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Coastal vulnerability assessment: a case study on erosion and coastal change along Tuticorin, Gulf of Mannar

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Abstract Assessment of vulnerability is essential for identifying and recognizing the coastal livelihood, socio-economic and ecological security status. However, coastal vulnerability assessments require a complex dataset including human and socio-economic factors. In this study, we investigated coastal vulnerability index (CVI) to map the vulnerability of Tuticorin coast toward coastal erosion using remote sensing data and geographical information techniques based on a multi-indicator approach. Gulf of Mannar located along the southeast coast of India and declared as a marine national park with high ecological diversity faces threat due to anthropogenic interventions as a result of industrialization, sand and coral mining, etc. CVI highlights the vicinity where the physical effects may be the greatest. Beach width was considered as an additional parameter, since a large number of coastal habitations were present adjacent to the beach along the study area. Coastal erosion, slope and relative sea level rise are the major factors affecting the coastal vulnerability in Tuticorin. CVI scores were categorized into four classes, viz., low, moderate, high and very high risk. Out of 84-km coastal stretch, 15 % falls under high risk, 12 % moderate vulnerability and 73 % the low vulnerable category. This approach provides an insight to assess the vulnerability and the degree of potential threat to the coastal system in order to prioritize actions and to develop adaptation measures.

Keywords Coastal vulnerability index · Erosion · GIS · Tuticorin coast · India

1 Introduction

Coastal zone is a broad transitional area where the land and adjacent ocean interacts, in which terrestrial processes and land use directly affect oceanic processes and uses, and vice

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versa. Coastal zones are continuously changing because of the dynamic interaction between the ocean and land. The dynamic processes that occur within the coastal zone produce diverse and productive ecosystems which are of great importance for human population. Presently, about 44 % of the total world population live within 100 km of the coastal zone. Rapid development has put numerous direct and indirect pressures on the coastal ecosystems in the form of destruction and degradation. Infrastructure development, urbanization and coastal development, overfishing, pollution and climate change are the major threats that affect the coastal areas around the world. This in turn poses a threat to the coastal systems, biological diversity and environmental regulatory functions. Predicting shoreline retreat and land loss rates is critical to planning future coastal zone management strategies and assessing biological impacts due to habitat changes or destruction (Thieler and Hammar-Klose 2000). The sandy beaches along the developing countries are experiencing acute erosion. The reasons for this include increased storminess, coastal submergence, decreased sediment movement, changes in the directional component of wave climate and human activities (Bryant 2005).

In developing countries, coastal erosion is a major crisis and it potentially impacts the coastal population and natural environment. The landward displacement of the shoreline caused by the forces of waves and currents is termed as coastal erosion. It is the loss of sub-aerial landmass into the sea due to natural processes such as waves, winds and tides, or even due to human interference. While the effects of waves, currents, tides and winds are primary natural factors that influence the coast, the other aspects eroding the coastline include the sand sources and sinks, changes in relative sea level, geomorphological characteristics of the shore and sand, etc. Anthropogenic effects that trigger beach erosion are construction of artificial structures, mining of beach sand, offshore dredging or building of dams or rivers. Vulnerability assessment is a complex process that must consider multiple dimensions of vulnerability, including both physical and social factors. Coastal vulnerability index (CVI) is one of the most widely used indices for calculating the vulnerability of communities toward the coastal erosion and sea-level rise. Nicholls and Klein (2005) demonstrated that vulnerability of coastal systems and to other drivers of change is determined by their sensitivity, exposure and adaptive capacity. Indeed, coastal systems suffer great damage due to direct and indirect effects related to population explosion, economic changes and substantial land use changes.

Understanding vulnerability is integral to a process of determining actions that facilitate adaptation, but how to characterize vulnerability in theory and practice is still widely debated (Eakin and Luers 2006). Kairu and Nyandwi (2000) set out procedures for assessing the susceptibility of the coast to change and noticed that the greatest concerns were erosion of sandy beach, sand dunes and beach plains. Bryan et al. (2001) used GIS-based spatial models to determine regional vulnerability to inundation and erosion along South Australian coast. Zhang et al. (2001) developed an erosion potential index based on storm tides, wave energy and storm duration for the Atlantic Coast. Monitoring changes in littoral profiles to develop signatures of erosion is one approach used to quantify coastal erosion (Kana 2003). Boruff et al. (2005) examined the vulnerability of US coastal countries to erosion by combining social vulnerability index with the coastal vulnerability index using physical risk parameters. Ragoonaden (2006) and Abuodha (2006) emphasized that sea-level rise may pose a serious threat causing beach erosion hazard along the Shanzu–Bamburi coastal zone and the Western Indian Ocean coastline. Mwakumanya et al. (2009) analyzed beach erosion hazard using the beach width analysis for Bamburi beach, Kenya. McLaughlin and Cooper (2010) developed a multi-scale coastal vulnerability index for coastal erosion to investigate the implications of spatial scale in depicting

coastal hazard risk, coastal vulnerabilities for national, local authority and site level. A multi-hazard and interdisciplinary approach is required in assessing coastal vulnerability. A multi-indicator approach is required in assessing coastal vulnerability to erosion, thus implying the evaluation of impacts induced by various drivers, such as sea level, wave height, geomorphology, tidal range, elevation and bathymetry. Indicator-based approaches express the vulnerability of the coast by set of independent elements that characterize key coastal issues such as coastal drivers, pressures, impacts, risk, exposure, sensitivity and damage.

Very little attention has been paid by the government, to suggest the policy implications and adaptation options for protecting the communities present along Indian coast. The design of interventions and policies must rely on analyses of risks and vulnerability and include vulnerable groups in adaptation measures (Heltberg et al. 2009). Understanding the causes of vulnerability can help define where and how to reduce erosion vulnerability and identify the institutions able to facilitate adaptation (Ribot 2009). McGray et al. 2007 suggested a continuum for framing adaptation approaches, ranging from a development to an adaptation end, with four categories: (1) addressing drivers of vulnerability; (2) building response capacity; (3) managing risks; and (4) confronting impacts. Necessary conceptual plans and mitigation strategies are needed to be developed by the local government in order to prioritize actions to protect the habitations and natural systems. Setback zone needs to be worked out in order to restrict development in vulnerable areas to reduce the impacts. By considering the complex nature of coastal zone dynamics and the long-term implications of climate change, coastal policy and management require new broad-scale integrated assessment and management tools across a wide range of scales. Assessment at different scales provides useful information to coastal zone management, and the results will be used for making policy decisions (Nicholls and Klein 2005). A more detailed approach at the local and regional level is essential to understand and manage the complexities of a specific study area and allows the identification of vulnerable areas that could support policy decision making in the design of appropriate adaptation strategies (Torresan et al. 2008). Realistic assessment of adaptation options requires detailed analysis to capture the potential variation in responses within a region for a certain time frame, rather than assuming a uniform adaptation response (Nicholls and Klein 2005).

The main objective of this paper is to assess the vulnerability of Tuticorin coast for erosion and coastal change using CVI based on multi-indicator approach, in a view to identify and quantify the low-lying areas. Beach width, bathymetry and coastal elevation are considered as additional parameters for calculating CVI. Remote sensing and GIS can be used as an effective tool to identify the areas that are vulnerable along the coast.

2 Study area

Tuticorin district (known as "Pearl City") is situated at the extreme southeastern corner of Tamil Nadu. The study was conducted in coastal stretch of ∼84 km falling within the latitudes of 8°35′ to 9°04′N and longitudes of 78°08′ to 78°22′E (Fig. 1). The study area is bounded on the north by the districts of Virudhunagar, Tirunelveli and Ramanathapuram and on the east by the Gulf of Mannar. Tuticorin experiences tropical climatic conditions with immensely hot summer and gentle winter. The annual average rainfall for the year 2011 is 645 m, and the district registers a maximum temperature of 35.7 °C and a minimum temperature of 24.4 °C. Tuticorin has a very high humidity being in the coastal sector. Rainfall along Tuticorin district is observed in the southwest and northeast monsoon
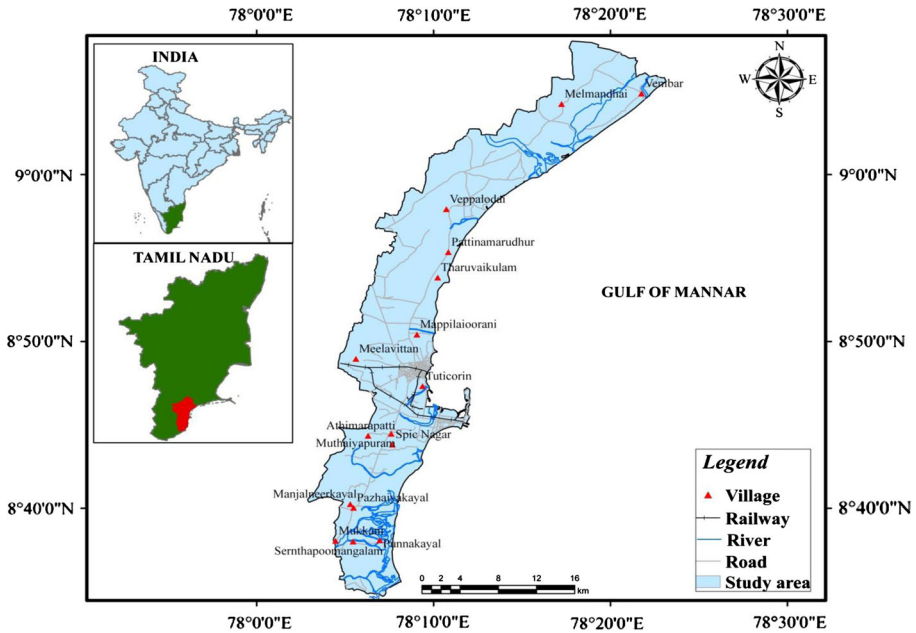
Fig. 1 Study area

seasons. Summer season commences from March and it extends till May. Built-up area, agricultural land, salt pans, wetlands, river, estuary, aquaculture, plantation, scrub land, current fallow land, tanks, sandy area, beaches, etc. are the major land use features identified along the district. Tuticorin has witnessed remarkable expansion, growth and development activities such as urban sprawl development and conversion of land into settlement, industrial area and saltpan (Soundaranayagam et al. 2011).

Gulf of Mannar is declared as a marine national park at 1986, and a buffer area of 10 km around the park was declared a Biosphere Reserve at 1989. Gulf of Mannar consists of 3,600 species of flora and fauna, making it one of the richest biodiversity hotspots in the world. Tuticorin and Vembar group are the two groups of islands falling in the study area. Gulf of Mannar is rich in seaweeds, seagrass, coral reef, reef fishes, pearl banks, sacred chank beds, fin and shellfish resources, mangroves and number of endemic and endangered species, including *Dugong dugong,* sea cucumber, sea horse, green turtle, etc. A total of 117 species of hard corals were recorded in the Gulf of Mannar, which serves as residence for fishes. Vilanguchalli Island is now 1 m below sea level, submerged due to excessive coral mining. Along Tuticorin district, severe erosion is evidenced in Tuticorin, Vaippar, Pachayapuram, Vembar and Duraisamypuram, while deposition took place in south of Vembar and Tuticorin harbor (Muthukumaraswamy et al. 2013). Illegal sand mining for the extraction of heavy minerals like Garnet, Ileminite and Rutile leading to severe erosion along the coast of Vaippar River and Kalaignanapuram is observed (The Hindu 2013). A severe cyclonic storm with a wind velocity of 100–130 kmph swept through the coastal villages of Tuticorin district on afternoon of November 13, 1992 leaving behind a trail of destruction along its path (Arumugham et al. 1993). Nineteen coastal villages were affected by this cyclone. Storm surges about 1–2 m high flooded a 70-km stretch of the coast up to 200–300 m inland. During 2004 tsunami, run-up level of 3 m was observed

Table 1 Data sources used for the study

S. No.	Parameters	Data sources
1	Shoreline change	Landsat MSS data (1979)
		Landsat TM data (1987 and 1999)
		IRS LISS-III data (2009 and 2011)
2	Rate of sea-level change	PSMSL data (1916–2005)
3	Elevation	SRTM data
4	Coastal slope	SRTM and NIO ETOPO2 merged data
5	Bathymetry	NIO ETOPO2 merged data
6	Mean tidal range	Tidecalc version 1.1 software
7	Significant wave height	INCOIS moored buoy data (2006)
8	Beach width	Field measurements
9	Geomorphology	IRS LISS-III data (2009)

from the tide gauges in Tuticorin port. A maximum inundation of 200 m was found near Tuticorin Port and minimum of 100 m observed near Vembar and Kallurani villages. Two deaths were reported in Tuticorin district. The study area is not much affected by the tsunami waves since it falls under the shadow zone due to the presence of Sri Lanka.

3 Data sources and methods

Vulnerability is a measure of the extent to which a community, structure, service or geographical area is likely to be damaged or disrupted by the impact of a particular hazard. Vulnerability index is a measure of the exposure of a population to some hazard. The method of computing CVI in the present study is similar to that of Gornitz and White (1991); Thieler and Hammar-Klose (1999); and Kumar et al. (2010). Table 1 indicates the data sources used for the study.

CVI variables are classified into two groups:

(1) geological variables—shoreline change rate, beach width, regional elevation, slope, bathymetry and geomorphology and
(2) physical variables—sea-level change rate, mean tidal range and significant wave height.

These variables include both the qualitative and quantitative information. Table 2 represents the risk parameters and its rating for calculating CVI. In this present study, ranking of these variables was assigned for every 100 m in the study area to get the comprehensive information about the vulnerable zones. The data sources for the CVI indicators were discussed in the following section.

3.1 Geological variables

Coastal shoreline change may occur due to both natural and the man-made processes. Natural processes include wave characteristics, near-shore circulation, sediment characteristics and transport, beach forms, etc. Anthropogenic activities that induce the shoreline erosion rates are sand mining and relative sea-level rise. The coast subjected to erosion can be considered as highly vulnerable since the low-lying coastal areas need to be protected.

Table 2 Coastal vulnerability classes

S. No.	Parameters	Risk ranking			
		Low (1)	Moderate (2)	High (3)	Very high (4)
1	Shoreline change rate (m/year)	>−0.1	(−1.0)−(−0.1)	(−2.0)−(−1.0)	<−2.0
2	Rate of sea-level change (mm/year)	<0.5	0.5–1.0	1.0–1.5	>2.0
3	Elevation (m)	>6.0	3.0–6.0	1.0–3.0	<1.0
4	Coastal slope (%)	1.2–0.9	0.9–0.6	0.6–0.3	<0.3
5	Bathymetry (m)	<−2.0	(−2.0)−(−1.0)	(−1.0)−(-0.5)	>−0.5
6	Mean tidal range (m)	4.0–6.0	2.0–4.0	1.0–2.0	<1.0
7	Significant wave height (m)	<0.5	0.5–0.8	0.8–1.0	>1.0
8	Beach width (m)	>150	100–150	50–100	<50
9	Geomorphology	Rocky cliffs	Low cliffs, alluvial plains	Cobble beaches, Lagoon, Estuary	Barrier beaches, sand beaches, salt marsh, mud flats, deltas, mangrove, coral reefs

In this study, ortho-rectified Landsat MSS and TM data for 1979, 1987 and 1999 and Indian Remote Sensing (IRS) satellite, Linear Imaging Self scanning Sensor (LISS)-III data for 2009 and 2011 were used to demarcate the shoreline changes. The satellite images obtained were taken as an input for spectral preprocessing. Using layer stacking method, the individual bands of the satellite data were converted into a false color composite image. Geometric transformation was done using first-order polynomial equation. Georectification/geometric correction process was carried out from the ground control points (GCPs) obtained from SOI toposheets using ERDAS Imagine 8.5 software and projected to universal transverse mercator (UTM) with reference to WGS-84 datum. The accuracy of the transformation, i.e., root mean square error, was restricted to 0.2 pixel. Resampling of the satellite images was done based on the nearest neighbor interpolation method. The shorelines of the study area were digitized using Arc GIS 9.3 software from multi-date satellite data. High water line boundary was considered as the shoreline proxy and demarcated using manual extraction method. The vector layers of shorelines were overlaid and erosion/accretion rates were calculated at 100-m intervals along Tuticorin coast using Digital Shoreline Analysis System (DSAS) software developed by United States Geological Survey (USGS 2005). Several statistical methods are used to calculate the shoreline change rates with the most commonly used being end point rate (EPR) calculations or linear regression rate-of-change statistic (LRR). LRR is the most commonly applied statistical technique for expressing shoreline movement and estimating rates of change (Crowell and Douglas 1997). LRR can be determined by fitting a least squares regression line to all shoreline points for a particular transect obtained from the analysis are used to calculate the erosion vulnerability along Gulf of Mannar. In order to assess the shoreline trend, an onshore baseline was created with a position of approximately 2 km distance behind the shorelines. Based on the baseline and shoreline, the erosion/accretion regimes were calculated for 100-m orthogonal transects along the coastline. The risk ratings were allocated based on the erosion/accretion rates obtained from the shoreline analysis.

The **elevation** of a geographical location is its height with respect to mean sea level. The effort to analyze the impact of coastal inundation requires data on the land surface elevations (Titus and Richman 2001). Higher elevated areas fall under low vulnerability zones since they experience less inundation. The reason for the low vulnerability is related to that the high elevations have more resistance to sea-level rise, tsunami run-up and storm surges due to cyclones. These coastal elevation data are also used to estimate the land potentially available for wetland migration in response to sea-level rise and the sea-level rise impacts to the human built environment (Anderson et al. 2005). The regional elevation dataset downloaded from Shuttle Radar Topography Mission (SRTM) with 90-m resolution is used for the analysis. Digital elevation model (DEM) was obtained by resampling the SRTM raster data, and the risk ratings were assigned to the entire coast based on the elevation values.

Slope is the degree of inclination or steepness of a line. Higher and lower slopes indicate steep and flat topography, respectively. Coastal locations having gentle land slope values have great penetration of seawater compared with locations with fewer slopes, and resulting land loss from inundation is simply a function of slope: the lower the slope and the greater the land loss (Klein et al. 2000). Determination of regional coastal slope identifies the relative vulnerability of inundation and potential rapidity of shoreline retreat because low-lying coastal regions should retreat faster than steeper regions (Pilkey and Davis 1987). The coastal area having lower slope was considered as highly vulnerable zone and vice versa. Contours obtained from SRTM data and bathymetry from Naval Hydrographic Chart and National Institute of Oceanography (NIO)-modified ETOPO2 gridded

bathymetry data extending for 5 km from landward and seaward side were used to calculate percentage of slope using Arc GIS software. Based on the slope values, risk scores were adopted for vulnerability analysis.

Bathymetry is the study of underwater depth of lake or ocean floors. Bathymetry can be measured using echo sounders, and it is an essential baseline for hydrodynamic, wave and inundation modeling. Bathymetric surveys can be used to identify the beach erosion, underwater landslides, sea-level rise and subsidence. The consequence of shallow bathymetry influences the wave height or tsunami run-up behavior (Satake 1988; Wash and Harry 1999). The higher the coastal bathymetry, the lower the inundation. For the present study, Naval Hydrographic Chart for Cape Comorin to Pamban region for 1976 and NIO-modified ETOPO2 gridded bathymetry data for 2007 were selected and processed to generate bathymetry DEM. Risk ratings were allotted based on the bathymetry values from the DEM data.

Beach width is defined as the horizontal dimension of the beach measured normal to the shoreline and landward of the high water mark line on coasts. Beach width may vary over timescales, where measurements can be used for beach monitoring, shoreline management, delineation of hazard line, identifying hotspots of erosion, etc. It can be used to monitor the changes due to the settlements along the coast. Beach width affects coastal vulnerability by acting as a buffer for dissipating wave energy, the wider the beach width, the greater its capacity to dissipate wave energy and reduce the impacts of extreme weather events and RSLR (Davies 2012). Coast having lesser beach width can be high vulnerable and vice versa. Beach width for different villages was obtained from field measured data during 2011 based on Emery method. The beach width was measured from the dunes at a semi-permanent benchmark. Two ranging poles, viz., one at the dune and one at the high water level, were placed along the coast. The distance between the two ranging poles was measured using a tape (Emery 1961; Masselink and Pattiaratchi 2001).

Geomorphology variable expresses the relative erodibility of various landform types (Pendleton et al. 2005). The general processes involved in the formation of geomorphic features are fluvial, eolian, glacial, tectonic, hill slope, igneous and biological processes. The vulnerability of beaches is related to their configuration, and their dynamics are influenced by local and regional factors and their geographic location. For instance, beaches comprised of volcanic boulders and rock outcrops provide a relatively stable substrate that may offer beach protection on the landscape, and whether the beach is favored by the occurrence of erosional or depositional processes. Conversely, beaches comprised of erodible substrates such as fine sand and unprotected by volcanic outcrops lead to high vulnerability through increased dynamics and geomorphic and ecological fragility. Geomorphic units including mangroves, mudflats, beach terraces, spit, salt pans, sandy beaches, sand dunes and estuaries are highly vulnerable to sea-level rise and coastal erosion. Geomorphology map was prepared from the satellite data at 1:50,000 scale. The data obtained were georeferenced using ERDAS Imagine 8.5 software and projected to the UTM with reference to WGS-84 datum. By onscreen digitization, various geomorphic classes were extracted using the visual interpretation keys developed by Space Applications Centre. Based on the geomorphology classes, risk ranks are classified.

3.2 Physical process variables

Sea-level rise potentially impacts the coastal population and natural environment. The sea-level rise can be attributed to two main factors, ocean thermal expansion and melting of glaciers and polar ice caps. Mean sea level is a measure of average height of the ocean's

surface, using a standard land elevation. Changes in mean sea level as measured by coastal tide gauges are called relative sea-level changes (Church and Gregory 2001). It is important to study the sea-level changes and its effects along the coastal areas. In the coastal vulnerability view, high sea-level rise was considered as the high vulnerable zone as it causes permanent flooding. Rate of sea-level change was computed from tide gauges of Permanent Service for Mean Sea Level (PSMSL). Tide gauge data from stations, viz., Vizag (in Andhra Pradesh), Chennai, Nagapattinam, Thangachimadam and Tuticorin (in Tamil Nadu), Kochi (in Kerala) and Mangalore (in Karnataka), from 1916 to 2005 were used. The risk ratings were assigned based on the obtained sea-level change values.

Tides are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the moon and the sun. **Mean tidal range** is defined as the difference between the highest high tide and the successive low tide. Together with the wind-generated waves, tides play an important role in coastal process, geomorphology, flood risk, species zonation and water quality. Higher tidal ranges lead to larger wave attack, resulting greater vertical range, and may thus result in a cause for more rapid erosion within that zone, leading to shore collapse. Lesser tidal ranges exhibit less wave energy concentrated on a narrower vertical range at the shore base and is thus likely to slower overall rate of shore retreat (Thieler and Hammar-Klose 1999). Lower tidal range always has the higher vulnerability and vice versa. Tidal ranges were computed from the Tidecalc version 1.1 software for Tuticorin Port and Pamban pass.

Significant wave height is defined as the mean wave heights, i.e., crest to trough of the one-third of the highest waves. Significant wave height is used as a proxy for wave energy which derives the coastal sediment budget (USGS 2001). Wave energy increases as the square of the wave height; thus, the ability to mobilize and transport beach/coastal materials is a function of wave height. High significant wave height can cause severe beach erosion whereas low significant wave height may have less impact. Significant wave height data from surface water buoy (SW 5) deployed off Tuticorin by Indian National Centre for Ocean Information Services (INCOIS) for 2006 were used to calculate the vulnerability of the study area.

Based on the ranking of the above parameters, coastal vulnerability index for the Tuticorin coast was calculated using the formula:

$$\text{CVI} = \sqrt{\frac{a*b*c*d*e*f*g*h*i}{9}} \tag{1}$$

where, a—Shoreline change rate; b—Sea-level change rate; c—Elevation; d—Coastal slope; e—Bathymetry; f—Mean tidal range; g—Significant wave height; h—Beach width; i—Geomorphology.

4 Results and discussion

4.1 Rate of shoreline change

Maximum erosion/accretion rates of −7.9 and 16.3 m/year are observed from the shoreline analysis and it is evident that the net accretion is dominant than the net erosion. Rate of shoreline change along Tuticorin district shows that 17.0 km of the coastal stretch at Vembar, Periyasamypuram, Kalaignanapuram and Punnakayal falls under very high risk category with erosion rates of more than −2.0 m/year and 11.04 km coast is under high risk. Severe erosion along these patches of the coast is subjected due to severe wave conditions prevailing during the northeast monsoon season and illegal sand mining for the

extraction heavy minerals like Garnet, Ileminite and Rutile. About 55.7 km of the coast occupy low and moderate risk categories. Accretion in curvilinear manner along the shoreline results in a formation of beach and similar paleo-beach ridges besides the beach. High accretion rates observed south of Tuticorin port is due to the northerly direction of the sediment transport from Thamiraparani estuary. During northeast monsoon, the sediments from Thamiraparani River are transported to the estuary. In southwest monsoon, sediments from estuary are transported and deposited till south Tuticorin harbor breakwater due to littoral drift. The direction of longshore sediment transport in Tuticorin is northerly from March to December, whereas it is southerly in January and February (Chandramohan et al. 1990). Figure 2a represents the shoreline change classes of the Tuticorin coast.

4.2 Rate of sea-level change

Sea level falling at the rate of −2.70 mm/year in Tuticorin coast is observed from the tide gauge data and from secondary sources. And, sea level is rising at the rate of 1.26 mm/year except Tuticorin coast and it is more vulnerable to get inundated in the later century. The sea-level change rates obtained from the coastal tide gauge data includes both the eustatic sea-level rise and regional SLR with isostatic and tectonic adjustment of the land surface. The study reveals that 34.6 km of the coastal stretch covering Vembar, Periyasamypuram, Vaippar and Pattinamarudhur has a very high risk rating (Fig. 2b) and the coastal areas at Tuticorin, Mullakadu, Punnakayal, Sankaraperi, Mapillaioorani and Keelarasadi falls under low risk category based on sea-level change rate. Loveson and Rajamanickam (1988) have pointed out that there is a possible fall in sea level along Tuticorin coast due to neotectonic emerging of the seafloor.

4.3 Elevation

The study region comprises of a maximum elevation of 31 m in the northern parts of Tuticorin, whereas a minimum elevation of 0 m is observed in the south due to the presence of mudflats and Tamiraparani estuary. Coastal elevation of the study area depicts that 49.2 km of the coastal stretch belongs to Kayalpattinam, Punnaikayal, Pazhaiyakayal, Mullakadu, Tuticorin and Vaippar exhibits very high risk category (Fig. 2c) since it has a flat topography, i.e., less than 1 m. Villages, viz., Mapillaioorani, Pattinamarudhur and Veppalodai, show high risk toward the coastal vulnerability. An elevation of 5 m observed near Periyasamypuram and Vembar belongs to moderate risk.

4.4 Coastal slope

Kayalpattinam, Punnakayal, Pazhaiyakayal, Mullakadu and Tuticorin areas are delineated as very high vulnerability zones. Figure 2d characterizes the vulnerability class for coastal slope. Majority of Tuticorin coast has lower coastal slope of less than 0.2 % which falls under very high risk category. About 22.1 km of the coastline has 0.4 % coastal slope categorized into high vulnerability covering Mapillaioorani, Pattinamarudhur and Tharuvaikulam village.

4.5 Bathymetry

Bathymetry of −1 m is found near Northern Kayalpattinam which belongs to the moderate risk category. The other areas such as Kayalpattinam South, Punnakayal, Pazhaiyakayal,
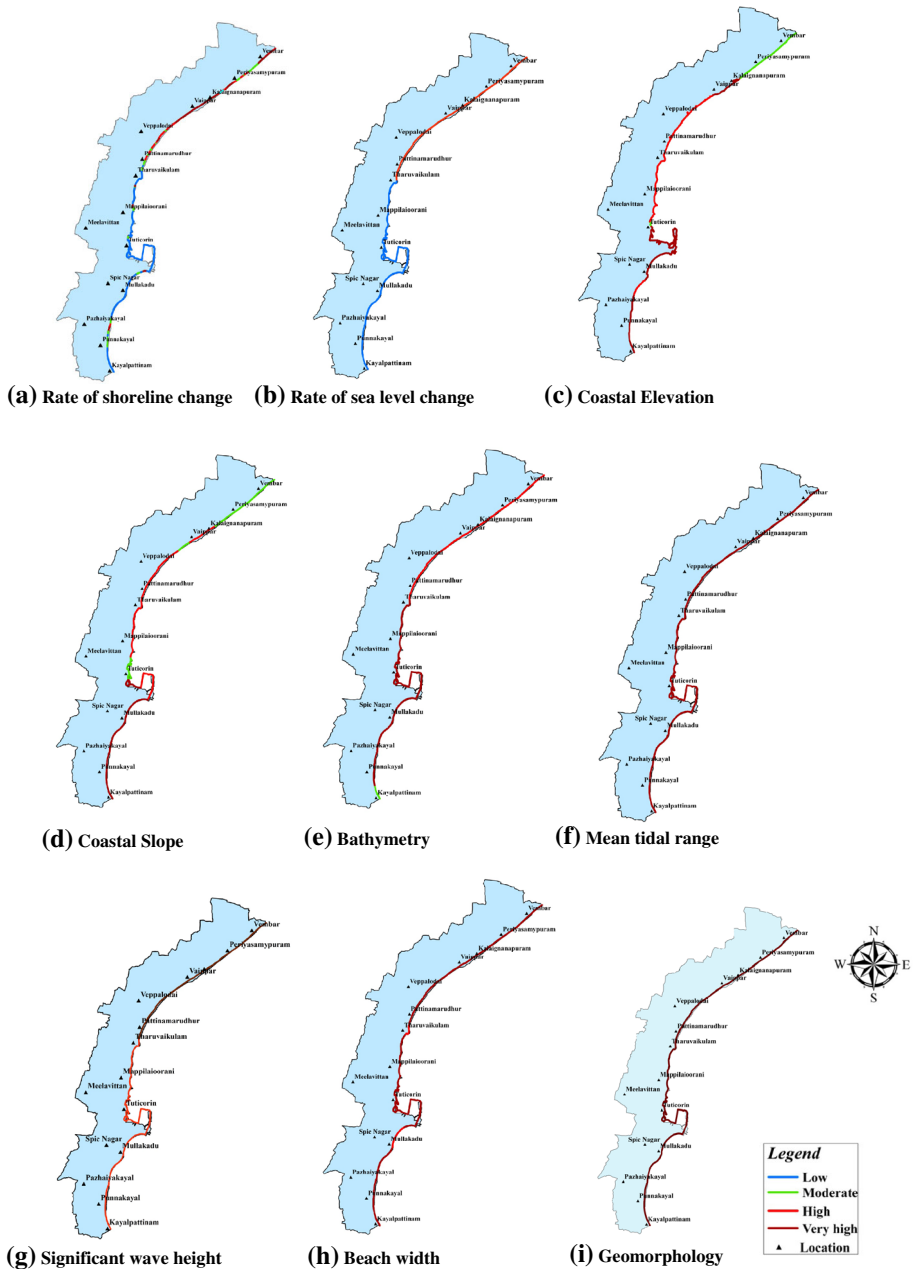
Fig. 2 Vulnerability classification for the parameters considered

Tuticorin, Mapillaioorani and Tharuvaikulam having bathymetry less than −0.5 m fall under very high risk since it has shallow bathymetry exhibit bay conditions along the coast. Vembar and Veppalodai are classified under high risk category (Fig. 2e).

4.6 Mean tidal range

Semidiurnal tides are observed, resulting in two high tides and successive low tides in the study region. The tidal range of the study area is 0.57 m. The microtidal environments (<1 m) experience high vulnerability compared with the macrotidal areas. The entire study area portrays very high risk category. The reason is based primarily on the potential influence of storms on coastal evolution and their impact related to the tidal range. Boori (2010) explained the fact on a tidal coastline, there is only 50 % chance of a storm occurring at high tide. Thus, for a region with a 4-m tidal range, a storm having a 3-m surge height is still up to 1 m below the elevation of high tide for half a tidal cycle. A micro tidal coastline, on the other hand, is essentially always near high tide and therefore always at the greatest risk of inundation from storms. Figure 2f represents the vulnerability class for mean tidal range of the study area.

4.7 Significant wave height

From the buoy data, significant wave height in the southern part of Tuticorin is 0.8 m, representing very high vulnerability category (Fig. 2g), whereas the northern Tuticorin has a wave height of 1.2 m which falls under high risk class. Differences in significant wave heights occur due to the high energy waves at Vembar and lower energy at Tuticorin, prevailing in the study area. Higher significant wave height values affect the longshore sediment transport, resulting in high erosion along few pockets of Tuticorin coast.

4.8 Beach width

Beach width is considered as an important parameter in this study due to the presence of numerous coastal habitations along the study region. Punnakayal, Tuticorin, Tharuvaiku-lam, Mapillaioorani, Pattinamarudhur, Periyasamypuram and Vembar coast having high number of fisherfolk population which is located within 50 m from the seaward region are under very high risk. Approximately 97 % of the coastline has the beach width lesser than 50 m, and it falls under very high risk class. As the beach width varies from 55 to 90 m along Kayalpattinam and Spic Nagar, they are grouped into high risk category. Figure 2h represents the beach width risk class for Tuticorin coast.

4.9 Geomorphology

Mangroves, salt pans, sandy beaches, sand dunes, beach ridges, beach terrace, harbor, mudflats, backwaters, buried pediments, settlements, teri upland, river, salt marshes, paleo flood plains, paleo channels, sand spit, tombolo and vegetation are the major geomorphic units present along the Tuticorin coast. Beach ridges are low, continuous beach or sand dunes often associated with the positions of ancient sea shores, present along the coastal plains of Tuticorin, frequent forms of Quaternary sediments. Sandy beaches are the product of waves interacting with shoreline (Selvavinayagam 2008). Sandy beaches and sand dunes are predominantly found along the northern parts of the district. Well-developed sandy beaches are found in the southern part of Tuticorin harbor due to longshore transport of sediments from Thamiraparani estuary. A thick patch of mangroves are noticed in the Korampallam Odai and Thamiraparani estuary. *Avicennia marina, Avicennia officinalis, Rhizophora mucronata* and *Acanthus illicifolius* are the mangroves species present along the estuarine area (Ravindran and Rajesh 2013). Two sand spits of 0.5–2 km are noticed in

the south of Tuticorin town comprising of sand and gravel, which may be formed due to the longshore sediment transport and low tidal energy along the coastal area. Stabilized beach terraces are formed near Veppalodai coast due to the compression of heavy minerals over years. Mudflats or mudbanks are found near Korampallam Odai and Thamiraparani estuary. Teri dune complex is an undulating terrain having loose heaps of red color sand and silt dust of eolian origin. They represent Pleistocene to Recent age formation. Teri dunes are found along the southern part of the Tuticorin district. Salt pans are found all along the Tuticorin district and it is the major economy contributor of the town. Figure 4 represents the geomorphology map of the study area.

The processes involved in the formation of geomorphic features along Tuticorin coast are fluvial, eolian and marine processes. Geomorphic units including mangroves, mudflats, beach terraces, spit, salt pans, sandy beaches, sand dunes and estuaries are very highly vulnerable to sea-level rise and coastal erosion. Study area has been classified in very high risk category in view of geomorphology (Fig. 2a).

4.10 Coastal vulnerability index

Based on the integration of the parameters, viz., rate of shoreline change, rate of sea level rise, elevation, coastal slope, bathymetry, beach width, mean tidal range, significant wave height and geomorphology, Tuticorin coast vulnerability towards erosion is demarcated as low, moderate, high and very high vulnerable categories.

CVI of the study area varies from 15.1 to 49.3. From CVI values, risk ratings can be categorized using 25th, 50th, 75th and 100th percentiles. Figure 3 categorizes the coastal vulnerability index of the study area. A total of 61.1 km of the study area covering Tuticorin, Mapillaioorani, Mullakadu and Spic Nagar falls under low risk category. Kalaignanapuram, Punnakayal, and Vaippar face high risk.

Tuticorin coast has gentle slope and topography with high erosion/accretion rates is responsible for high CVI values. Table 3 represents the risk classes for the different parameters and the length of coastline falling under hazard category. The vulnerability of the study area mainly depends on the shoreline rates, slope and relative sea-level rise. In the present study, coastal elevation, beach width and bathymetry are considered as additional parameters. Pazhayakayal, Kalaignanapuram and Vaippar are the villages that will be affected by physical and geological processes. Of the coast, 73 % falls under the low hazard category. Of the study area, 12 and 15 % have moderate and high risk, respectively (Fig. 4). Kumar et al. (2010) derived the CVI for Orissa coast using tsunami run-up as an additional parameter and stated that about 62 % of the study area comes under moderate risk category. Arun and Kunte (2012) reported that 27.79 km of the Chennai coast is highly vulnerable due to high erosion.

5 Adaptation measures

Special attention should be paid to the low-lying coastal areas that are vulnerable to erosion, and those areas are supposed to be delineated as high risk zones. Highest priority can be given to mitigate the effects of erosion due to anthropogenic activities. Improvement in land management, erosion control, dune reinforcement, protection of existing natural barriers, strengthening of infrastructure, banning beach mineral mining etc. are the best adaptation options to protect the coastal areas. Engineering options such as sea wall construction and dikes construction can minimize the effects of erosion along sensitive
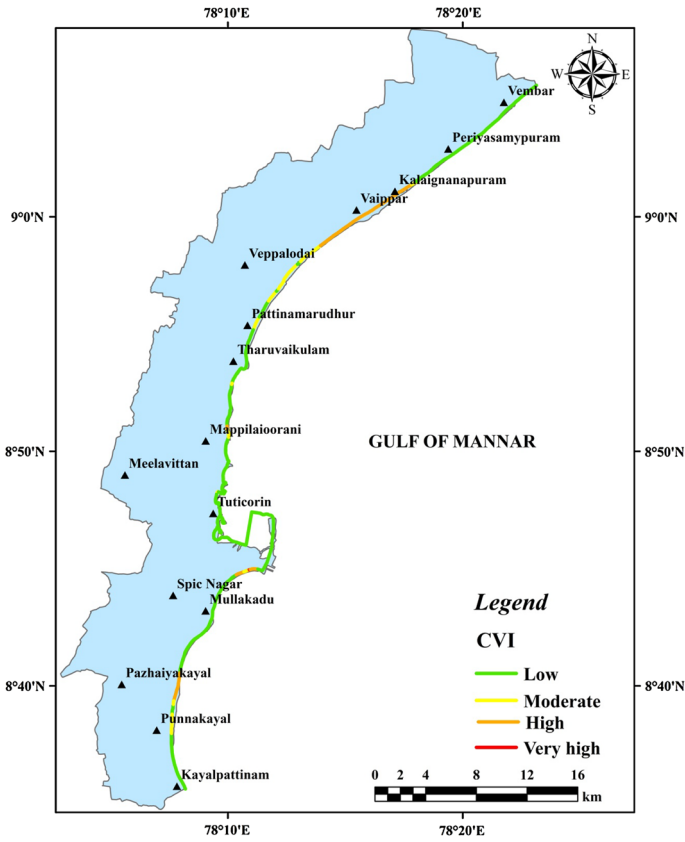
Fig. 3 CVI for Tuticorin coast

Table 3 Risk classes for different parameters

CVI category	CVI values	Length (km)	Villages falling under the vulnerable category
Low	15.1–23.6	61.1	Kayalpatinam, Mullakadu, SPIC Nagar, Tuticorin, Mapillaioorani, Tharuvaikulam, Periyasamypuram and Vembar
Moderate	23.6–32.1	10.0	Punnakayal, Pattinamarudhur and Veppalodai
High	32.1–40.7	12.6	Pazhayakayal and Vaippar
Very high	40.7–49.3	–	–

areas. Latest satellite measurements and GIS techniques can be used to delineate the high risk zones. Suitable policy framework and adaptive measures can be established to prevent the losses in future.

6 Conclusion

The vulnerability of the study area mainly depends on the shoreline change rates, slope and relative sea-level rise. In the present study, coastal elevation, beach width and bathymetry
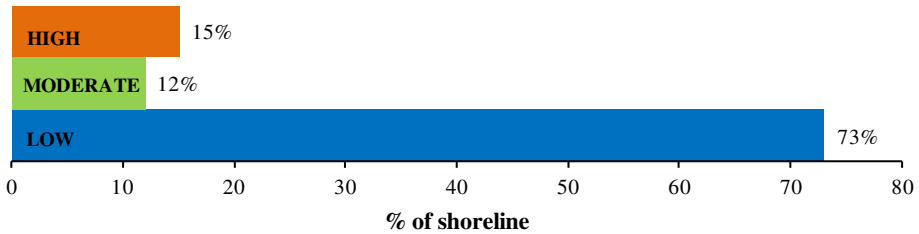
Fig. 4 Percentage of Tuticorin shoreline at vulnerability categories

are considered as additional parameters. Beach width of the study area is considered for this study to identify the risk due to coastal inundation, since a large number of coastal habitations are present in the study area. Of the coastal stretch, 12.6 km, viz., Pazhai-yakayal, Vaippar and Kalaignanapuram villages falls under high risk category. CVI can be used as a stochastic approach to identify the relative risk due to coastal erosion.

Coastal Regulation Zone (CRZ) notification is issued by the Ministry of Environment and Forests (MoEF) of the Government of India in 1991 and amended in 2011, under Environmental Protection Act (1986). It has been declared to ensure the livelihood of the coastal communities, to conserve and protect coastal areas, natural hazards in coastal areas, sea-level rise due to global warming, coastal stretches of the country and water area up to its territorial water limit excluding Andaman and Nicobar and Lakshadweep Islands as CRZ. And the notification restricts setting and expansion of industrial zones and disposal of hazardous waste in the coastal zone. The CRZ notification though it is active in India, but is not fully operational in coastal zones. Severe stress have been noticed in the coastal zones due to illegal mining, disposal of solid and hazardous waste, domestic sewage and industrial effluents poses threats to the local ecosystem.

These factors need to be identified by the local governments and a strict enforcement of the CRZ notification should be adopted to protect the coastal ecosystem and to reduce impacts. The geological and physical observations combining with geospatial techniques can be useful for policy makers and coastal managers to protect the natural and coastal communities along the coast.

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