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Shoreline change and potential sea level rise impacts in a climate hazardous location in southeast coast of India

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Abstract Climate change impact on the environment makes the coastal areas vulnerable and demands the evaluation of such susceptibility. Historical changes in the shoreline positions and inundation based on projected sea-level scenarios of 0.5 and 1 m were assessed for Nagapattinam District, a low-lying coastal area in the southeast coast of India, using high-resolution Shuttle Radar Topography Mission data; multi-dated Landsat satellite images of 1978, 1991, 2003, and 2015; and census data of 2011. Image processing, geographical information system, and digital shoreline analysis system methods were used in the study. The shoreline variation indicated that erosion rate varied at different time scales. The end point rate indicated the highest mean erosion of −3.12 m/year, occurred in 73% of coast between 1978 and 1991. Weighted linear regression analysis revealed that the coast length of 83% was under erosion at a mean rate of −2.11 m/year from 1978 to 2015. Sea level rise (SLR) impact indicated that the coastal area of about 14,122 ha from 225 villages and 31,318 ha from 272 villages would be permanently inundated for the SLR of 0.5 and 1 m, respectively, which includes agriculture, mangroves, wetlands, aquaculture, and forest lands. The loss of coastal wetlands and its associated productivity will severely threaten more than half the coastal population. Adaptation measures in people participatory mode, integrated into coastal zone management with a focus on sub-regional coastal activities, are needed to respond to the consequences of climate change.

Keywords Climate change impact · Shoreline change · Sea level rise · Remote sensing · GIS · Adaptations measures

Introduction

Shoreline changes happen over a wide range of time scales and associated with coastal features such as waves, tides, periodic storms, sea level rise (SLR), and human developmental activities (Appeaning Addo et al. 2008). The shoreline position can change due to predictable short-term variations in sea level that depend on astronomical and meteorological factors (Pugh 2004) and less predictable changes in the shape and volume of the sediments along the profile of the shore (Pardo-Pascual et al. 2012). The International Panel on Climate Change (IPCC) fifth assessment report indicated that the rate of SLR since the mid-nineteenth century has been larger than the mean rate during the previous two millennia, and the global averaged SLR was 1.7 mm/year (1.5 to 1.9) between 1901 and 2010 and 3.2 mm/year (2.8 to 3.6) between 1993 and 2010. Global mean SLR will continue to increase and will not be uniform across regions during the twenty-first century, very likely at 52–98 and 28–61 cm by the year 2100 for high and low emission scenario correspondingly (IPCC 2014).

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Potential responses to these SLR scenarios depend on the landforms that occur within a region and include increased likelihood for erosion and shoreline retreat for all coastal types (Gutierrez et al. 2007). Regional and local factors (e.g., changes in land elevation) will influence future relative SLR for specific coastlines around the world (Martinich et al. 2013).

The impact of SLR and extreme coastal flooding are felt at the local level, but much emphasis is given to assess the impact at national level (Lichter and Felsenstein 2012). As the SLR or shoreline changes cannot be the same for all regions, demands localized studies for vulnerable areas. Detailed local studies will be able to provide a clear picture on the implications of SLR (Hennecke et al. 2004) and will aid to identify the correct adaptation measures to cope with climate vulnerability. Visualization of inundation will be helpful to understand the vulnerability and provides vital information for future planning and informed decision making (Walsh et al. 2004). Remote sensing (RS) technology and Geographical Information System (GIS) has been recognized as indispensable tools for spatial decision making from local to national level and also for quantifying the shoreline changes on temporal scales and impact of SLR projections (Maiti and Bhattacharya 2009; Ford 2013).

Shoreline changes have been studied using either conventional mapping or digital shoreline analysis systems in many coastal countries (To and Thao 2008; Alemayehu et al. 2014; Morton et al. 2004; Joesidawati and Suntoyo 2016). In India, studies have been carried out for the assessment of the coastal vulnerability index using coastal slope, coastal geomorphology, shoreline change rate, tidal height, and wave height for different maritime states such as Orissa (Kumar et al. 2010), Kerala (Mohan and Jairaj 2014), Andhra Pradesh (Rao et al. 2008; Ahammed et al. 2016), Karnataka (Jana and Hegde 2016), Nagapattinam, Kanyakumari and Tuticorin of Tamil Nadu (Mujabar and Chandrasekar 2013; Natesan et al. 2015; Mageswaran et al. 2015), and Alibag of Maharashtra (Vidya et al. 2015). Though assessment of shoreline changes has been attempted in the past, the expected impact due to shoreline changes and SLR on the natural and human resources have not been studied so far in many countries including India. Changing shorelines will have a more adverse impact on low-lying coastal regions; thus, regional impact studies in vulnerable areas can give the data required for planning protection and prevention measures. A close perusal on the literature indicated that scarce information is available on the impact of shoreline change and sea level rise on the natural resources. In this context, Nagapattinam coast of Tamil Nadu was taken for the model study as the region is well known for the vulnerability to extreme climatic events with low-lying topography. In the present study, we have assessed the shoreline changes and SLR impact of the inundation of land resources and population for Nagapattinam district of Tamil Nadu located in the southeast coast of India as a representation of a climate hazardous low-lying coastal region.

Study area

The Nagapattinam district of Tamil Nadu (Fig. 1) having an area of 2585 sq. km is situated between 10.10° and 11.20° north latitude and 79.15° and 79.50° east longitude. It is classified as a multi-hazard prone district due to heavy winds, cyclones, floods being a regular feature and also worst hit during the last Tsunami in 2004. The wave penetration in to the main land has ranged from 2 to10 m. Total population in the district was 1.5 million as per the 2011 census of Government of India. The topography is plain and the elevation of the study area above mean sea level has ranged from − 3 to 14 m with an average of 9 m. The average daily temperature varied from 24.6 to 32 °C. The district receives southwest monsoon (SWM) of about 265.2 mm/year from June to September and northeast monsoon (NEM) of about 908 mm/year from October to December. NEM season was categorized as period of alert due to extreme climatic events. The Point Calimere wild-life sanctuary in the district is a protected area for conserving black buck, an endangered and endemic species of India. The details of the study area were obtained from the district website of Government of Tamil Nadu (www.nagapattinam.tn.nic.in).

Materials and methods

Data used

We used Landsat imagery pertaining to path 152, rows 53 and 54 from US Geological Survey (USGS) for the study. Landsat 1/multi-spectral scanner (MSS) data dated April 14, 1978 (60 m resolution), Landsat 5/thematic mapper (TM) data dated April 03, 1991 (30 m resolution), and Landsat 7/enhanced thematic mapper (ETM+) data dated

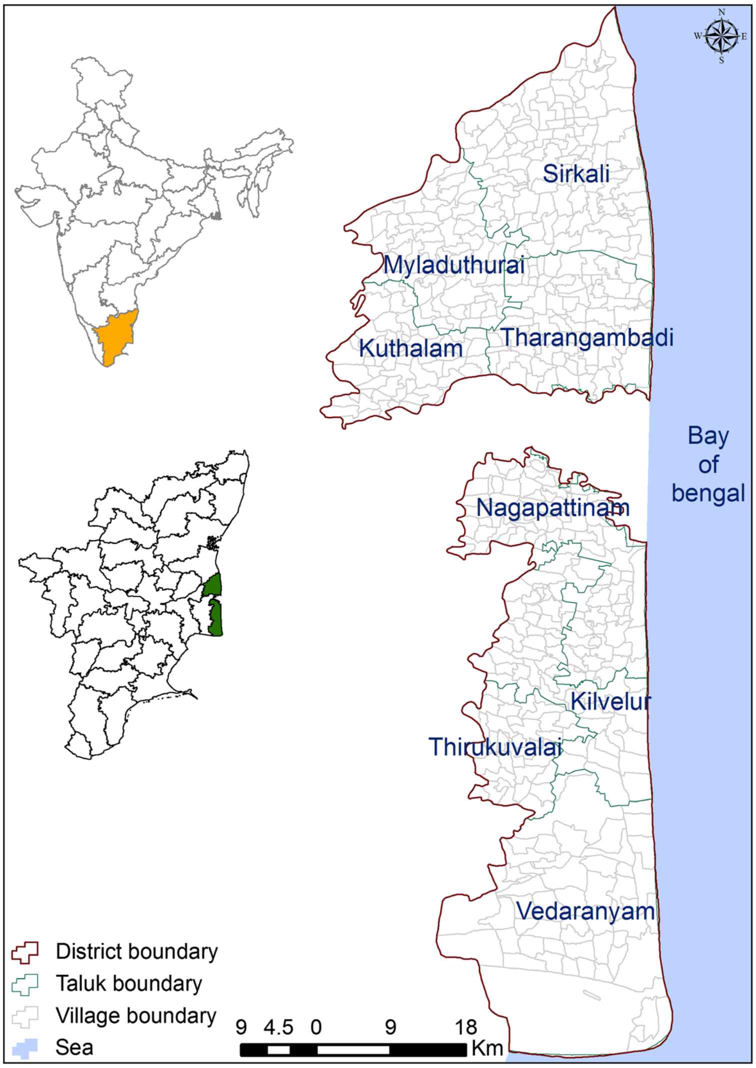

Fig. 1 Location of the study area

April 28, 2003 and April 21, 2015 (30 m resolution) available online (www.earthexplorer.usgs.gov) were used. Survey of India topographic maps (58 M 11, 12, 15–16 and 58 N 9, 10, 11, 13, 14, 15) were used for the delineation of the district and the taluk boundary. Shuttle Radar Topography Mission (SRTM) data of latitude N10, N11 and longitude E79 dated 23 Sept. 2014 with 90 m resolution were downloaded from http://srtm.csi.cgiar.org/ for the topographic elevation data.

Shoreline change estimation

Delineation of shoreline position from satellite images were carried out by mapping of high water line, digitized from the images pertaining to 1978, 1990, 2003, and 2015. Studies have indicated the high water line as effective shoreline which can be clearly mapped from digital satellite images (Pajak and Leatherman 2002; Selvan et al. 2014). Digital Shoreline Analysis System (DSAS) version 4.3 developed by Thieler et al. (2009), an extension of Arc GIS version 10, was used for the assessment of shoreline changes. Transect spacing of 500 m and transect length of 2000 m was used with auto detect cast direction. Confidence level was set to 90% to compute error bars in linear regression statistics.

Historic rates of shoreline changes were calculated by using end point rate (EPR) and weighted linear regression rate (WLR). In EPR, the shoreline change rate was calculated between two shoreline positions by dividing the distance of shoreline movement by the time elapsed. WLR was used to calculate the rate of change involving more than two period shoreline positions by plotting a least squares regression line to shoreline points to a specific transect of all shoreline points, as EPR cannot accommodate more than two coastlines. Linear regression rate includes all data, regardless of changes in trend or accuracy, and calculates the changes based on accepted statistical concepts and easy to employ (To and Thao 2008). In the rate of shoreline change analysis, weightage value based on uncertainties associated with each shoreline was added in WLR method. The error of uncertainty from different sources includes image resolution errors (E_r), seasonal error (E_s), tidal fluctuation error (E_{td}), and digitizing error (E_d). The total shoreline position error E is expressed by the equation for one period

$$E = \sqrt{E_r^2 + E_s^2 + E_{td}^2 + E_d^2}$$

The error (E) was calculated for each period and then annualized to estimate the error for shoreline change rate at any given transect. For our study, T is the 37-year period of analysis. The maximum annualized error using best estimate is 0.177 m/year. To calculate the type and the extent of land eroded, two consecutive period shorelines were overlaid on the satellite image of earlier period, eroded extent was extracted, and the area statistics were arrived.

DEM and mapping of inundation zones

Digital elevation model (DEM) was derived from SRTM data using spatial analyst tool of ARC GIS. SRTM DEM has the spatial resolution of 90 m, with horizontal and vertical precisions of 45 and 15 m, respectively (Sun et al. 2003), and the relative accuracy to the coastline is less than 1 m (Demirkesen et al. 2008). Inundation zones were derived from the DEM for 0.5 and 1 m SLR scenarios. Using ArcGIS version 10, the Landsat data of 2015 was visually interpreted onscreen for the land use land cover (LULC) categorization based on the classification scheme developed by National Remote Sensing Agency (NRSA 1995). Ground truth verification was carried out to check the doubtful classes and to identify the features using Juno Global Navigation Satellite System (GNSS). The number of checkpoints in each land class was set as 20. The accuracy of the classification was evaluated using error matrix and Kappa coefficient (Campbell and Wynne 2011). LULC and village maps were overlaid on the projected inundation zones to assess the extent and impact of inundation. Population statistics of inundated villages (subset of Taluks) were calculated based on the census data of 2011 available in the website of Government of India (data.gov.in).

Results

Assessment of short-term and long-term shoreline changes

To assess the shoreline change, a total of 256 transects were generated with a spacing of 500 m. There are 68 transects (1 to 68) in Sirkali Taluk, 28 transects (69 to 96) in Tharangambadi, 32 transects (97 to 128) in Nagapattinam, 29 transects (129 to 157) in Kilvelur, and 99 transects (158 to 256) in Vedananyam. The shoreline positions overlaid on satellite images (Fig. 2) indicates the erosion, accretion, and stable segments of the study area. Rate of changes in shoreline positions at different time interval using EPR and WLR is given in Table 1.

Short-term shoreline change using EPR

The short-term shoreline changes (Fig. 3) between two shoreline positions (1978 and 1991, 1991 and 2003, 2003 and 2015) indicated the negative (erosion) and positive (accretion) changes on the shore. We observed varying rates of erosion and accretion rates in the three periods of the study. The changes in shoreline between 1978 and 1991 indicated the erosion and accretion in 73 and 15% of the shore, respectively, and stable pattern in the remaining 12%. The mean erosion rate was − 5.68 m/year and the maximum erosion of − 14.96 m/year occurred in the transect 24. The mean accretion rate was 6.81 m/year and the maximum accretion of 36.82 m/year was observed in the transect 12. The mean EPR and net shoreline movement (NSM) was − 3.12 m/year and − 40.56 m, respectively.

Between 1991 and 2003, the shore of 37% eroded, 35% accreted, and the remaining 28% found to be stable. The high rate of erosion of − 55.67 and − 55.04 m/year were observed in the transect 11 and 12, respectively, near bar mouth area. The accretion occurred at the maximum rate of 23.06 m/year in the transect 248. The mean erosion and accretion rate was

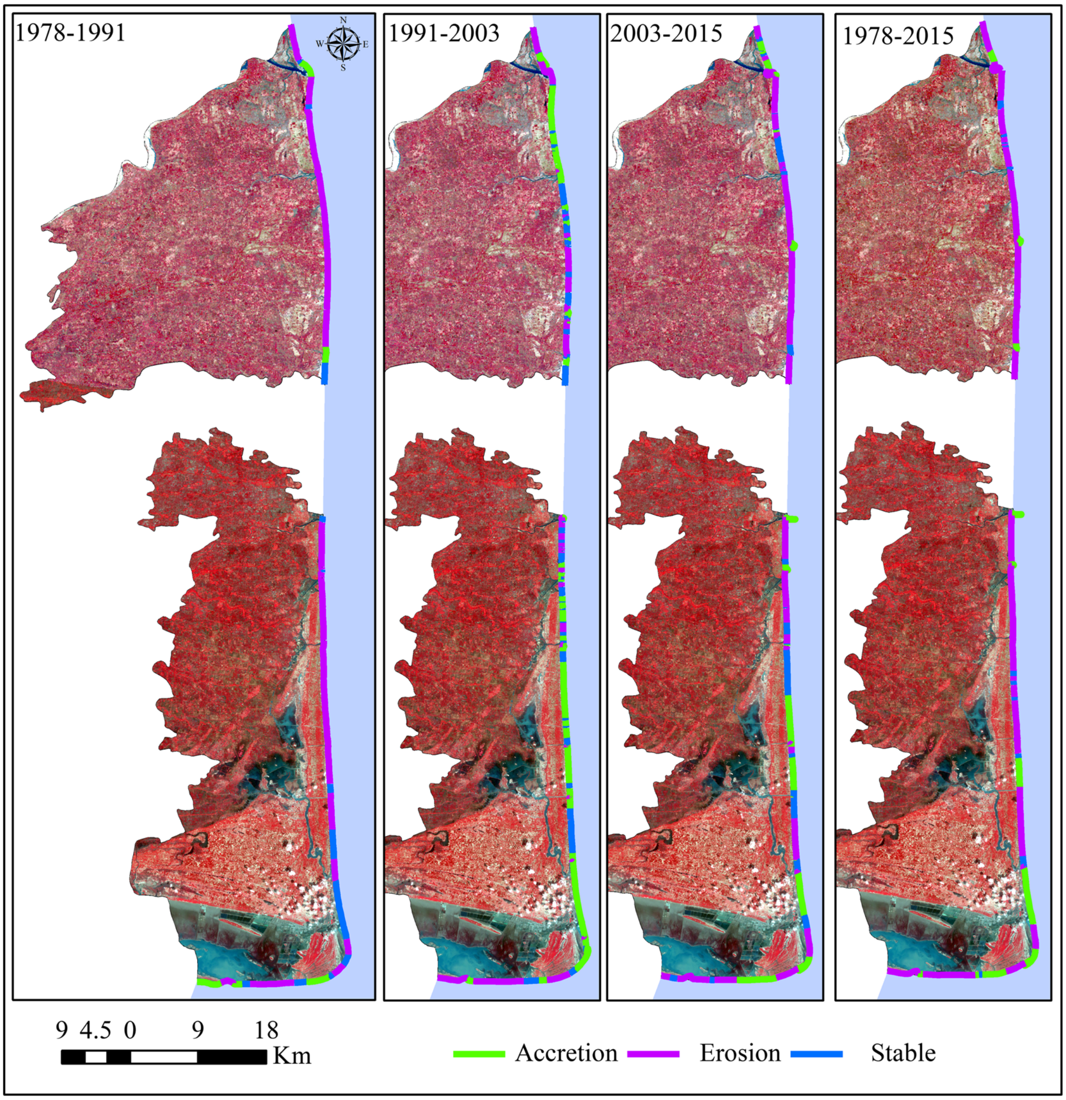

Fig. 2 Shoreline positions overlaid on satellite images of 1978–2015

Table 1 Rate of changes in shoreline positions at different time interval using EPR and WLR with the transect number in brackets

Method	Period	Shoreline change	Erosion				Accretion				Stable
		Mean (m/year)	%	Max (m/year)	Min (m/year)	Mean (m/year)	%	Max (m/year)	Min (m/year)	Mean (m/year)	%
EPR	1978–1991	−3.12	73	−14.96 (24)	−0.44 (179)	−5.68	15	36.82 (12)	0.13 (91)	6.81	12
	1991–2003	−0.91	37	−55.67 (11)	−0.11 (218)	−7.62	35	23.06 (248)	0.17 (207)	5.36	28
	2003–2015	−1.43	61	−23.89 (13)	−0.2 (7)	−3.47	22	24.2 (217)	0.06 (160)	4.02	17
WLR	1978–2003	−2.53 ± 11.13	74	−11.07 (249)	−0.58 (142)	−4.31 ± 9.93	20	11.87 (13)	0.07 (207)	2.52 ± 11.37	6
	1991–2015	−1.39 ± 8.57	66	−27.8 (12)	−0.15 (7)	−3.59 ± 8.78	30	18.12 (216)	0.38 (136)	3.03 ± 8.25	4
	1978–2015	−2.11 ± 2.98	79	−8.32 (249)	−0.06 (148)	−3.08 ± 2.79	21	10.56 (217)	0.26 (111)	2.59 ± 3.92	0

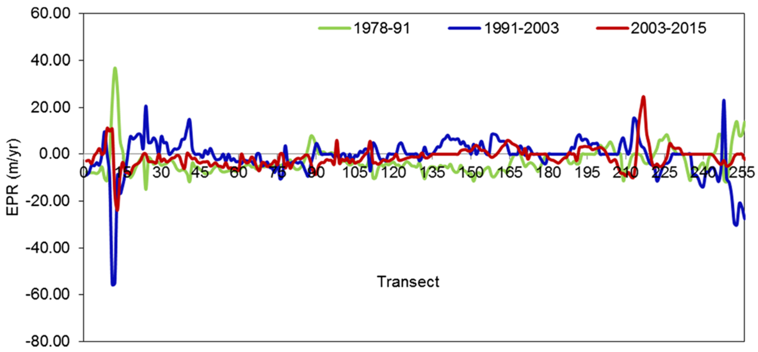

Fig. 3 Periodical short-term shoreline change using EPR

7.62 and 5.36 m/year, respectively. The mean EPR and NSM was − 0.91 m/yr. and − 8.19 m, respectively.

Between 2003 and 2015, 61% of shore experienced erosion, while the remaining 22 and 17% showed accretion and stable pattern, respectively. The mean EPR and NSM was − 1.43 m/year and − 21.45 m, respectively. The mean erosion rate was − 3.47 m/year with the maximum rate of − 23.89 m/year in transect 13. The mean accretion rate was 4.02 m/year with the maximum rate of 24.2 m/year at transect 217. Transects from 11 to 13 located in the bar mouth area have faced the high rate of changes compared to other transects.

Long-term change rate using WLR

Rates of shoreline change using WLR (Fig. 4) were calculated for the period from 1978 to 2015 and also for the periods from 1978 to 2003 and 1991 to 2015. The change rate estimation from 1978 to 2003 using three shoreline positions of 1978, 1991, and 2003 indicated the maximum erosion and accretion rate of − 11.07 m/year at the transect 249 and 11.87 m/year at the transect 13, respectively. Among 256 transects, 74% faced erosion while the remaining 20% experienced accretion and only 6% maintained stable condition. The mean rate of change was − 2.53 m/year and the mean of 90% confidence interval was 11.13. Hence, the reported rate of shoreline change was − 2.53 ± 11.13 m/year while NSM was − 56.30 m within the first 25 years of period of study.

The change analysis of the period between 1991 and 2015 involving 1991, 2003, and 2015 shoreline positions indicated that the change was − 1.39 ± 8.57 m and NSM was − 33.38 m. Along the shoreline, 66% transects eroded while the remaining 30% accredited within 25 years. The maximum erosion and accretion of − 27.8 and 18.12 m/year was observed at transect 12 and 216 correspondingly.

The change analysis for the period from 1978 to 2015 revealed that 79% transects eroded while the remaining 21% transects accredited. The high erosion rate was − 8.32 m/year at transect 249 and accretion rate was 10.56 m/year at the transect 217. The mean erosion rate was − 3.08 ± 2.79 m/year while the mean accretion rate was 2.59 ± 3.92 m/year. The overall loss of shoreline position in 37 years was 85.20 m occurred at a rate of − 2.11 ± 2.98 m/year.

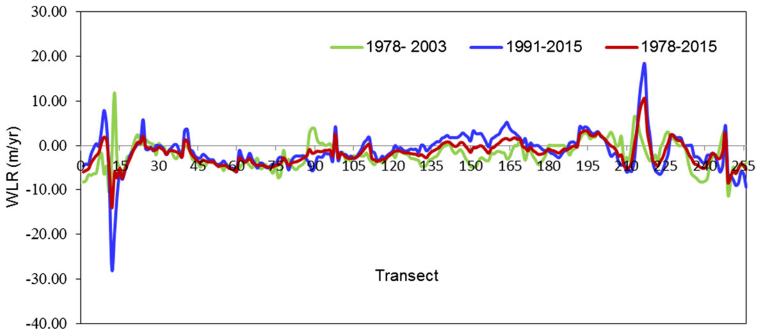

Fig. 4 Periodical long-term shoreline change using WLR

Impact of changes in shoreline positions on land use

Assessment of changes in shoreline positions on coastal resources (Table 2) indicated that 107 ha of mudflats had formed due to accretion, and 75 ha was lost due to erosion from 1978 to 1991 along the coast. In addition, the sandy area of 587 ha and scrub land of 22 ha were also lost. Between 1991 and 2003, sandy beach of 183 ha was formed but, simultaneously, 32 ha was lost. The mudflat of 69 ha was lost, but this was reversed by the formation of 70 ha at different locations. During 2003 and 2015, 122 ha of mudflat, 139 ha of sand, and 151 ha of scrubland were lost but, at the same time, 61 ha of mudflats and 102 ha of sandy areas were formed at other places. Overall, the loss of 359 ha of sandy areas, 141 ha of mudflats, and 349 ha of scrub lands due to erosion has been observed. At the same time, formation of 59 ha of sand, 30 ha scrub lands, and 59 ha of mudflat due to accretion was mapped. The construction of a port (17 ha) had resulted in shoreline movement towards sea. Overall, the erosion of 849 ha and the accretion of 165 ha indicates the varying intensity of shoreline movements at all periods of study consequential to shoreline dynamics.

Extent of inundation due to SLR

Mapping of elevation and LULC

DEM derived from SRTM data (Fig. 5a) showed the low-lying nature of the study area. The land use derived from the satellite image of 2015 (Fig. 5b) has been categorized into 13 classes as agriculture, aquaculture, forest, industry, mangroves, mudflat, saltpans, coastal plantation, sand, scrub land, settlement, waterbodies, and wetlands. The accuracy assessment indicated the user accuracy of 94% and producer accuracy of 96% with a Kappa coefficient of 0.95, showing the near-perfect classification. The agricultural land, settlement, waterbodies, and mudflat were the four major land use of the study area and covered an area of 190,735 ha, 23,687 ha 13,028 ha, and 10,629 ha, respectively. The aquaculture farms of 3899 ha and salt pan of 4408 ha were also present in the study area. Mangroves of 348 ha and wetlands of 3312 ha indicated the ecological importance of the study area. The sand category occupied 736 ha. The Point Calimere reserve forest occupied an area of 1573 ha, and the scrubland covered an area of 5951 ha including 162 ha of coastal plantation.

Inundation of land resources due to 0.5 and 1 m projected SLR

Projected SLR impact on land use (Fig. 5c, d) indicated the extent of inundation and the type of land classes to be affected. The quantification of land use and area of inundation to the projected SLR are given in Table 3. The analysis indicated the inundation of 14,122 ha to 0.5 m SLR and 31,318 ha to 1 m SLR. The agricultural lands of about 5455 ha (2.86%) and 15,552 ha (8.15%) will be under risk due to 0.5 and 1 m SLR. Rice, pulses (Green gram, Black gram), ground nut, and sugarcane are the major crops cultivated in the district. In addition to the loss of agricultural lands, salinization of agricultural lands, erosion, and riverine flooding may pose a serious threat due to seawater movement towards land side and will result in reduced productivity in cultivable lands. Out of the 348 ha of mangroves (*Avicennia* species), 14 and 65 ha will be under severe threat, resulting to a loss of 4.13 and 18.54% of mangroves at 0.5 and

Table 2 Changes in land classes due to shoreline changes at different time interval from 1978 to 2015

LULC Classes	1978–1991		1991–2003		2003–2015		1978–2015	
	Accretion (ha)	Erosion (ha)	Accretion (ha)	Erosion (ha)	Accretion (ha)	Erosion (ha)	Accretion (ha)	Erosion (ha)
Mudflat	107	75	70	69	61	122	59	141
Port	0	0	0	0	17	0	17	0
Sand	0	587	183	32	102	139	59	359
Scrubland	12	22	16	48	0	151	30	349
Total	119	684	269	149	180	412	165	849

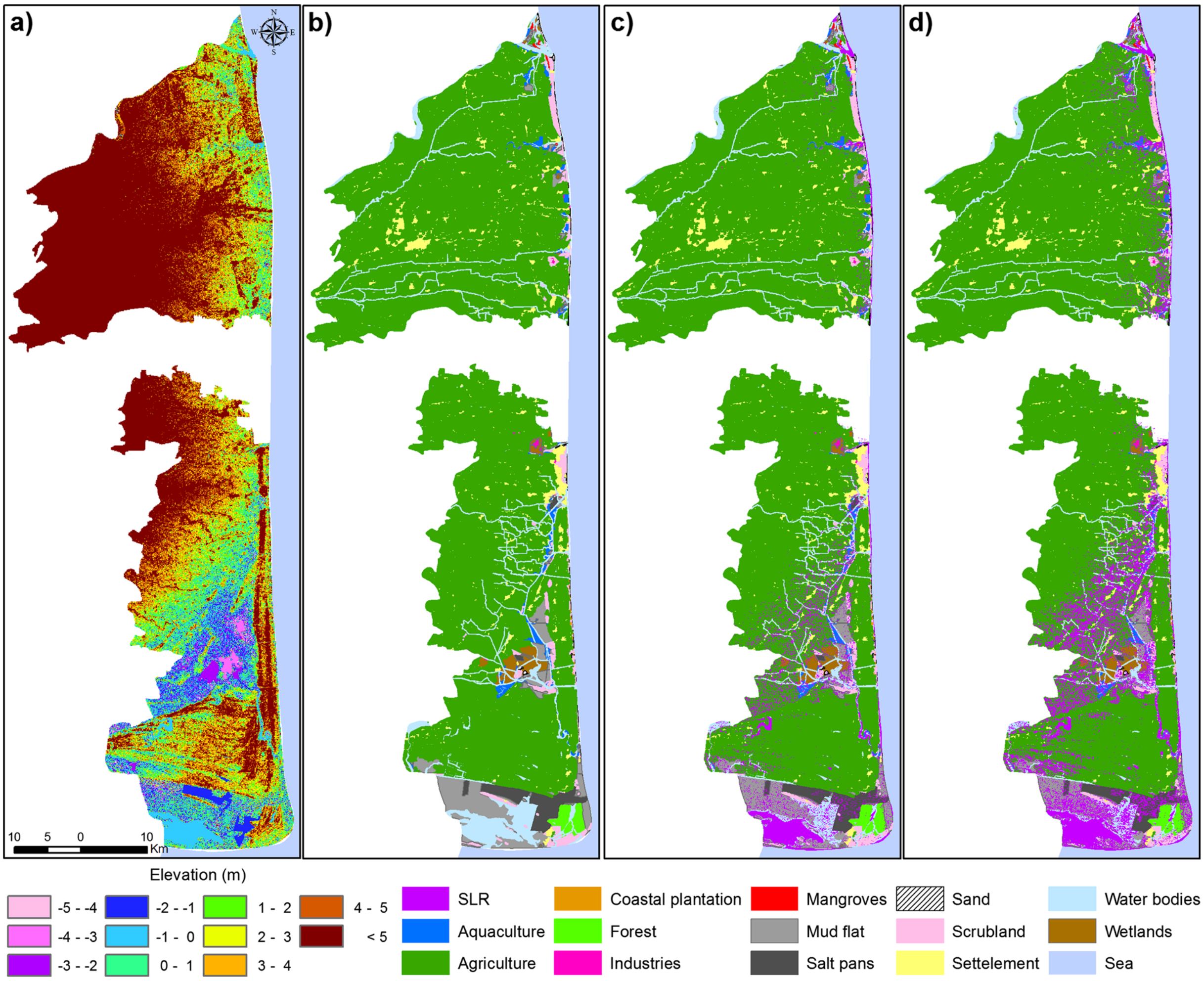

Fig. 5 **a** Elevation map based on SRTM data. **b** Land use and land cover map. **c** Inundation in study area due to 0.5 m SLR. **d** Inundation in study area due to 1 m SLR

1 m SLR. Mangroves can adapt to SLR to a certain extent by building up the soil (Spalding et al. 2014) but do not survive when the rate of SLR is more than the rate of sediment formation (Gilman et al. 2008). The Point Calimere wild life and bird sanctuary forest land of 44 and 139 ha, accounting 2.71 and 8.81%, will be inundated to the projected scenarios of 0.5 and 1 m SLR. In addition, wetlands of 441 and 875 ha are likely to be inundated due to rising sea level at 0.5 and 1 m. Of aquaculture farm lands, 573 and 1403 ha out of 3899 ha is likely to be submerged due to 0.5 and 1 m SLR, representing 14.7 and 35.98% of the aquaculture area. *Litopenaeus vannamei* and *Penaeus monodon* are the two shrimp species farmed using intensive aquaculture practices. *L. vannamei* is alien to Asia and cultured under controlled environmental conditions since 2009; hence, their exposure to the environment due to inundation of shrimp ponds may lead to potential establishment of the exotic species in the local environment. The exotic species will compete with the native species for food and may disturb the ecological integrity of the host ecosystem. The study area had 4408 ha of salt pans, out of which 526 and 1264 ha will be under water due to SLR of 0.5 and 1 m. The human settlement of 105 and 422 ha will be at risk.

The populations that live in this district and directly depend on these resources belong to villages of seven taluks namely Kilvelur, Nagapattinam, Sirkali, Thirukkuvalai, Tharangambadi, Vedaranyam, and Mayiladuthuri. The area of inundation in each taluk is given in Table 4. Out of 506 villages, 225 villages belonging to five taluks with a population of 829,350

Table 3 Extent of inundation in coastal resources at 0.5 m and 1 m SLR

S. No	LULC class	Area (ha)	Area of inundation at 0.5 m SLR (ha)	Area of inundation at 1 m SLR (ha)
1	Aquaculture	3899	573	1403
2	Agriculture	190,735	5455	15,552
3	Forest	1573	44	139
4	Industries	275	4	8
5	Mangroves	348	14	65
6	Mud flat	10,629	2299	4584
7	Salt pans	4408	526	1264
8	Sand	736	155	243
9	Scrubland	5951	501	1442
10	Settlement	23,687	105	422
11	Water bodies	13,028	4005	5321
12	Wetlands	3312	441	875
Total		258,581	14,122	31,318

(51.39%) and 272 villages belonging to six taluks with a population of 963,711 (59.62%) will be inundated to 0.5 and 1 m SLR, respectively. Among the villages likely to be inundated, the Vedaranyam taluk will be at major threat as 53 villages out of the total of 54 villages will face inundation. Thus, the fishing and farming communities of these villages who depend on the coastal natural resources are at high-risk.

Limitations of the study

We have used the SRTM 90 m resolution elevation data of 2011 for creating DEM that restricted the projection of SLR from 50 cm. More accurate information on extent of inundation can be obtained by the use of high-resolution elevation images like light detection and ranging (LIDAR) images, which are not available at present for the developing nations like India. Population data of 2011 was used in the study as the country updates the census data once in 10 years. Total population of inundated village was considered as the population at risk due to lack of sub village level census data, in spite of varying extent of inundation. We assess the impacts of SLR using existing patterns of land use, rather than trying to forecast their future conditions. However, absence of these data should not delay the impact assessment and initiatives to be taken to prepare the

Table 4 Coastal villages and population at risk due to SLR

Name of the taluk	Details of taluks			Inundation to 0.5 m SLR			Inundation to 1 m SLR		
	Number of villages	Area (ha)	Population	Number of villages	Area (ha)	Population	Number of villages	Area (ha)	Population
Kilvelur	55	27,777	138,474	29	1624	83,899	40	3930	102,642
Kuthalam	57	19,865	131,948	–	–	–	–	–	–
Mayiladuthurai	61	25,365	259,634	–	–	–	3	1	5782
Nagapattinam	87	31,283	282,784	42	563	204,918	51	2056	220,725
Sirkali	89	46,106	319,715	54	1034	189,728	65	2979	254,558
Tharangambadi	68	28,739	207,059	19	307	87,485	30	1314	114,026
Thirukkuvalai	35	14,728	60,771	28	1140	49,568	30	3769	52,226
Vedaranyam	54	64,713	216,065	53	9454	213,752	53	17,267	213,752
Total	506	258,581	1,616,450	225	14,122	829,350	272	31,317	963,711

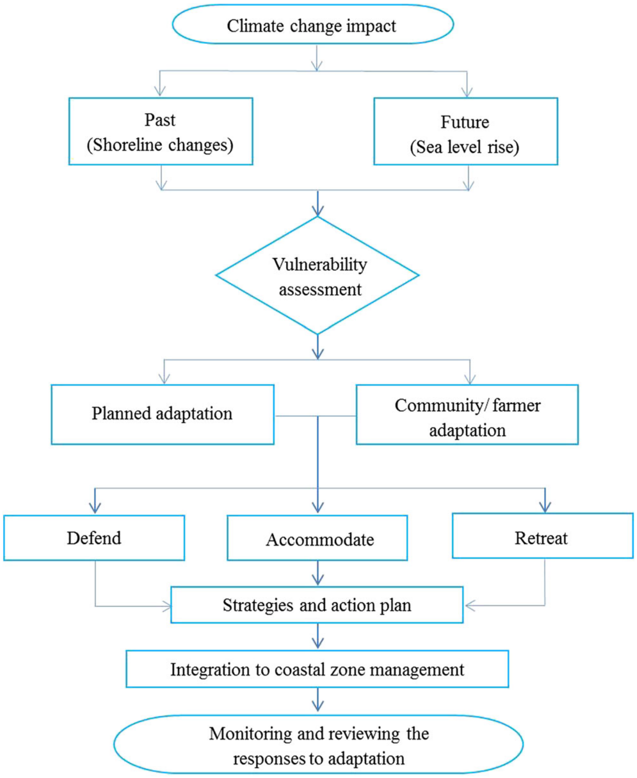

Fig. 6 Framework for the adaptation measures to the impacts of shoreline changes and SLR

low-lying densely populated coast of developing nations to face the challenges that arise from climate change.

Discussion

Assessment of past and subsequent changes to the coast due to climate change is necessary to understand and quantify the management measures for sustainability. Based on publically available satellite images and SRTM data, it has been shown that visualizing shoreline changes and submergence due to a near-future sea level rise is possible. Physical and ecological characteristics of the coast will be modified because of sea level rise, changes in shoreline, changes in precipitation, increasing frequency, and intensity of storms and consequences of climate change (Khan et al. 2012; Arnell and Gosling 2016). Using the Nagapattinam coast as a representative example of low-lying coastal areas in densely populated developing nations, the importance of impact assessment of past and future climate changes on coastal land has been demonstrated to identify the most vulnerable areas and also the appropriate adaptation measures. The coastal area used in the study has 9 m average elevation above mean sea level, indicating its low-lying nature. McGranahan et al. (2007) marked the area below 10 m elevation which is hydrologically connected to sea as low elevated zone. EPR and WLR methods indicated that the majority of the study area has undergone erosion and registered a net shoreline landward movement of 85.8 m in 37 years. The changing shoreline trend observed varies at different time periods. The shorelines from 1978 to 2003 eroded at a faster rate compared to other periods of the study. The erosion occurred due to regular shoreline occurrences such as waves, tides, and storm surges and was amplified due to the sandy nature of the soil, which makes it easily susceptible to erosion. We are able to identify the high eroded transects at different timescales of study. The high-erosion regions require immediate adaptation measures not only to protect the beach but also to save the socioeconomic life of the inhabitants of vulnerable areas. The findings of our study indicated that the changes in shoreline positions in the recent past are supportive to a certain level in accepting the shoreline response to potential sea level rise. IPCC fifth assessment report indicated that low-lying areas will gradually experience adverse effects such as submergence, coastal flooding, and coastal erosion due to climate change. Exact demarcation of inundation areas is a tough task due to the continuously changing shoreline and nearby geography by several coastal processes. The inundation susceptibility of a certain segment of coastlines to flood or SLR over different timescales depends not only on environmental factors such as elevation above mean sea level, geomorphology, coastal slope, historic coastline modification rate, wave height and range, rate of greenhouse gas emissions, rate of SLR but also on the socioeconomic vulnerability to adopt protective and mitigative measures (Pilkey and Cooper 2004).

Small changes in sea level will have huge impact on the coastal zones which are low lying and hence would be exposed to faster erosion and shoreline change (Pye and Blott 2006). The increase in sea level will continue for several decades even in the absence of future variations in atmospheric composition because of the changes that have already occurred (Wigley 2005). East Asia and the Pacific (EAP) region faces the maximum potential economic loss due to climate change impacts on wetlands (Blankespoor et al. 2012).

In this case study, the shoreline changes had a major impact on three coastal resources namely, mudflat and sand and scrub lands, which resulted in total land loss of 849 ha. The movement of shoreline will indirectly disturb the other land use due to sea water inundation towards landside and may cause flooding during storm surge and cyclones. The study indicated that inundation projected due to sea level rise had a larger impact on agriculture, aquaculture, wetlands, mangroves, forest, and human settlements in the Nagapattinam district. The forests and wetlands particularly Point Calimere wild life sanctuary in the district, responsible for conserving biodiversity and sustaining local livelihoods may be lost in future.

The study indicated that SLR is likely to affect agriculture more than other activities. To cope with the changing scenario, there is a need for adaptation planning at government and community levels. Introducing salt-tolerant crops, short-duration varieties, changing crop calendar, adopting comprehensive farm insurance scheme, and developing exclusive disaster support program will help the agriculture farmers. Aquaculture farms in the district are facing flooding and crop loss during heavy rains and cyclones. A few adaptation measures are already being followed in aquaculture. As the district is climate hazardous, a section of farmers have adopted modification in farm design with recirculation canals around the farms. Proper farm design with strong periphery bunds can reduce the potential long-term problems in flood-prone areas, but most of the existing aquafarms in Nagapattinam district did not have designs to prevent flooding. On earlier occasions, intervention by the integration of farm water recirculation and reservoirs into aquaculture farm's design in the district not only protected the farms from the adverse impacts of flooding but also significantly reduced the need for external water sources for water exchange (Jayanthi et al. 2017a). The farm recirculation canal around the ponds with an elevation below the ground level helps to hold the water during heavy rains for future use in aquaculture farms. Engineering structures with proper design and implementation can help to manage the shoreline changes and SLR (Jayanthi 2011, Williams et al. 2016). In addition, the Pacific white shrimp, *Litopenaeus vannamei* (dominant shrimp species being cultured in India), can sustain the water salinity up to 50 ppt (Perez-velazquez et al. 2007); hence, aquaculture can be an alternative livelihood option to make use of affected/unutilised agriculture lands. During the ground truth verification, the farmers have also stated that aquaculture farms get inundated even in case of heavy rains for shorter duration and suggested for regular desilting and deweeding the canals for free flow of the rain water and the same was recommended in the comprehensive district level planning recommendations to Government of Tamil Nadu (Jayanthi et al. 2017b).

Barriers and buffers along the coasts can be an effective risk reduction measure against gushing waters. The massive casuarina shelterbelt raised by the Tamil Nadu Forest Department for a distance of about 12 km in the study area can be considered as a proven model of coastal protection. Local people perceive that the natural sand dunes in South Poigainallur village of Vedaranyam taluk with a length of 6 km and height of 20–30′ have protected the village during the Tsunami in 2004, whereas the other coastal villages were affected to a larger extent.

The study indicated the loss of mangroves due to shoreline changes and SLR in the future. Formation of sand spits due to shoreline changes in the mouth region can decrease the tidal water inflow into mangrove land, which can reduce its extent. Researchers have indicated that SLR and reduced rainfall or freshwater flow can increase the stress on mangroves (Alongi 2008; Ellison 2015). It is known that *Avicenia* species can tolerate high salinity variation (Ball 1988). Landward side zonation by constructing the canal for freshwater inflow in mudflats (Selvam et al. 2002) can be a planned adaptation.

As the shoreline is eroding in most of the transects in the study area, a better option for adaptation will be involving the local communities to plant and maintain the mangroves in the suitable areas along the coast to enhance the accretion through root mat growth and sediment trapping in root systems. The mangrove response to changes in the shore depends on species ability to colonize the new habitat at a rate that keeps pace off with the rate of SLR and the rate of sediment accretion (Duke et al. 1998). Land use near shore regions and prevailing environmental conditions such as hydrology and sediment composition determines the capacity of mangrove to grow landward (Gilman et al. 2008).

We identified the highly eroding transects due to shoreline changes and also calculated that more than 50% of the population in the study area will be affected with 0.5 m SLR itself. Vulnerability can be reduced by further enhancing local communities to accommodate the climate change impacts by changing their practices to suit the environmental modifications (Shackley and Deanwood 2003). The risk of adverse outcomes from projected climate change can be reduced through adaptation activities incorporated into coastal zone management plan, as an attempt to increase the resistance and resilience to climate change stressors. Adaptation options may vary from short term to long term, planned adaptation to the community level or individual level adaptations based on the environmental conditions, the timing of the management, and the geographical location. Considering the low-lying nature of the study area and predicted extent of inundation, three strategies can be used to reduce the impacts of shoreline change and SLR (Fig. 6): (1) retreat (e.g., creating setback zones, banning new development in areas likely to be inundated, relocating the buildings and discontinuing the growth in risky regions), (2) accommodate (e.g., changing the farm design, varieties, crop calendar), and (3) defend (e.g., barriers or shelters, reducing greenhouse gas emissions). We recommend to have combination of plans and community/individual adaptation to face the impacts of shoreline changes and SLR. Defending and accommodating the climate change impacts will be better for the developing nations with high population as they have to manage the competing space need for livelihood and also development. Common constraints on implementation arise from limited financial resources, lack of transparency in implementation and monitoring, absence of public participation, and lack of integrated coastal zone management and different opinions of risks. The anticipated increase of SLR in response to continuing climate change will worsen the vulnerability of many low-lying densely populated coastal regions of the world.

Conclusion

The main theme of the study was to assess changes in the shoreline positions in the past and also the likely scenario in the future to derive the coastal adaptation measures to protect the low-lying coastal region. Multi-temporal satellite data, GIS, and DSAS were used to assess the rate of shoreline changes that occurred and the expected extent of inundation due to projected SLR and to indicate the vulnerability of the coastal zones and the population at risk. Though this study covers this particular coastal region, it can be taken as a representative finding of likely threats of climate change for low-lying regions of developing countries. National-level, large-scale studies can picture the overall impact due to changes in the coast but may not present the susceptibility of disaster-prone regions. The result of this study reveals that more studies are required to identify overall consequences for discrete vulnerable provincial regions at the national level to enable the policy makers and coastal zone managers to identify the hotspots and plan for suitable adaptation measures with integrated coastal zone management.

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