellite imagery. Chockalingam (1993) states that the beach ridges along the coastal plains of Tuticorin are formed during Pleistocene to recent age. He also states that the ridges are low, essentially continuous beach or beach dune materials (sand, gravel, and shingle) heaped up by the action of wave and currents on the backshore of a beach beyond the present limit of storm waves or the reach of ordinary tides, and occurring as a single or as one of a series of approximately parallel deposits. The beach ridges have been recognized as representing successive still-stand position of sea of an advancing shoreline from satellite imagery (Selvavinayagam 2009). So, in addition to the sediment supply from the Thambraparani River, the sea level variations along the coast of Tuticorin may also help to reclaim the land along the coast. Loveson and Rajamanickam (1988) have also pointed out the possible fall of sea level in Tuticorin coast due to neo-tectonic emerging of the seafloor. Claudia et al. (2008) insists that the long-term change in shoreline can be considered basically the changing of sea level relative to the land and the increase and decrease in sand supply to the coast that causes the shoreline to retreat or advance over a period of about 50 years or more.

Short-term shoreline changes

During the period 1999–2006, the Kanyakumari and Ovari coastal zones have experienced more erosion activities due to both natural and man-induced activities. But the Tuticorin coastal zone has more accretion due to the presence of Thambraparani River which is a major sediment discharge system along the study area. The Tiruchendur coastal zone has also experiences more accretion. The erosion and accretion made in various grids of coastal zones are shown in Tables 5 and 6. The short-term variation of erosion and accretion made along the different grids are shown in Fig. 5.

1. Kanyakumari zone: Erosion is more in grids 1 and 2 and low in grid 3. But accretion is more along the grid 3 and less in grids 1 and 2. The grid 1 has an erosion of 0.323 km^2 and an accretion of 0.037 km^2 . The western part of the grid has sand dunes in east–west direction.

These sand dunes and the beaches along the grid have experiences more erosion due to both natural and human-induced activities. The southeast monsoon also enhances the erosion along this grid.

The erosion along the Palayar estuary which is witnessed by the recent Indian Ocean tsunami in this grid is comparatively less. Also the sediments discharged from the Palayar River are deposited along the grid and produces an accretion of 0.037 km^2 . The net growth observed in this grid is -0.286 km^2 with a rate of $-40,857 \text{ m}^2/\text{year}$. The grid 2 has an erosion of 0.145 km^2 and an accretion of 0.082 km^2 . The western part of the grid has experience erosion where as accretion is made along the eastern part. The eastern part of the grid has slightly bay and curved shaped that enhance to trap sediments. During the southwest monsoon the sediment eroded along the western part of the grid are transported toward the eastern side and deposited along the coast of this grid. The net growth observed along this grid is -0.063 km^2 and the coast is eroding at a rate of $-9,000 \text{ m}^2/\text{year}$.

The grid 3 has an erosion of 0.021 km^2 and an accretion of 0.166 km^2 . This grid has experienced more accretion than the other grids present in the Kanyakumari zone. During monsoon the sediment discharge from the rivers Hanuman Nathi and Uppar are deposited in the eastern part of grid between the coast of Perumanal and Idinthakarai. This makes the grid to have more accretion. The net growth observed along this grid is $+0.145 \text{ km}^2$ with a rate of $+20,714 \text{ m}^2/\text{year}$.

2. Ovari zone: The fourth and fifth grids of this zone have experienced more erosion and the sixth grid has less erosion. The grids 4 and 6 have also

Table 5 Short-term erosion and accretion along the grids

| Coastal zone | Grid no. | Erosion and accretion during 1999–2006 | | | |
|--------------|----------|--|-----------------------------|------------------------------|--|
| | | Erosion (km^2) | Accretion (km^2) | Net growth (km^2) | Growth rate (m^2/year) |
| Kanyakumari | 1 | 0.323 | 0.037 | -0.286 | -40,857 |
| | 2 | 0.145 | 0.082 | -0.063 | -9,000 |
| | 3 | 0.021 | 0.166 | 0.145 | 20,714 |
| Ovari | 4 | 0.183 | 0.078 | -0.105 | -15,000 |
| | 5 | 0.398 | 0.000 | -0.398 | -56,857 |
| | 6 | 0.139 | 0.263 | 0.124 | 17,714 |
| Tiruchendur | 7 | 0.137 | 0.156 | 0.019 | 2,714 |
| | 8 | 0.196 | 0.051 | -0.145 | -20,714 |
| | 9 | 0.000 | 0.327 | 0.327 | 46,714 |
| Tuticorin | 10 | 0.101 | 0.128 | 0.027 | 3,857 |
| | 11 | 0.168 | 0.479 | 0.311 | 44,429 |
| | 12 | 0.089 | 0.113 | 0.024 | 3,429 |

Table 6 Net erosion and accretion made during 1999–2006

| Coastal zone | Erosion and accretion during 1999–2006 | | | |
|--------------|--|------------------------------|-------------------------------|------------------------------------|
| | Erosion (km ²) | Accretion (km ²) | Net growth (km ²) | Growth rate (m ² /year) |
| Kanyakumari | 0.489 | 0.285 | −0.204 | −29142 |
| Ovari | 0.720 | 0.341 | −0.379 | −54143 |
| Tiruchendur | 0.333 | 0.534 | +0.201 | +28713 |
| Tuticorin | 0.358 | 0.720 | +0.362 | +51714 |

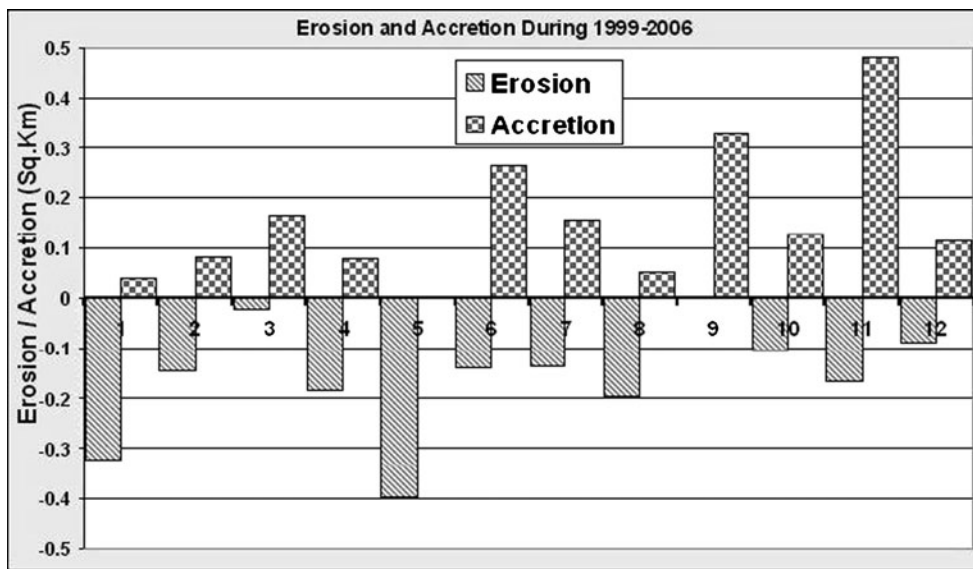
experienced accretion whereas no accretion is found in the fifth grid. The grid 4 has an erosion of 0.183 km² and an accretion of 0.078 km². The northern part of this grid experience erosion where as the southern part of the grid has accretion due to the littoral sediment drift along the Perumanal coast. The southeast monsoon also enhances the accretion along this grid. The sediments discharged from the rivers Hanuman Nathi and Uppar deposited along the southern part of this grid. The net growth observed along this grid is −0.105 km² and the coast of this grid is eroding with a rate of −15,000 m²/year.

The fifth grid of the Ovari zone has experienced maximum erosion among all the grids of entire study area and it faces severe erosion threat. This grid has an erosion of 0.398 km². No accretion has been noticed along the entire stretch of this grid. The coast between Navaladi and Ovari have been eroding at a very high rate (−56,857 m²/year). The sixth grid has experience an erosion of 0.139 km². But it experiences an accretion of 0.263 km². The Periatthalai breakwater heavily traps the sediments along the shoreline of the grid. The net growth observed along this grid is +0.124 km² with a rate of +17,714 m²/year.

3. Tiruchendur zone: The Tiruchendur coastal zone experiences both erosion and accretion, but accretion dominates. The seventh and eighth grids of this zone have experiences erosion whereas no erosion is noted in the ninth grid. But more accretion is noted along the ninth and seventh grids of this zone. The grid 7 has an erosion of 0.137 km² and an accretion of 0.156 km². The southern part of headland along this grid experience more erosion whereas the northern part of the grid has experienced more accretion due to the littoral sediment drift and trapping of sediments along bay and curved coasts.

The southeast monsoon also enhances the erosion along the southern part of the headland and accretion along the northern part. The sediments eroded from the southern part of the headland are drifted along the northerly direction and deposited along the bay of this coast. The sediment discharged from the Karamanyar River also deposited along the bay. A small spit has also been developed due to sediment transport and drift. The Fig. 8 shows the recent spit developed along this grid. The net growth observed along this grid is 0.019 km² with a rate of 2,714 m²/year. The low net growth and rate of change is due to the more or less equal amount of accretion and erosion made on either side of the headland of this grid. The grid 8 has an erosion of 0.196 km² and an accretion of 0.051 ha. The net growth observed along this grid is −0.145 km² and the coast of the grid is eroding at a rate of −20,714 m²/year. The ninth grid of this Tiruchendur coastal zone has no erosion and experiences an accretion of 0.327 km². Well-developed narrow beaches are developed along the coast Kayalpattinam present in the grid. The net growth observed along this grid is +0.327 km² with an accretion rate of +46,714 m²/year.

Fig. 5 Variations of erosion and accretion (short-term) along the grids



4. Tuticorin zone: All the grids have experienced erosion and accretion. The grid 10 has an erosion of 0.101 km^2 and an accretion of 0.128 km^2 . This grid is highly dynamic due to the presence of the Punnakayal estuary formed by the Thambraparani River. The southern part of the grid has experiences more erosion and the northern part is accreting. The more or less equal amount of erosion and accretion leads to very low net growth rate. The shoreline along the grid has a net growth of $+0.027 \text{ km}^2$ with a rate of $+3,857 \text{ m}^2/\text{year}$. Spits have been developed at the mouth of the estuary of the Thambraparani River.

The grid 11 has experienced heavy accretion among all the grids of the study area. The coast along the southern part of the grid is concave shaped thereby enhancing the trapping of sediments. The sediment discharge from the Thambraparani River has been drifted by the littoral currents and transported to the curved coast and deposited along the coast up to the south harbor breakwater in Tuticorin. Even though this grid has experienced more accretion (0.479 km^2), it has an erosion of 0.168 km^2 , mostly along the northern part of the grid. The net growth made in the grid is $+0.311 \text{ km}^2$ with a rate $44,429 \text{ m}^2/\text{year}$. The grid 12 has an erosion of 0.089 km^2 and an accretion of 0.113 km^2 . The net growth observed along this grid is -0.024 km^2 with an accretion rate of $+3,429 \text{ m}^2/\text{year}$. Table 6 gives the net erosion and accretion made along the different zones during 1999–2006. The table also shows the net or effective growth and the rate of the coastal zones along the study area.

The Kanyakumari coastal zone has a net erosion of 0.489 km^2 and a net accretion of 0.285 km^2 . This coastal zone has a net growth of -0.204 km^2 and it undergoes erosion at a rate of $29,142 \text{ m}^2/\text{year}$. The Ovari zone has also experienced an erosion of 0.72 km^2 and an accretion of 0.341 km^2 . This coastal zone faces a severe threat (erosion rate is $-54,142 \text{ m}^2/\text{year}$) due to the heavy erosion prevailing along the coast. The Tiruchendur coastal zone experiences an erosion of 0.333 km^2 and an accretion 0.534 km^2 . This coastal zone has reclaimed a land of 0.201 km^2 with a rate of $28,713 \text{ m}^2/\text{year}$. The Tuticorin coast has also experiences more accretion. The erosion made along this zone is 0.358 km^2 and the accretion made is 0.72 km^2 . This zone has a net accretion of 0.362 km^2 with rate of $51,714 \text{ m}^2/\text{year}$.

Long- and short-term shoreline changes

Both long- and short-term changes of shoreline are very essential to extract the information on the dynamics and

trend of a coast. Table 7 shows the comparative data of both long- and short-term changes on all the coastal zones of the study area. It shows that the rate of erosion along the Kanyakumari coast is increased from $-27,433 \text{ m}^2/\text{year}$ to $-29,142 \text{ m}^2/\text{year}$ due to both natural and man-induced processes. Nayak (1992) also identified that Kanyakumari as one of the major erosion coast in India during the period 1967 to 1992. The construction of artificial barriers like breakwater and Jetties enhances the erosion along the Kanyakumari coast (Chauhan et al. 1996). Figure 6 shows the variation of net growth rate of different grids along the study area.

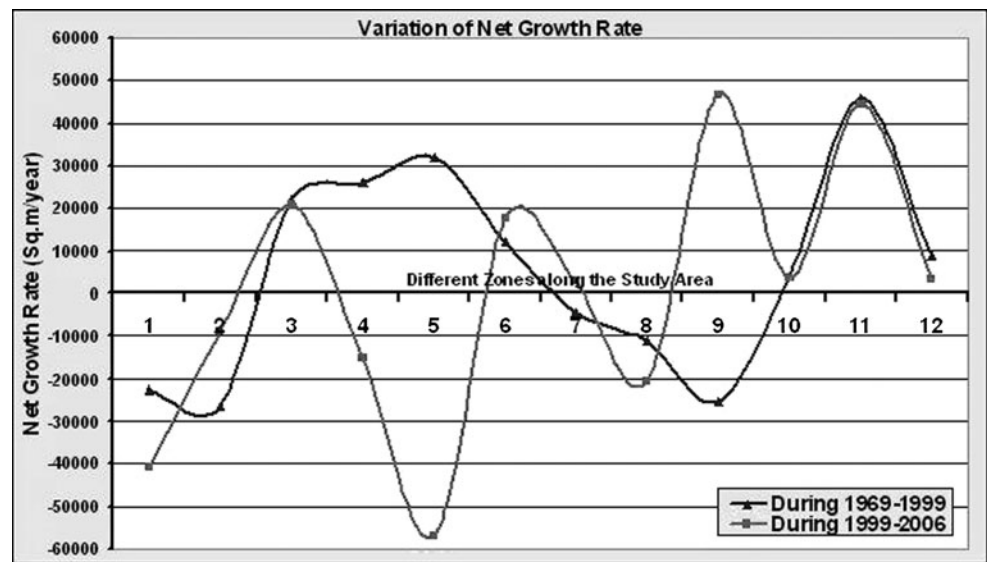
The present study indicates that, during the period 1969–1999, the Ovari coast experienced more accretion at a rate of $+70,000 \text{ m}^2/\text{year}$. The Tiruchendur coastal zone experiences an erosion of -1.228 km^2 with a rate of $-40,933 \text{ m}^2/\text{year}$. But during 1999–2006, the Ovari coast has experienced more erosion. During this period, the beach placer mining is more prominent. Usha and Subramanian (1993) have also reported that the coast near Ovari is exposed to severe erosion. But the Tiruchendur coast has experienced accretion. Sanil Kumar et al. (2006) also identified the Tiruchendur as one of the prograding coast along the Tamil Nadu coasts. Therefore a reverse trend (between long- and short-term) has been observed along these coasts. This reverse trend indicates the rapid change in the geological and hydrological aspects, littoral drift along these coasts. Claudia et al. (2008) insists the short-term shoreline change that occurs about 10 years or less may be in the opposite direction of the long-term trend. It is difficult to understand and predict such variations.

Shoreline change is a direct result of coastal erosion and the effect of the breaking waves in the near-shore zone as well as the near-shore currents. The breaking waves in the near-shore zone and the near-shore currents are responsible for the transportation of beach sediments that results in shoreline change. This is part of the larger-scale process known as littoral transport, which is the movement of material by waves and currents in the coastal zone. With respect to the sand supply, a given length of coastline, there may be a surplus, be in balance, or have a deficit in its sand

Table 7 Short- and long-term shoreline changes

| Coastal zone | Long-term (1969–1999) | | Short-term (1999–2006) | |
|--------------|------------------------------|--|------------------------------|--|
| | Net growth (km^2) | Growth rate (m^2/year) | Net growth (km^2) | Growth rate (m^2/year) |
| Kanyakumari | -0.823 | -27,433 | -0.204 | -29,142 |
| Ovari | +2.100 | +70,000 | -0.379 | -54,143 |
| Tiruchendur | -1.228 | -40,933 | +0.201 | +28,713 |
| Tuticorin | +1.749 | +58,300 | +0.362 | +51,714 |

Fig. 6 Variation of net growth rate along the different grids



supply budget. The sand supply would be in balance for a particular area if the amount of sand leaving the area were being replaced by an equal amount of sand arriving from drainages and adjoining areas. Over a short time period, shoreline erosion may occur in an area followed by a build-up of sand supplied by the alongshore transport of sediment, even though over the long-term, the area will be in a state of dynamic equilibrium. A large reduction in the sand supply, or a long-term reduction in supply to an area, creates a deficit in the sand budget that must be balanced, usually by increased shoreline erosion. The Fig. 7 also indicates that the slight reduction of net growth rate along the coast of Tuticorin zone.

Factors modifying the shorelines

The shoreline change is caused by a complex interaction of various natural and human-induced coastal processes. The natural processes due to geology and geomorphology, the combined action of waves and currents, variations in sea level, tectonics, and storms modify the shorelines. The human activities that could intensify the coastal erosion include: manipulation of hydrological cycles through mainly dam construction; buildings on beaches; coastal structures such as harbors, beach protecting structures, and jetties; and mining of beach sand and live coral, destruction of protective coral reef systems; and destruction of coastal vegetation (Fig. 8).

1. Coastal geology and geomorphology

The coastal geology and geomorphology plays a vital role in modifying the shorelines. The various coastal landform features such as headland and bays, beaches, mud flats, estuaries, and sand dunes along the study area have involved in the shoreline changes. The

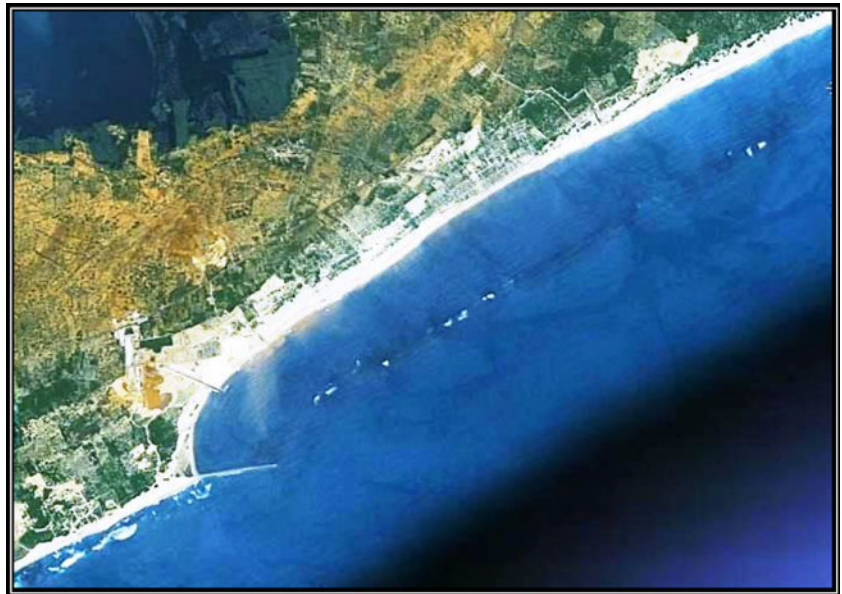
present study reveals that the coastal zones of Kanyakumari and Ovari are under severe threat of coastal erosion. The Kanyakumari coastal zone (grid no. 2) has exposed rocky coast and narrow continental shelf. More erosion has been noted along this coast. The high wave energy acting on the soft part of the rocky coasts produces more erosion and forms cliffs. They also modify the shoreline along the coast of Kanyakumari. Similar effect has also been observed in the Kenyan coast (Arthurton 1992; Nyandwi 2001). The Ovari coastal zone is experiencing severe coastal erosion due to low-lying sandy beaches and dunes which enhances the coastal erosion. The Tiruchendur coastal zone has headlands and bays which results in both erosion and accretion along the coast. The Tuticorin coastal zone has curved sandy beaches and estuaries which easily traps the sediments and leads to accretion.

2. Natural causes and conditions

Natural processes and climatic conditions are important in determining the nature of wave impacts responsible for sediment transport, erosion and accretion, and shoreline changes. Natural processes are constantly changing which results in alternating periods of accretion and erosion. These processes are influenced not only by daily or hourly changes in tides, etc., but also over longer timescales as sea level and climate change.

- (a) Sea level changes: The changes in sea level may also induce the erosion or accretion along coasts. The present study reveals that the Tuticorin coastal zone has more advancing at a rate of 2–6 m/year. A long-term geological process of utmost importance to a shoreline is relative sea level change,

Fig. 7 Progradation of shoreline along breakwater



which can occur as the result of a change in water volume of the oceans or the subsidence or emergence of the land by geologic processes. In Tuticorin coastal zone, the relative change in the sea level might be involved in modifying the shorelines. The relative sea level change causes the shoreline to be out of equilibrium with the sea level and brings into play processes that tend to restore equilibrium. These processes can cause the shoreline either to erode or accrete. A lowering of sea level or an increase of the land elevations due to tectonic changes leads to a relative sea level drop and the appearance of a shoreline of emergence (Dean and Dalrymple 2004).

(b) Shortage of sediments: Erosion and inundation brought about by river flows, tides, winds, and rain are among the most important natural processes which determine the shape and dynamic character of the coastline. Coastal features such as sand dunes and beaches, mangroves, and mudflats are formed by the deposition of sediments. Throughout most of coastal region, growth and its related sedimentary processes have been and are some of the principal contributors to the coastal geomorphology. The Indian Ocean Commission publication Manuel (IOC 2000) clearly emphasizes that the present shortage of sediment on the

Fig. 8 Spit developed along Manappad headland



shoreline due to natural reasons is one of the causes of erosion in the islands of the Indian Ocean. During 1969–1999, the Ovari coastal zone has experienced more accretion due to excess amount sediment discharged through the rivers. However, the contrary is now happening, whereby there is a natural shortage of sediment. Sediment discharges from rivers are considerably reduced due to the construction of dams, developmental activities, and encroachments. This makes the sandy beaches along the zone more vulnerable to erosion.

3. Waves, currents, and sediment transport

Waves are the prime movers for the littoral processes at the shoreline. The dynamics and kinematics of water waves are discussed in several researches including Wiegel (1964), Mei (1983), and Dean and Dalrymple (1991, 2004). The long-shore sediment transport rate is the major factor influencing on the evolution of the shoreline change (Chin-Wen-Hung et al. 2008). Littoral transport plays a major role in the development of certain shoreline features like spits and bars, and is causing considerable coastal erosion and accretion (King 1974).

The coastal zones of Tuticorin-south, Kayalpatinam have accretion due to the littoral drift of sediments transported through the Tambraparani River. During northeast monsoon, the sediments from the river are drifted by the littoral processes towards south direction. These sediments are deposited along the coast of Kayalpatinam. During the southwest monsoon, the sediments from the river are drifted by the littoral processes towards northern direction. Chandramohan et al. (2001) studied the long-shore sediment transport rates (LSTR) along the Indian coast and he estimated high LSTR in Idinthakarai, Navaladi, and Ovari.

4. Human interventions and anthropogenic activities

Now-a-days, the human interventions and anthropogenic activities also have great impact on shoreline changes. The anthropogenic activities contributing to shoreline change could broadly fall into four main categories as described below.

(a) Obstruction of sediment supply or modification of water flow: Reduced sediment supply (caused by offshore extraction, protection of eroding shoreline and damming of sediment-rich rivers) has contributed to the further loss and degradation of coastal habitats including beaches and mangroves. The construction of coastal structures such as groins and jetties in Kanyakumari, Koottapuli, Periathalai, and Tuticorin may interfere with the process of

long-shore drift, modifying the sediment budget and exacerbating erosion of the adjacent beach or beach head in a down-drift direction. The construction of dams on rivers leading to the ocean has reduced sediment supply to the coast through trapping.

The present study indicates that the Kanyakumari zone is undergoing more erosion due to natural geological and hydrological processes along the coast. The Kanyakumari coast faces problems due to tourism and other developmental projects along the coast. The construction of artificial barriers like breakwater and Jetties enhances the erosion along the Kanyakumari coast (Chauhan et al. 1996; Nayak 1992). The Fig. 9 shows a construction work made along the coast of Kanyakumari which may also induce erosion at the nearby area of the coast.

(b) Coastal sand mining and removal of beach sediments: The coasts of Kanyakumari, Navaladi, Idinthakarai, and Ovari are mined for sand. The high LSTR also indicates the severe erosion along these coasts. Though banned in most of the places of the study area, beach sand is still being mined for construction and other purposes. The Fig. 10 shows the illegal beach sand mining along the Kanyakumari coast.

Littoral transport plays a major role in the development of certain shoreline features like spits and bars, and is causing considerable coastal erosion and accretion (King 1974). Chandramohan et al. (2001) studied the long-shore sediment transport rates along the Indian coast and he estimated high LSTR in Idinthakarai, Navaladi, and Ovari. Usha and Subramanian (1993) have also reported that the coast near Ovari is exposed to severe erosion in June and November. The above coasts are mined for sand, and have high LSTR. It may lead to severe erosion and accretion along the coast. Also the mining industrialists do not carry out any reclamation or refilling activities. Unplanned excavation can lead to severe erosion problems arising from either the net loss of sand itself, or via creation of erosional “hot spots” resulting from the focusing of wave energy on specific points along a shoreline. These points, can be identified using traditional beach surveys or predicted using numerical models of wave transformation (Work and Otay 1996; Hilton 1994), explained the importance of sustainable sand mining in coastal areas. So the concept of sustainable management should be interpreted in the man-

Fig. 9 Constructions along the Kanyakumari coast



agement of the near-shore coastal sand mining industry. These coasts have high erosion hazard due to anthropogenic activities. It divulges the fact that the presence of (barrier) islands, river input, and wave pattern dictates the rate of erosion. It is also evident that if the river input gains over the erosion activity, the beach could manage to survive without much threat for maintaining its volume.

- (c) Removal of vegetation and natural protections: There are several factors which protect shorelines from erosion and help to preserve our coastal environment. They are sand dunes, coral reefs, vegetation cover etc. (Arthurton 1992). The small

sand dunes along the Ovari coastal zone have flattened for various developmental projects and agriculture. These natural protections have been greatly affected by the human-induced activities which causes for the coastal erosion.

Conclusions

The present work on shoreline changes reveals that the study area faces both erosion and accretion. The Kanyakumari coastal zone is still having erosion problem due to both natural and human-induced activities. The Ovari zone

Fig. 10 Sand mining along the Kanyakumari zone



was accreted during 1969–1999. But presently the entire coast faces severe threat of erosion. Tiruchendur coast has experienced severe erosion during the period 1969–1999. During 1999–2006, the shoreline along Tiruchendur has experienced both erosion and accretion. However, presently the shoreline is advancing at some places with small rates. The Tuticorin coast has experienced heavy accretion from 1969 to 2006. The natural and geological influences, availability of sediment, and relative sea level rise enhances the advancement of shorelines. The shoreline change rate studies also reflect both short- and long-term changes along the various coastal zones of the study area.

Coastal changes are attracting more focus since they are important environmental indicators that directly impact coastal economic development and land management (Welch et al. 1992; Stokkom et al. 1993). Rajamanickam (2006) implies that the natural character of sandy beaches is to change shape constantly and to move landward (retreat) or seaward (advance). The shoreline accretion which is a positive phenomenon may create more usable land for recreation or other purposes. On the other hand, shoreline erosion may also cause various problems. Reliance on statistical methods of shoreline change analysis can often yield misleading results, whereas defining modes of change based on geomorphic principles and hence understanding the reasons for shoreline change provides a practical management tool. Galgano and Leatherman (2005) insist that we should not anticipate that shoreline change rates and coastal configurations will remain uniform through time; instead we should realize that accelerations and deceleration in rates of erosion/accretion and trend reversals could occur.

The present study shows that accretion was predominant along the study area during the period 1969–1999. But recently (from 1999), most of the coastal zones have experience heavy erosion. It also indicates the reversal of shoreline modifications in some coastal zones. The coastal zones along the headlands have more erosion and accretion. The zones where sand is mined have relatively more rate of erosion than that of other zones. The mining industrialists do not carry out any reclamation or refilling activities along the study area. Unplanned excavation can lead to severe erosion problems arising from either the net loss of sand itself, or via creation of erosional “hot spots” resulting from the focusing of wave energy on specific points along a shoreline. Improper and unsustainable sand mining leads to severe erosion problem along this area. So the concept of sustainable management should be interpreted in the management of the near-shore coastal sand mining industry.

Thus the present study clearly focuses the influences of both natural and anthropogenic coastal processes made in the study area. It is also recommended that proper beach filling and nourishment projects should be made in the

coast to save the coastal area from severe hazards. The other statistical methods such as variances, standard deviations, and confidence intervals will be performed in future study.

Acknowledgment The authors are thankful to Dr. Bhoop Singh, Director, NRDMS, Department of Science and Technology, New Delhi for his kind help in completing the work. The authors are also thankful to the Department of Science and Technology, New Delhi for providing the financial assistance under NRDMS Scheme (ES/11/546/2000 and ES/11/936(5)/05).

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