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Coastal hazard mapping in the Cuddalore region, South India

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Abstract It is estimated that nearly one-third of India's population lives on the coast and is dependent on its resources. Shoreline erosion, storm surges and extreme events have resulted in severe loss of human life, damage to ecosystems and to property along the coast of India. Studies carried out in the Cuddalore region of South India reveal that this low-lying coastal zone, which suffered significant erosion during the last century, has been severely affected by the tsunami of 2004, storm floods and cyclones. In response to these impacts, a variety of coastal defense measures and adaptation strategies have been implemented in the region, although with only limited success. In order to inform future coastal planning in this region, the work reported here identifies a composite hazard line, seaward of which coastal flooding events will have a return interval of less than 1 in 100 years. The area landward of the coastal hazard line will be unaffected by 100 years of coastal erosion at present day rates. The study directly supports the Integrated Coastal Zone Management (ICZM) Plan of the Tamil Nadu State through the identification and assessment of coastal hazards and the overall vulnerability to coastal flooding and erosion. The key results from this pilot study will be used directly by the State of Tamil Nadu in the protection of the coastal livelihoods, better conservation measures and sustainable development along the coast. This study is a step toward mapping the hazard line for the entire coast of India that helps protect human lives and property.

Keywords Coastal erosion · Flood hazard · Vulnerability · Event return interval · Composite hazard line

1 Introduction

More than three hundred million people, or nearly 26 % of the total population, live in the coastal zone of India. As the population increases, more and more people are exposed to natural coastal hazards such as storm surges, tsunamis and shoreline erosion. Considerable

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variation occurs in the frequency, magnitude and seasonality of these events. While the west coast of India is affected by the seasonal tropical cyclones during the southwest monsoon (June–September), the east coast is affected by the northeast monsoon (October–December) and is highly vulnerable to storm surge events. From 1,737 onward, there have been 23 major surge events in the Bay of Bengal, accounting for >10,000 human lives lost during each event (Murthy et al. 2006).

Studies of individual hazards such as storms, cyclones, tsunamis, sea-level change and shoreline change have been carried out by several researchers in the North Indian Ocean, Arabian Sea and the Bay of Bengal (Dube et al. 2006; Indu Jain et al. 2006; Unnikrishnan and Shankar 2007; Kumar et al. 2008 and Rao et al. 2009). Annual maximum water levels observed at Chennai tide gauge station were obtained from the Survey of India for a period of 23 years from 1987 to 2010, which indicate that the sea level along the Indian coast has been rising at the rate of about 1.3 mm year^{-1} on average (INCCA 2010). Nicholls and Leatherman (1995) estimate (assuming no adaptation and the population in 1990) that a 1-m rise in sea level could displace nearly 7 million people from their homes in India.

Flood hazard mapping identifies coastal areas that are at risk of flooding under extreme conditions, with the key objective to reduce the impact of coastal flooding. Erosion mapping helps identify areas that are prone to high erosion risks along the coastline (Linham and Nicholls 2010). Hazard mapping involves the identification of shorelines that are potentially susceptible to the impacts of storm surge, a rise in sea level and erosion. Future sea-level rise due to climate change seems likely to involve an increase in the frequency of storm surge flood events and the accelerated erosion of shorelines, and this must be seen as a central component of any hazard mapping. The probability of a flood of a given magnitude occurring can be expressed as:

- a return interval (i.e., highest flood expected in 100 years)
- a probability (e.g., 0.01)
- a percentage (i.e., a 1 % chance in any given year)

Although in theory all hazard return intervals can be mapped, in practice, it may be best to select one type of event that represents the limit of risk for coastal communities. The line proposed in this study is that of the 100-year event return interval. The main purpose of choosing a 1-in-100-year event return interval is due to:

- Design life of coastal infrastructure including houses, buildings and power plants
- Limit to sea-level rise predictions and
- International standards recommend 1-in-100-year event return interval

The composite hazard line is the most landward of the following

(a) 1-in-100-year flood inundation line which includes the predicted surge level, regional (local) sea-level variation and global (eustatic) sea-level rise due to climate change (IPCC 2007);
(b) a line demarcating estimated shoreline displacement (accretion or erosion) after a 100-year period.

Such hazard mapping can provide an initial or precautionary guide for coastal planning and management responses to rise in sea level and can, in turn, form the basis for vulnerability mapping, which identifies the impact of hazards on coastal communities. Several case studies have developed methods for hazard mapping (Nicholls et al. 2007; Healy and Dean 2000; Sindhu and Unnikrishnan 2012).

Along the coast of Tamil Nadu, India, the Nagapattinam–Cuddalore region experienced the worst impacts of the tsunami surge and inundation caused by the Great Sumatra Earthquake of 26 December 2004 (Mw 9.3). Surge heights along this coastal region were of the order of 2–5 m, with inundation distances of many hundreds of meters into the hinterland. In the Cuddalore District, maximum run-up during the December 2004 tsunami ranged from 2.5 to 3.3 m with inundation distances between 330 and 1,680 m (Subramanian 2006). Subsequently, Cyclone Nisha in 2008 and Cyclone Thane in December 2011 created surge heights between 1 and 1.5 m. In view of the vulnerability of the Cuddalore coastal area to coastal hazards, this study sets out to examine the magnitude and frequency of flood events caused by cyclones, storm surges and tsunamis by extrapolating the existing frequencies. It also provides existing erosion rates along this stretch of coastline and extrapolates these into the future. The principal aim of the study is to combine these two estimates of future hazard in order to delineate a "Composite Hazard Line" (flood hazard mapping + erosion mapping) for the coast of Cuddalore District, Tamil Nadu.

Composite hazard line mapping is a key component in appropriate land use planning in flood-prone areas (Linham and Nicholls 2010). Since 1991, coastal planning and decision making in India have been carried out using the Coastal Regulation Zone (CRZ) Notification under the Environment (Protection) Act 1986 issued by the Ministry of Environment and Forests, Government of India. The notification, first issued in 1991, defined the CRZ as the area between the High Tide Line (HTL) and 500 m on the landward side and the inter tidal region [between the Low Tide Line (LTL) and the HTL]. Activities in this zone were restricted, some prohibited and some permitted, based on an arbitrary distance.

The CRZ 1991 Notification was modified and reissued in 2011 with the aim of protecting life and assets of coastal communities, conservation and protection of inter-generational resources and enhanced livelihood security of coastal communities (Ramesh et al. 2010). As an important component of the CRZ 2011, mapping of "composite hazard line" is being undertaken to delineate the boundaries of the coastal zone in mainland India. Delineation of the composite hazard line is now established based on historic erosion rates or extreme water levels rather than adopting arbitrary distances which do not truly represent the threat from erosion or coastal flooding. As a pilot study, a composite hazard line map along with current land use pattern has been prepared for a short coastal stretch of the Cuddalore District, based on flooding and erosion lines, for the first time in India.

2 Study area

Cuddalore (11°44′45″N and 79°45′56″E) is a large industrial town in the State of Tamil Nadu, South India, which has experienced rapid rates of coastal development. The coastal stretch of Cuddalore extends from Gadilam estuary in the north to Pichavaram mangroves in the south, a total length of 42 km (Fig. 1) along the Bay of Bengal. The Bay of Bengal experiences severe tropical cyclones in northeast monsoon (October through December), and nearly 60 cyclonic surges and severe cyclonic surges in past century (IMDeAtlas 2011) have been reported.

The storm surges are well known for their destructive potential and impact on human activities due to associated strong winds along the coast and heavy rainfall. An added risk factor is that large parts of the coastal zone are low lying and with a gentle slope, resulting in large inundation, and therefore increased vulnerability of the region. Coastal regions that have a gentle topography are more vulnerable than those with a steep topography. The east

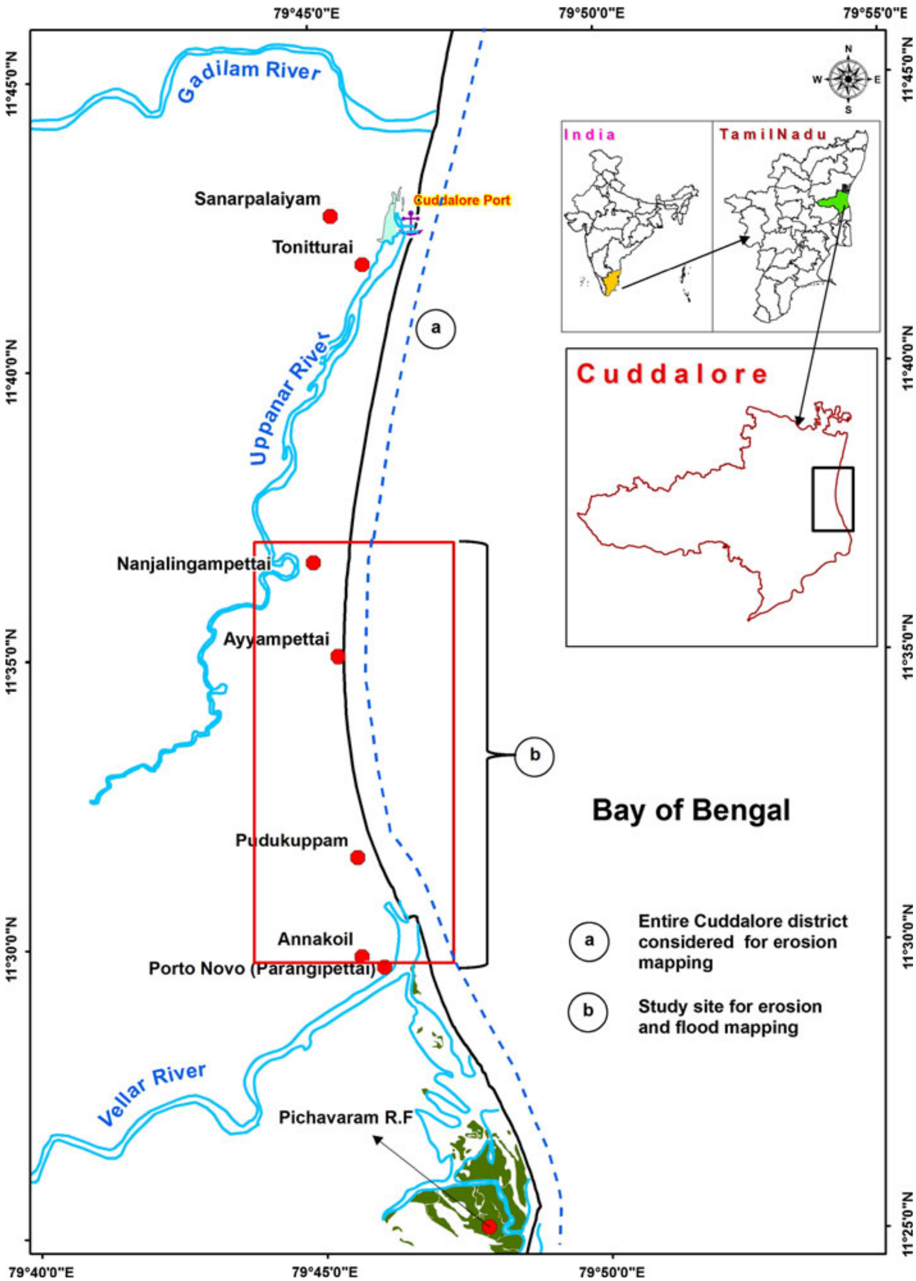

Fig. 1 Map of Cuddalore District and the study area for composite hazard mapping, Tamil Nadu, India

coast of India is more vulnerable than the west coast, because the former is low-lying and more prone to the occurrence of cyclones than the latter.

Shoreline change assessment was made for the entire Cuddalore District (marked as “a” in Fig. 1), while a pilot study for hazard line mapping has been carried out for a shorter stretch of 14 km within the district (marked as “b” in Fig. 1). The geomorphology of the Cuddalore coastal stretch includes the coastal plain with an average width of 6 km. Its coastal landforms include strandlines, raised beaches, sand dunes, mangrove swamps and tidal flats with predominantly sandy beaches on the northern side and mangrove swamps to the south. The coastal towns of Cuddalore in the North and Porto Novo (Parangipettai) in the South are the most densely populated along this region. Unlike the west coast of India, the wettest period of the year is during the northeast monsoon. An analysis of the annual cyclones and severe cyclonic storms in the Bay of Bengal region clearly indicates that although the frequency of cyclones has decreased after 1980, there has been a marginal increase in the occurrence of severe cyclonic storms, which in turn implies an increase in storm magnitude (Dube et al. 1997). An added risk factor is that large parts of this coastal zone are low lying with a gentle slope, resulting in wide inundation areas, thus increasing the vulnerability of the region (Murthy et al. 2006).

3 Methodology

Two key factors are used to delineate the composite hazard line: (1) lateral shoreline movement to deal with erosion and (2) topographic elevation to deal with flooding. Following this, the study methodology is described under three major headings: (1) erosion mapping; (2) coastal flood hazard mapping; and (3) land use/land cover analysis and socioeconomic impacts.

3.1 Erosion mapping

Shoreline change is the horizontal movement of a specific shoreline; however, the precise definition of a shoreline is always a problem. Depending on the location and data source, different proxies for shoreline position are used to document shoreline change, including the high water line, wet-dry line, vegetation line, dune toe or crest, toe or berm of the beach, cliff base or top and the instantaneous water line as extracted from satellite imagery (Thieler et al. 2009). In order to verify the accuracy of the demarcated shorelines, various control points were selected at severely eroding sites, as visually observed from satellite images. A total of eight different data sources in addition to the Survey of India topographical map were used to obtain historical shorelines in this study and are listed in Table 1. Ground control points (GCPs) were selected based on their stability through time and their proximity to the shoreline (Thieler et al. 2009). Differential Global Positioning System (DGPS) coordinates were recorded during field survey for these sites to corroborate with the GCPs. The DGPS coordinates were later compared with the shorelines created in GIS.

Several methods are proposed in the literature to estimate the rate of shoreline change. These include the End Point Rate (EPR) by Fenster et al. (1993), and the Average of Rates (AOR), Linear Regression Rate (LRR) and Jackknife (JK) by Dolan et al. (1991). Each method has its own advantages and limitations, depending upon various factors such as accuracy in shoreline measurement, temporal variability, number of shoreline positions and total time span of shoreline data acquisition. The LRR method for calculating the rate of shoreline change was adopted for this study, since it minimizes the potential errors and short-term variability through the use of a statistical approach (Douglas and Crowell 2000).

The Digital Shoreline Analysis System (DSAS) as defined by the USGS (2005) and Himmelstoss (2009) was used to determine the rate of change for the shoreline of the

Table 1 Data sources consulted and used for analysis of shoreline change

Sensor	Spatial resolution (m)	Years
LANDSAT—I	57	27 Jan 1977
LANDSAT TM	30	29 Jan 1991
LANDSAT TM	30	11 Nov 1999
IRS LISS III	23.5	8 Feb 2001
EO-1, advance land imager	10	16 Mar 2005
LANDSAT TM	30	7 Feb 2006
EO-1, advance land imager	30	14 Feb 2009
CARTOSAT-II	2.5	*Month* 2011

Cuddalore region. This method computes rate-of-change statistics from multiple historic shoreline positions inherent in a GIS environment. The created layers of multi-date shorelines [1972, 1977, 1991, 1999, 2001, 2005, 2006, 2009 and 2011] were used as an input for the DSAS model to calculate the rate of change since 1972 for a period of 39 years. Baselines were created at $\sim$1 km landward of the 1972 shoreline but did not include the smaller creeks and areas such as river mouths and spits. For the Cuddalore coastal region, this method represented about 42 km of shoreline along 141 transects. The DSAS-generated transects, perpendicular to the baseline, were 300 m apart. With reference to the baseline, seaward shift of the shoreline along transect was considered as positive (accretion), while landward shift was considered as negative (erosion). The rate of shoreline variations was calculated using LRR method in the ARCGIS environment to identify erosion and accretion areas along the coasts of the study area, similar to the studies carried out by Himmelstoss (2009).

A minimum of 4 shoreline years at each DSAS transect was used for the calculation of rates of shoreline change. Rates were not calculated at (1) river mouths/creek openings, (2) ports and harbors and (3) other coastal structures (seawalls/ripraps). Eight different classes for shoreline change have been considered, based on the intensity of erosion/accretion (Table 2). Erosion control works (such as seawalls and groynes) have been undertaken to protect the highly eroding coastal stretches of India, and in order to differentiate already protected coasts from critical areas of high erosion, such coastal structures have been classified as “Artificial Coasts”. These artificial coasts were highly eroding but are currently protected and managed.

3.2 Flood hazard mapping

Flood hazard mapping helps identify coastal areas that are at risk of flooding under extreme conditions. Hazard mapping defines the potential for harm using event return intervals (Pethick 2009). The return interval for each flood event was computed from past events. Prediction into the future was made through extrapolation, using statistical distributions (i.e., the 100 years flood height from data collected over the past 20 years from Chennai Port tide gauge data). These data were transferred from the Chart Datum (CD) to Topographic Map Datum (OD). In order to determine which areas are at risk of flooding, coastal topographic survey was undertaken along the Cuddalore coast (marked “b” in Fig. 1) using a Total Station (LeicaTc405), with reference to the Survey of India Benchmark located at the Cuddalore Port. About 5,500 control points were obtained from the Low Tide

Table 2 Shoreline change statistics for the coastal district of Cuddalore

Classification of coast	Extent (km)	Percent of coast
High erosion zone (<−5 m $year^{-1}$)	0.69	1.64
Medium erosion zone (−2 to −5 m $year^{-1}$)	5.13	12.22
Low erosion zone (−0.5 to −2 m $year^{-1}$)	7.65	18.23
Artificial coast (seawalls/riprap)	0.79	1.89
Stable coast (−0.5 to + 0.5 m $year^{-1}$)	10.72	25.54
High accretion zone (>5 m $year^{-1}$)	1.68	4.00
Medium accretion zone (2–5 m $year^{-1}$)	5.73	13.65
Low accretion zone (0.5–2 m $year^{-1}$)	9.58	22.83
Total length of coastline	41.98	100.00
Number of ports and fishing harbors	1	
Number of fish landing centers	5	
Number of groynes/breakwaters	2	
Number of jetties	3	

Line (LTL) to the 5 m topographic contour elevation, that is, approximately 2 km from the High Tide Line (HTL). The topographic survey helped to demarcate the extent of landward movement of extreme water levels.

The water-level data were then ranked in ascending order, and the return intervals were calculated using Gumbel Distribution. The return intervals were then plotted against the maximum water-level elevation for each year by using the topographic datum in log x axis. A trend line (log-linear) was drawn using the prediction equation to extrapolate to a 100-year event. To this, the impact of regional sea-level rise was added to determine the 100-year return interval. The flood and erosion lines for a given time interval were mapped and a composite hazard line was drawn, based on the most landward of the two lines and the composite hazard line represents a margin of safety. The concept of composite hazard line mapping is shown in Fig. 2.

3.3 Land use/land cover analysis

Geometrically and radiometrically corrected satellite images using ERDAS IMAGINE were utilized for identifying the land use and land cover from satellite images. Delineation of land use/land cover mapping was carried out through on-screen interpretation of the satellite imagery. LISS III (2011) false color composites of bands 3,2,1 were used with a spatial resolution of 23.5 m. The spectral information contained in the original and transformed bands was used to characterize each class pattern, and to discriminate between classes. Various key interpretation elements such as size, shape, shadow, tone, color, texture and pattern were identified for delineating different land use patterns. The National Remote Sensing Centre classification scheme (NRSC 2010) was adopted for extracting the information of land use/land cover classes from satellite imagery. Based on this classification scheme, land use features were digitized in ArcGIS geodatabase, and 23 land use/land cover features were classified from the satellite imagery up to level III. The quantification of land use/land cover statistics was made using geo-processing technique in

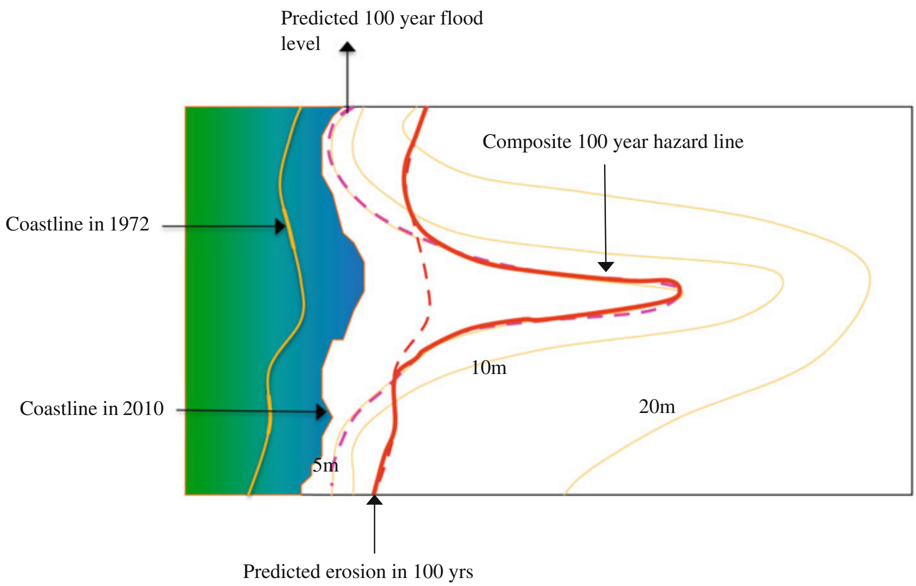

Fig. 2 Concept of composite hazard line (after Pethick 2009)

ArcGIS 10, which calculates a summary statistics for each land use category. Physical vulnerability and land use parameters were correlated with the socioeconomic data obtained from the Central Marine Fisheries Research Institute (CMFRI 2006).

4 Results and discussion

4.1 Shoreline change analysis

Changes in shoreline, as a result of the processes of accretion and erosion, were defined using measurements of change in shoreline location between the years 1972 and 2011. Shoreline change trend reversals indicate that the shoreline of Cuddalore District has undergone both erosion and accretion on a long-term basis (Fig. 3). The primary source of sediment to the Cuddalore coast is the long-shore drift moving from south to north and from the mouth of the Vellar River. The volume of annual gross sediment transport is estimated to be 0.40×10^6 m^3 $year^{-1}$, and the volume of annual net sediment transport is 0.13×10^6 m^3 $year^{-1}$ toward north.

Overall, the coast of Cuddalore District can be classified as an “accreting coast.” Of the total length of 42 km, about 40.5 % of the coastline is accreting compared with 32.1 %, which is categorized as high, medium or low erosion zone (Table 2). The shoreline was stable, that is, showing no marked change, in 25.5 % of the coast, while an “artificial coast” (riprap/seawalls) was present along 1.9 % of the coast. It is evident from the shoreline change observed for the coast of Cuddalore that the location of shoreline protection structures such as seawalls/and riprap adjacent to the Cuddalore Port has resulted in erosion on the northern part of the structure.

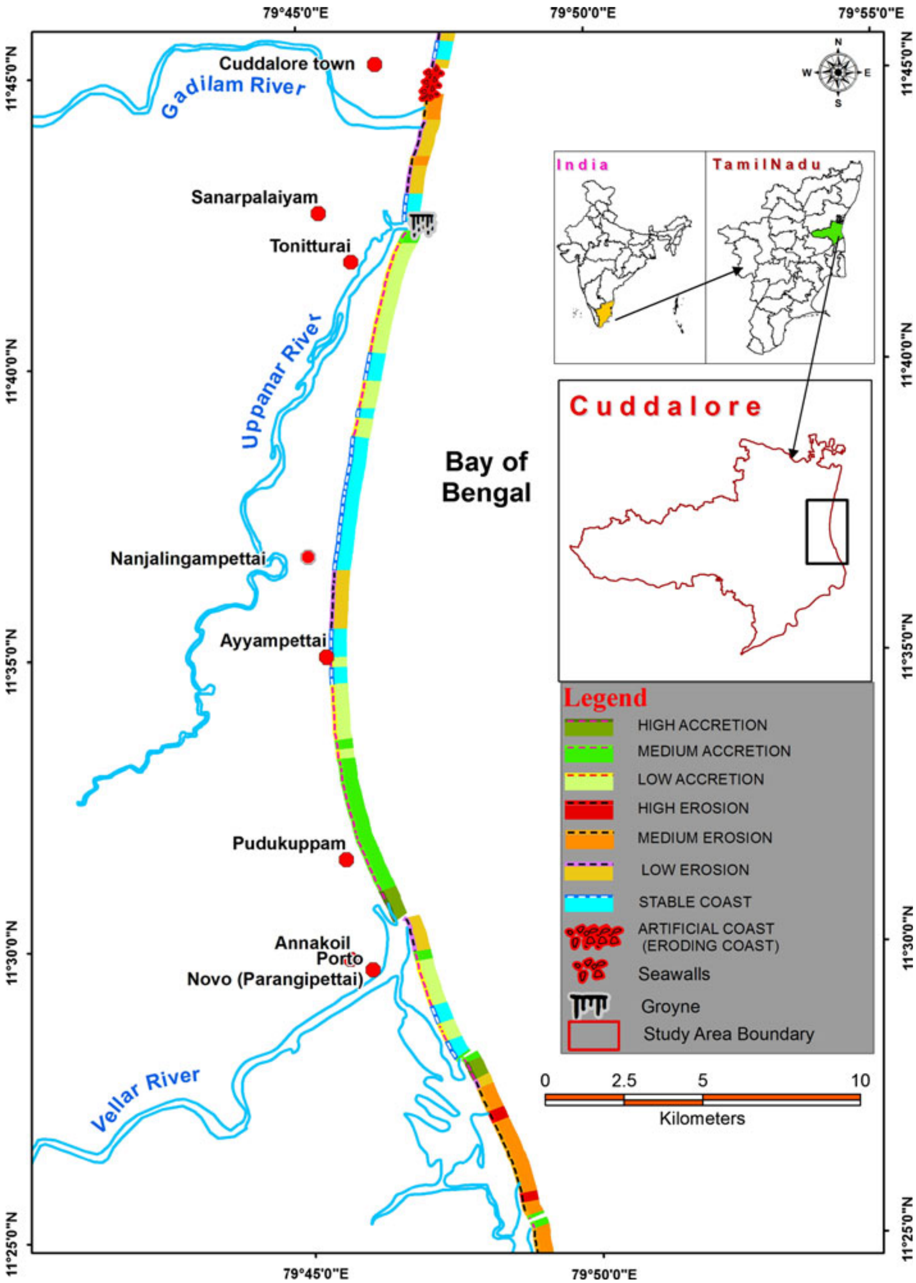

Fig. 3 Erosion mapping along the coast of Cuddalore District

Rates of shoreline change are more uniform along the central part of the study site between Vellar and the Uppanar rivers (Fig. 3). The average net rate of shoreline change here was +0.15 m $year^{-1}$. It was observed that 1.6 % of this coastline was classified as

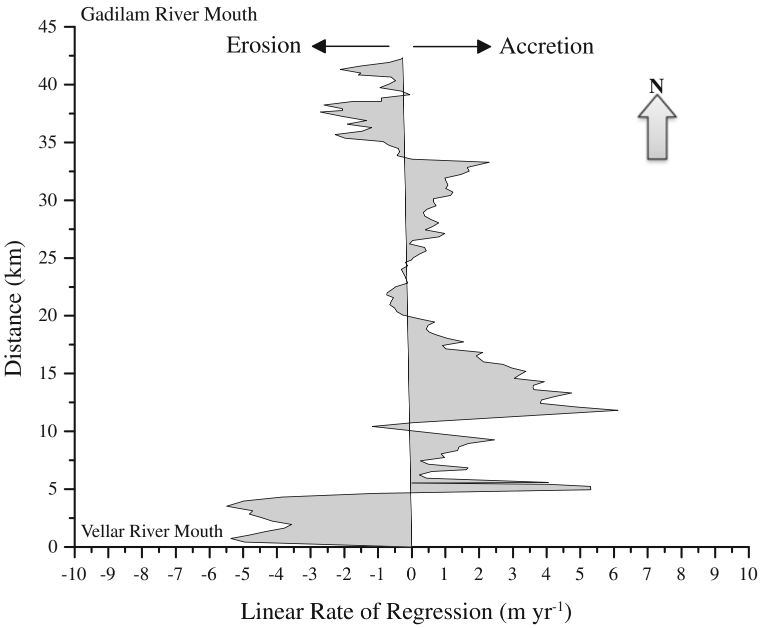

Fig. 4 Linear regression rate (LRR m $year^{-1}$) of erosion and accretion along the coast of Cuddalore District for period from 1972 to 2010

"highly eroding" (<-5 m $year^{-1}$) and, in addition, the already highly eroded but protected coast (classified as artificial coast) was estimated to be 1.9 %, totaling 3.5 % of the 42-km-long coast (Table 2).

Medium erosion was observed south of Vellar River mouth at Pichavaram and between Uppanar and Gadilam rivers in the north (Fig. 3): It appears that river mouth dynamics determine the erosion/accretion pattern along this section of the coast. High rates of erosion were observed along the shores of Pichavaram Mangrove Reserved Forest, probably due to reduced inflow from the Coleroon River, a major tributary of the Cauvery. There are groynes lining the south and north of Uppanar river mouth leading to the Old Cuddalore Port. Littoral drift is predominantly toward the north, and thus, sediment accretion occurs on the southern side of the groyne with erosion on the northern side, limiting long-shore sediment transport and reshaping the coastline over a period of time.

Linear Regression Rate (LRR) of shoreline change (Fig. 4) was calculated at each transect (300 m) as the slope of the linear regression through all shoreline positions from 1972 onward to the most recent (2010). The single highest erosion rate measured for the Cuddalore coast is -5.5 m $year^{-1}$ near Chinnavaikal, located south of the Vellar River (Fig. 4). The highest accretion rate of $+6.1$ m $year^{-1}$ was observed near Pudukuppam, north of the Vellar River mouth. Field observations at the Vellar river mouth indicate the presence of a conspicuous sand spit, extending from the south to north by shore-welding processes, resulting in the formation of sand barriers across the river mouth. It is observed that erosion is dominant along two coastal stretches of the Cuddalore District: (1) south of Vellar River, extending up to the Pichavaram mangroves, and (2) north of Uppanar River,

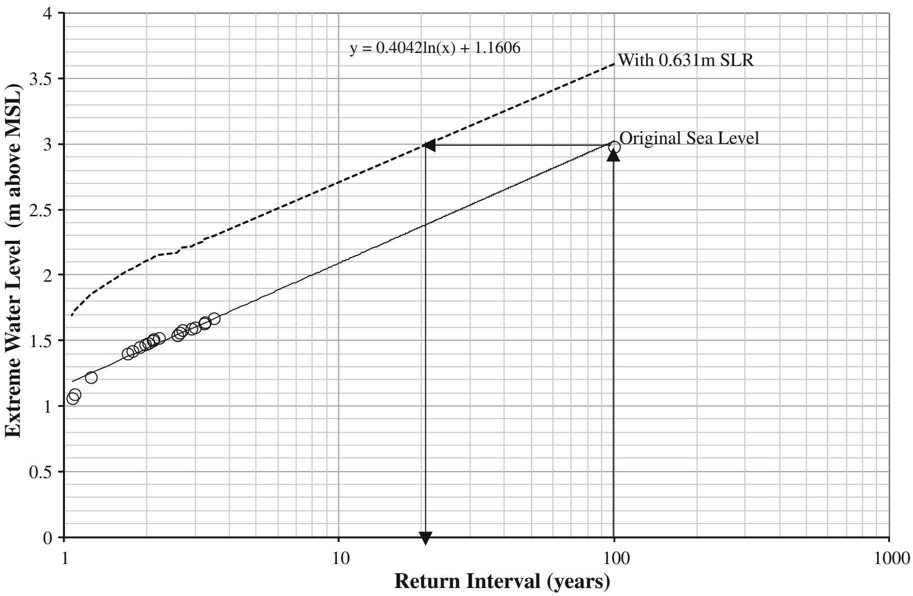

Fig. 5 Flood frequency probability curve using Gumbel Distribution

extending up to Cuddalore Town. The region between Uppanar River in the North and Vellar River in the South is either accreting or stable.

4.2 Flood hazard analysis and composite hazard line

The flood hazard mapping study was undertaken for a short stretch (14 km) along the Cuddalore District (marked "b" in Fig. 1), in response to a recent increase in the level of destruction caused by tsunami and cyclones in this region: (1) Tsunami (December 2004); (2) Cyclone Nisha in November 2008 and (3) Cyclone Thane in December 2011.

Using the Gumbel distribution, the 1-in-100-year flood/surge level was estimated to be 2.98 m MSL (Fig. 5). To this, the annual MSL rise of Chennai (0.041 m), obtained from the Survey of India (1952–2008), and the global sea-level rise (of 0.59 m) as given by the IPCC (2007) were added to determine the 100-year return interval. Based on this, the 1-in-100-year extreme flood level including local MSL and global sea-level rise was calculated to be 3.611 m MSL for the Cuddalore coastal region as follows:

1. Extreme flood level calculated using the Gumbel Distribution: 2.98 m MSL
2. Annual MSL of Chennai: 0.041 m
3. Global (IPCC) sea-level rise: 0.59 m

i.e., $2.98 + 0.041 + 0.59 = 3.611$ m MSL

SLR increases the probability of flooding in coastal zones, unless flood protection measures can be upgraded (Linham and Nicholls 2010). From the flood frequency probability curve (Fig. 5), it is evident that a 0.631-m rise in sea level along the Cuddalore coast causes a sea level previously seen only once every 100 years on an average, to occur approximately once every 21 years instead. Once the extreme water level for the

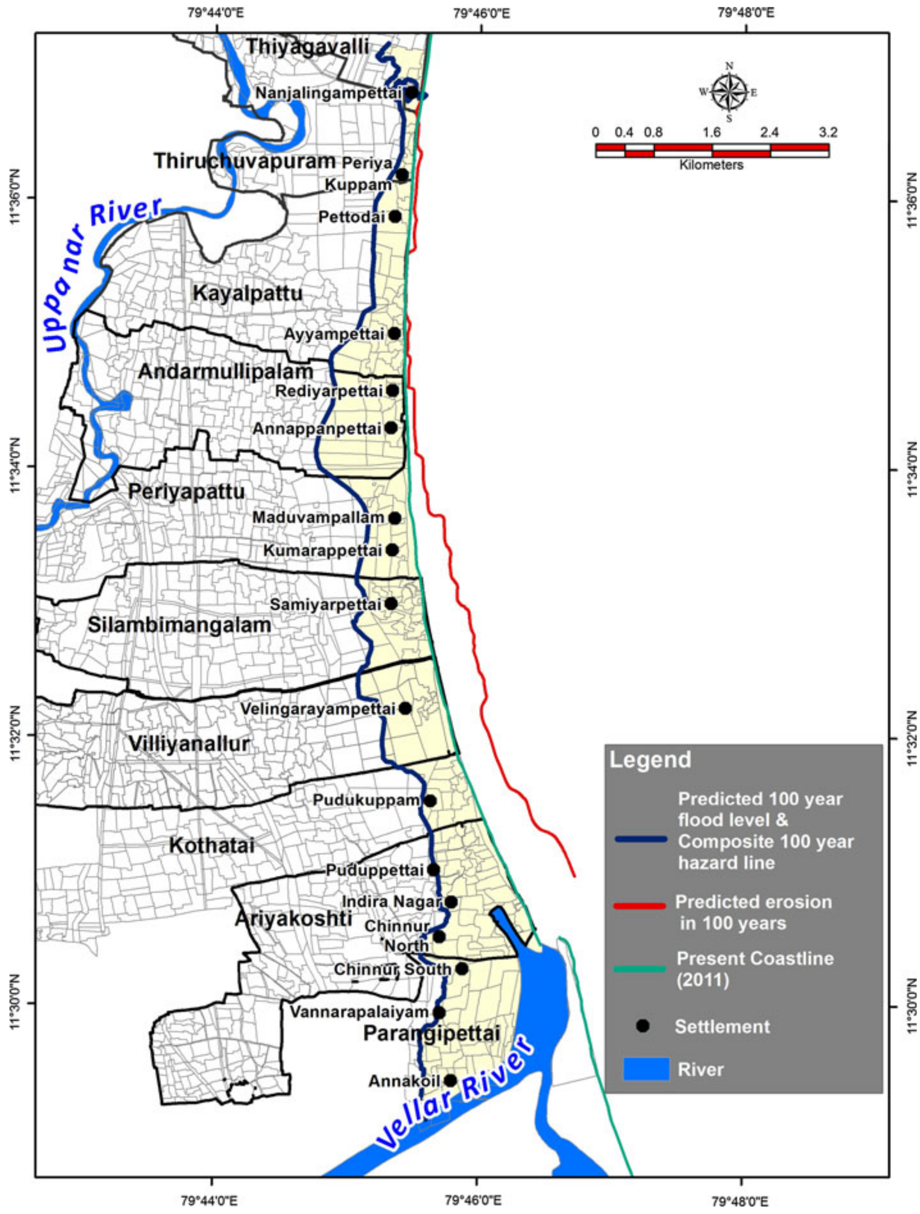

Fig. 6 Lines depicting the predicted erosion in 100 years, predicted 100-year flood level and the Composite 100-year hazard line on a cadastral map of the Cuddalore coast

1-in-100-year return period was determined, the results were transferred to a Cadastral map for the study area in GIS (Fig. 6). The dark blue line on the map is the predicted 100 years flood level. The red line on the map represents the predicted erosion in 100 years.

The more frequent occurrence of extreme water levels will be exacerbated by the degradation of natural coastal ecosystems such as the Pichavaram mangroves (south of the study area) and sand dunes along a major stretch of the Cuddalore District that currently serves as natural coastal defenses. It is also a fact that coastal communities along the Cuddalore coastal region relied upon these natural defenses in extreme events such as the Indian Ocean tsunami in December 2004, Cyclone Nisha in November 2008 and cyclone Thane in December 2011.

The predicted 100 years flood level and the predicted erosion in 100 years were transferred to the cadastral map of the study area in order to demarcate a "Composite Hazard Line," which was represented by the more landward of the two lines. It was observed that for this coastal stretch along the Cuddalore District, the flood line was always the most landward, and thus, the predicted 100 years flood line becomes the composite hazard line (Fig. 6).

Mahendra et al. (2011) made an assessment of multi-hazard vulnerability along the Cuddalore–Villupuram coast and had concluded that river systems act as the flooding corridors that carry larger and longer hinterland inundation. Similar results have been observed in this study, where the settlement of Annakoil (Parangipettai Village) located at the mouth of the Vellar River is subject to maximum inundation. In the longer term, such flood hazard maps can support planning and development by identifying the high-risk locations along the highly vulnerable Cuddalore coastal region.

4.3 Coastal land use/land cover and socioeconomic impacts within the hazard line

Information about the different land uses along the coastal stretch of Cuddalore was prepared to allow assessment of the implications of a storm surge on these land uses. The land use map was prepared on a 1:50,000 scale using LISS III data and classified under 23 major classes for a total coastal length of 14 km and a coastal area of 172.18 km^2. Of this, fallow land (35 %), cropland (17.7 %), plantation (13.5 %) and settlement with vegetation (7.6 %) were the most dominant land use classes (Table 3).

The composite hazard line was overlaid on the land use/land cover map, suggesting that the most dominant land use patterns were (1) settlement with vegetation; (2) vacant land; (3) fallow land; and (4) sand dunes (Fig. 7). The maximum limits of inundation were observed to be at two locations: (1) 2050 m landward at Annakoil in the south and (2) 1,125 m landward at Annapanpettai in the north. Annakoil is a major settlement along this coastal stretch, and our analysis indicates that it is the most vulnerable settlement to flooding. It is estimated that a total area of 11.72 km^2 along this coastline is vulnerable to the predicted 100-year flood event (Table 4).

Vulnerability of Fisher Population along the Cuddalore Coastal stretch was studied using the Marine Fisheries Census data of 2005, obtained from the Central Marine Fisheries Research Institute (CMFRI 2006). Of the 10 coastal villages comprising 14 settlements studied, the marine census indicates that there are 12,975 fishers living in settlements within the hazard line (Table 4). The data also indicate that over one-fourth (2,994) of this population comprise active fishers with 1,068 fishing crafts, of which nearly one-third (340) are mechanized boats. It can be observed that higher fishing population and greater number of fishing crafts are recorded in the southern villages closer to the Vellar River than in the north. This suggests that these villages possess greater fishing capacities, and it can be expected that their socioeconomic resilience would also be greater. However, greater fishing capacity could also mean higher dependency on fisheries for a livelihood and therefore greater vulnerability. Villages with less fishing capacity may possess diverse livelihoods, not dependent upon the sea or coastal area—in which case these communities may have greater resilience to coastal changes. Thus, by incorporating the composite

Table 3 Land use and land cover assessment for the Cuddalore coastal region up to a distance of 10 km landward from the coast

Land use	Area (km^2)	Area (%)
Fallow land	60.04	34.87
Crop land	30.48	17.70
Plantation	23.35	13.56
Settlement with vegetation	13.07	7.59
River	11.08	6.43
Dense mangroves	6.79	3.94
Aquaculture	5.52	3.20
Industry	3.46	2.01
Mud flat	3.31	1.92
Afforestation mangroves	2.57	1.49
Settlement	2.24	1.30
Sandy area	1.91	1.11
Vacant land	1.88	1.09
Sparse mangroves	1.72	1.00
Dune with vegetation	0.93	0.54
Sandy beach	0.83	0.48
Dune without vegetation	0.75	0.44
Canal	0.73	0.42
Land with scrub	0.68	0.39
Land without scrub	0.47	0.27
Tank	0.25	0.15
Salt affected land	0.11	0.06
Water logged area	0.02	0.01
Total	172.18	100.00

hazard line into the current land use, it is possible to understand the extent and socioeconomic implications for people and assets at risk of flooding. This may help ensure proper safeguards of people and property along this coastal area due to hazards such as tsunamis, storm surges and coastal erosion. Thus, the assessment of coastal vulnerability to climate-related impacts is a basic prerequisite for obtaining an understanding of the risk of climate change to natural and socioeconomic coastal systems (Sterr 2008).

4.4 Advantages of hazard line mapping for coastal management in India

Mapping of the composite hazard line is planned for the first time for the entire coastline of India, and this pilot study directly helps determine the appropriate methodologies to be followed. This will assist in the definition of the spatial dimensions of the coastal zone of India in the context of establishing planning boundaries of the state/local integrated coastal zone management (ICZM) plans. The composite 100 years hazard line will incorporate the effects of recurrent coastal hazards, including potential incremental effects induced by climate change (most notably sea-level rise) within the ICZM plans. The composite hazard line would help coastal planners by providing a minimum elevation above sea level to be applied for future development and is a highly effective method of minimizing property damage due to coastal flooding and erosion. The creation of composite hazard maps would promote greater awareness of the risk of flooding and erosion to the coastal population.

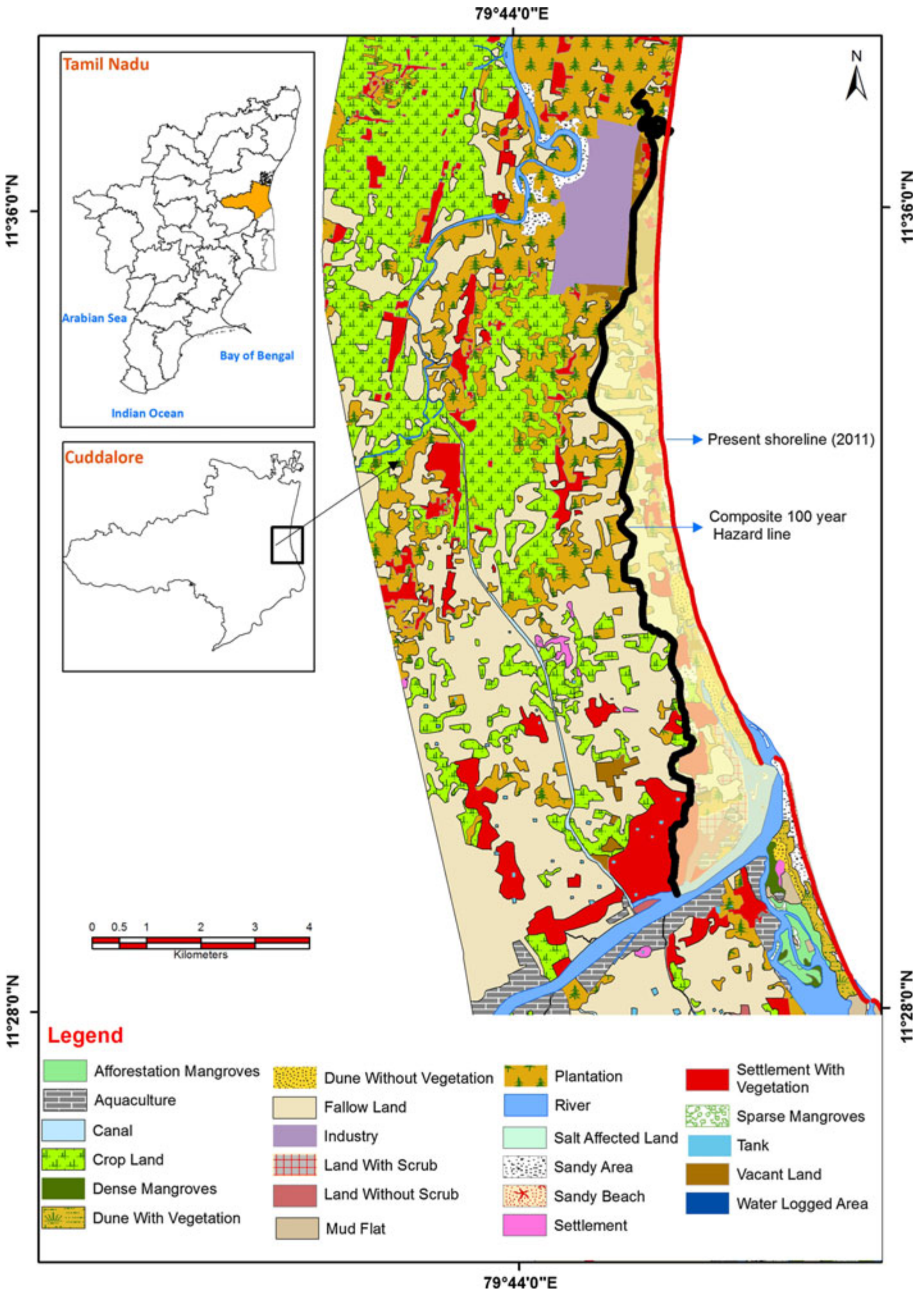

Fig. 7 Composite 100-year hazard line overlaid on the land use and land cover map of the Cuddalore coast

This is beneficial in encouraging the coastal people within this hazard zone to prepare for the occurrence of flooding. In addition, potential strategies that can be undertaken to mitigate the identified hazards can be identified.

Table 4 The area of coastal fishing villages located within the hazard zone along with their socioeconomic status in the Cuddalore coast

S. no.	Name of village	Name of settlement	Area of village (km^2)	Area within hazard line (km^2)	%	No. of fisher population	No. of full time active fishers	Total fishing crafts	Mechanized fishing crafts
1	Thiyagavalli	Nanjalingapettai	14.36	0.27	1.86	404	90	72	8
2	Thiruchuvapuram	Periyakuppam	6.51	0.27	4.11	1,211	383	72	12
3	Kayalpattu	Pettodai	7.58	1.51	**19.96**	627	183	71	26
4		Ayyampettai				533	161	24	0
5	Andarmullipalam	Rediyar pettai	7.61	1.51	**19.86**	746	228	90	6
6		Annappanpettai				698	24	22	0
7	Periyapattu	Maduvampalam	8.07	1.03	12.77	NA	NA	NA	NA
8	Silambimangalam	Samiyarpettai	7.93	1.03	12.98	2,224	123	139	7
9	Villiyanur	Velingarayam Pettai	9.26	1.34	14.48	490	12	25	0
10	Kothatai	Pudukuppam	8.36	0.67	8.07	1,340	374	40	3
11	Ariyakoshti	Pudupettai	8.94	1.88	**21.04**	1,698	615	257	167
12		Indira nagar			NA	534	120	23	9
13		Chinnur North			NA	658	198	61	30
14	Parangipettai	Chinnur South	4.80	2.20	**45.85**	1,076	316	127	49
15		Parangipettai				736	167	45	23
Total			83.43	11.72	14.0	12,975	2,994	1,068	340

The bold values indicate villages where $\geq$ 20 % of the area, fall within the hazard line

5 Conclusions

The purpose of this study is to understand the current risks, added risks expected from climate change and perceived vulnerability to the growing coastal problems in the context of coastal management. This study confirms the previous findings that the coastal stretches of Cuddalore District are in the high-risk zones for multi-hazards. The results of a pilot study presented here suggest that inundation already creates critical management challenges along the Cuddalore coast. Such information and data would assist local state governments in preparing for the impacts of erosion, inundation risks and future sea-level rise, along the Indian coastline. Using this concept, the Survey of India has initiated hazard line mapping the entire coast of mainland India using aerial photography and very high-resolution satellite imagery.

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