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Coastal vulnerability assessment of Vedaranyam swamp coast based on land use and shoreline dynamics

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Abstract

In the recent decades, the 60-km coastal stretch of Vedaranyam swamp located in the southern coast of Tamil Nadu is identified as a major 'Vulnerable Hotspot', due to increased land-based infrastructures and associated episodic hazards including floods attributable to heavy rain, cyclones, storm surges, earthquakes and tsunami. In order to assess the impact of the land use/land cover changes (LULC) on the historical shoreline of this geographical area, vulnerability study between the periods 1978, 1998 and 2017 was attempted. The LULC change analysis from 1978 to 2017 indicated significant increase in aquaculture farms, salt pans and settlement areas upon conversion of crop lands, mudflats, coastal dunes and scrub lands especially along the coast. The end-point rate resulting from the shoreline analysis over the study period showed evidences of accretion and erosion ranging from 9.93 to -2.28 m year^{-1} while the net shoreline movement transects about -107.79 to 382.71 m, respectively. Changes in the land uses and shoreline dynamics of the study area were considered as key parameters for the vulnerability assessment of this coast. This analysis will help to create awareness among the people about impacts of land use changes and effects of natural hazards such as coastal erosion, inundation and their consequences which includes loss of life and properties. The stress driving vulnerability parameters, namely sea-level rise, relief, wave exposure, surge potential, were considered for calculating the vulnerability index of the 60-km coastline considered for the study. The outcome of the study indicates that about 6 km of the coast is very highly vulnerable, 45 km is highly vulnerable, and 9 km is moderate vulnerable to episodic natural hazards.

Keywords Land use/cover · Erosion · Accretion · Sea-level rise · Coastal vulnerability

1 Introduction

Coastal zone is a dynamic connection of land and sea. Globally, most of the coastal zones exhibit erosion of different magnitude due to growing human populations, which is linked to land use changes (Williams et al. 2009), besides rapid growth of commercial activities

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such as aquaculture farms, salt pans, tourism activities, ports and harbours (Gowing et al. 2006). Land use/cover modification can have major detrimental impact on terrestrial and aquatic ecosystems (Lambinet et al. 2000; Tilman 1999), which in turn could influence the human population. Extensive studies have been conducted especially in the last few decades in this aspect (Cochard et al. 2008; Arkema et al. 2013; Nel et al. 2014; Spalding et al. 2014; Narayan et al. 2016). A Digital Shoreline Analysis System (DSAS) applied on mangrove shoreline changes along the Giao Thuy Coastal area (Nam Dinh, Vietnam) during 2005–2014. The results showed that mangrove area increased to about 2487 hectares during the years from 2005 to 2014 (Thinh and Hens 2017).

Linking these land-based changes with the shoreline changes, with the help of significant tools like remote sensing and GIS techniques, could be an effective step towards the better regulation and management of the coastal region. This paper attempts to study the LULC on a multi-decadal scale and correlating it with the long time shoreline changes in the Vedaranyam swamp coast located along the southern Tamil Nadu. DSAS is a multivariate tool, used to assess and quantify the erosion/accretion range of the coast Thieler et al. (2009). In worldwide, studies has been carried out for the coastal vulnerability assessment using coastal slope, coastal geomorphology, shoreline change rate, tidal height and wave height for different maritime places such as Italy (Pantusa et al 2018), Ghana (Addo 2013), Barcelona (Koroglu et al. 2019) and USA (Arkema et al. 2013). In India, Andhra Pradesh (Ahammed et al. 2016), Karnataka (Jana and Hegde 2016), Orissa (Kumar et al. 2010), Kerala (Mohan and Jairaj 2014), Maharashtra (Vidya et al. 2015) and Nagapattinam, Kanyakumari and Tuticorin of Tamil Nadu (Natesan et al. 2015; Joevivek et al. 2013; Mageswaran et al. 2015; Rajan et al. 2019).

Almost all of the world's shorelines are undergoing erosion (retreating landwards), and this has been attributed to various factors, among which rising sea level is considered as the underlying driver. Beaches erode laterally much faster than sea-level rises vertically. Higher water levels cause coastal inundation, for example, of wetlands; however, in the case of beaches, 90% during the shore recession is due to erosion, which is technically defined as the physical removal of material from the beach. Coastal erosion rates are about 100 times the rate of sea-level rise (SLR), which means every millimetre of SLR results in 10 cm of beach erosion (Leatherman et al. 2003; Nunn et al. 2017). The composite vulnerability parameters provided the useful metrics for evaluating the vulnerability of this coastal region. Identification of vulnerable areas plays a crucial role in risk reduction. The InVEST model has been applied for evaluating coastal vulnerability and to inform spatial planning among others (Arkema et al. 2013).

2 Study area

Vedaranyam swamp coast is situated at the southern portion of the coastal districts of Nagapattinam and Thiruvarur in Tamil Nadu. The unique characteristics of the coast is that it is the only coast aligned perpendicular to the country's east coastline. The study area encompasses large wetland complex, comprising of mangroves, mudflats, reserved forest, tidal creeks and lagoon embedded with salt pans and aquaculture farms (Fig. 1). The swamp land in Muthupet lagoon is the main tourist attraction in Thiruvarur district, and the Point Calimere wildlife sanctuary at Kodiyakarai in Nagapattinam district is a protected area for endangered and endemic species of India. The study area also includes archaeological and heritage places such as Ramar Padam, Modi Mandapam and old Chola lighthouse.
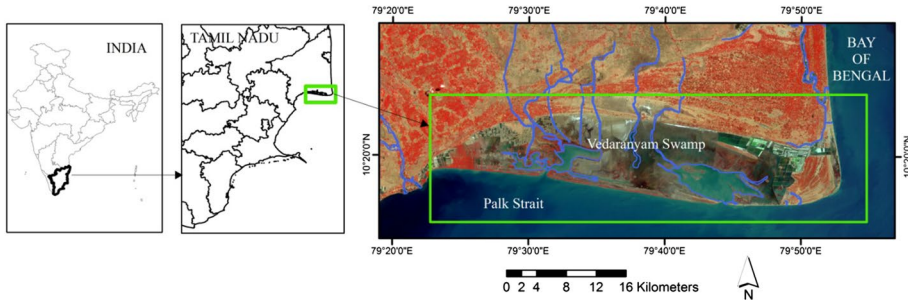
Fig. 1 Location map of the Vedaranyam swamp

The distributaries of Cauvery, namely Paminiyar, Koraiyar, Kandaparichanar, Kilaithangi-yar and Marakkakoraiyar, discharge their waters into the wetlands and form a large lagoon before reaching the sea.

3 Methodology

Remote sensing and GIS techniques were used for extracting coastal land use/cover and Digital Shoreline Analysis System (DSAS) model for long-term shoreline changes for a period of 39 years from 1978 to 2017 for the study. The satellite images of 1978, 1998 and 2017 were georeferenced using ERDAS Imagine software and transformed to UTM projection, WGS 84 in Zone-43 N. Land use/land cover map for the Vedaranyam swamp coast was mapped up to the landward extent of ecologically sensitive areas. Visual interpretation using standard interpretation elements was carried out based on Level III land use/land cover classification scheme adopted by Space Application Centre (SAC). Vectorization and coding of land use/land cover layers were prepared using ArcGIS software.

Shoreline change evaluations are based on comparing three historical shorelines extracted from satellite imageries for the time period and limited field surveys. Shoreline indicators for multi-date satellite images were used to extract the wet/dry line, vegetation line and artificial structures using ArcGIS. After the extraction of the shoreline from satellite images, the DSAS model developed by the USGS in ArcGIS software was used to calculate the rate of shoreline movement. In order to calculate the rate of change statistics, the baselines were constructed landward side for a distance of ~1 km adjacent to the series of shoreline positions. Orthogonal transects to the baseline at 300 m interval were generated using DSAS model. The end-point rate (EPR) method for calculating the rate of shorelines change was categorized into seven classes, namely erosion, accretion and stable. EPR statistics is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and most recent shoreline. The major advantage of the EPR is the simple calculation and minimal requirement of 2 shoreline dates. End-point rate = (distance in metres)/(time between oldest and most recent shoreline).

The coastal vulnerability index (CVI) is derived from a combination of seven relative risk variables to generate a single indicator using InVest model. According to that, the square root of the variables vulnerable parameters is divided by the total number of variables and is described below,

$$\text{CVI} = \left(R_{\text{Geomorphology}} * R_{\text{Relief}} * R_{\text{Habitats}} * R_{\text{SLR}} * R_{\text{WindExposure}} * R_{\text{WaveExposure}} * R_{\text{Surge}} \right)^{1/7}$$

LULC features and historical shoreline rates were used for assessing the impacts of coast, and seven risk variables such as geomorphology, natural habitats from LULC layers, shoreline change rate, sea-level rise (SLR), relief, wave exposure, surge potential were used to create vulnerability index. The following parameters have been used to derive the CVI:

1. Wind, wave and storm surge (global) generated from the WAVEWATCH III model
2. Relief from SRTM 30 m (country-specific).
3. Sea-level rise (projected up to 2100)—[Country-specific: NCSCM-Survey of India Data].
4. Shoreline dynamics (1978 to 2017).
5. Geomorphology and decadal changes of land use [e.g. Mangrove, Reserved Forest, Coastal dune have been interpreted from Landsat Satellite images];

Vulnerability index status of the coastal region and vulnerability rank are derived by acquiring, analysing and processing the data from the InVest model and GIS databases. CVI values are classified into four different categories (low vulnerability, moderate vulnerability, high vulnerability and very high vulnerability) using percentiles as limits.

4 Ranking for coastal vulnerability index

The model computes the physical exposure index by combining the ranks of the seven biological and physical variables at each shoreline segment based on a mixture of user- and InVEST model-defined criteria. (Sharp et al. 2015). This model calculates a coastal vulnerability index by combining the ranks of seven bio-geophysical variables for every shoreline segment: shoreline change, the extent of coastal ecosystems, wind and wave exposure, sea-level rise and relief. Ranks vary from very low vulnerability index (rank = < 1.5) to very high vulnerability index (rank = > 4.5) (Tables 1 and 2). Geomorphology and natural habitat rankings were adopted using the ranking scheme suggested by the InVEST user guide which is similar to the one proposed by Hammar-Klose and Thieler (2001). The thematic layers land use/cover (LULC), geomorphology, erosion/accretion status and physical parameters were overlaid using the assigned weightages in ArcGIS software, and furthermore, the summation of weightages was grouped into five classes for ranking the coastline.

5 Result and discussion

5.1 Land use/cover changes

Historical changes of shoreline and land use/cover (LULC) were found to adversely influence the wellbeing of the Vedaranyam swamp coast. Increasing density of human population and their associated livelihoods such as intensive aquaculture and salt pan activities along the coast were identified as the major causes for coastal zone instability from the study. The assessed land use/cover (LULC) changes for the years 1978, 1998 and 2017 using satellite datasets of Landsat TM, ETM are shown in Figs. 2 and 3. Table 3 indicates the spatial changes of LULC of the coast.

Table 1 Weightage of coastal vulnerability index criteria. *Source*: Sharp et al. (2015), Gornitz (1990) and Hammar-Klose and Thieler (2001)

Rank	Very low	Low	Moderate	High	Very high
Variable	1	2	3	4	5
Geomorphology	Rocky; high cliffs; seawalls	Medium cliff; indented coast, small seawalls	Low cliff; Alluvial plain, rip-rap walls	Beach; estuary; lagoon	Barrier beach; sandy beach; mud flat; delta
Land use and human activities	Coral reef; mangrove; coastal forest scrub land	Salt marshes, dune vegetations, vegetations	Low dune, sea grass	Scattered villages, agricultural lands, salt pans	No habitat
Shoreline change (m year^{-1})	≥ 5	2 to 5	2 to −2	−2 to −5	≥ -5
Relief, sea-level change, wave exposure, surge potential	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile

Table 2 Ranking of coastal vulnerability index

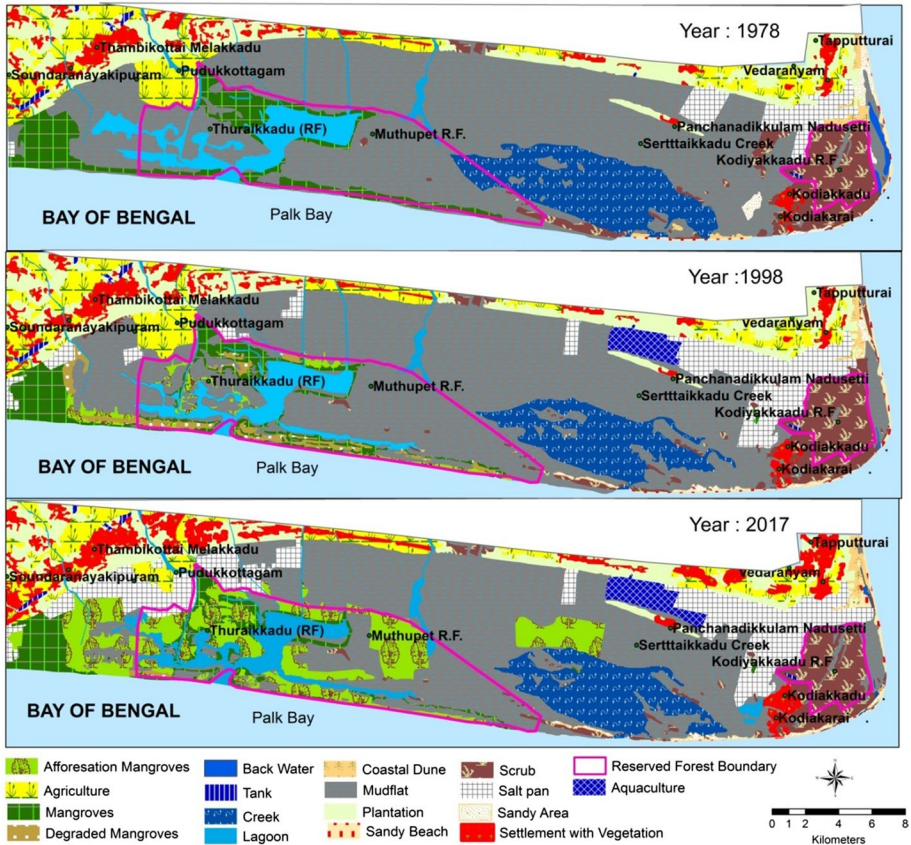| Coastal vulnerability index		
If values	< 1.5	Very low vulnerability
	1.5 to 2.5	Low vulnerability
	2.5 to 3.5	Moderate vulnerability
	3.5 to 4.5	High vulnerability
	> 4.5	Very high vulnerability

Fig. 2 Land use/cover mapping for Vedaranyam swamp coast

Agricultural land which covered a total area of about 98.15 km² of the land in 1978 has indicated that 17% and 15% decrease in 1998 and 2017, respectively, assumed to be the result of expansion of settlement areas and salt pans. Settlement areas increased from 21.65 km² to 30.35 km², and salt pans showed a giant growth of 41.68 km² between 1978 and 2017. Scrub lands were no exception for human habitation as indicated in Table 3. Vedaranyam region is a swamp area with mangrove forest cover as the main natural resource. One of the major indications of the study is the conversion of mangrove forest
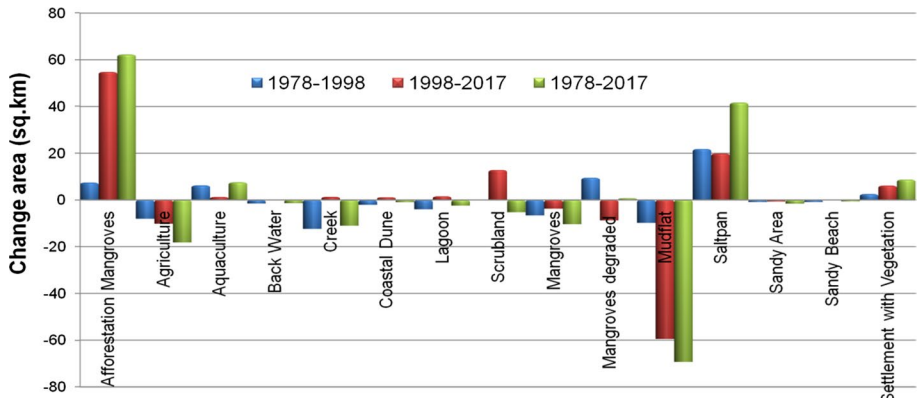
Fig. 3 Land use/cover change area for Vedaranyam swamp coast

Table 3 Land use/cover change area statistics

Land use/cover classification	1978	1998	2017	1978–1998	1998–2017	1978–2017	1978	1998	2017
	Change area (km^2)						Area (%)		
Afforestation Mangroves	–	7.46	62.26	7.46	54.80	62.26	0.00	1.36	11.36
Agriculture	98.15	90.12	79.98	− 8.03	− 10.14	− 18.17	17.91	16.42	14.59
Aquaculture	0.19	6.46	7.74	6.27	1.29	7.55	0.03	1.18	1.41
Back water	1.66	0.15	0.33	− 1.51	0.18	− 1.33	0.30	0.03	0.06
Creek	44.55	32.17	33.52	− 12.38	1.35	− 11.03	8.13	5.86	6.12
Coastal dune	3.69	1.62	2.78	− 2.07	1.16	− 0.91	0.67	0.29	0.51
Lagoon	23.58	19.61	21.18	− 3.97	1.57	− 2.40	4.30	3.57	3.86
Scrubland	33.75	33.59	28.51	− 0.16	12.83	− 5.24	6.16	6.12	5.20
Mangroves	31.54	24.93	21.18	− 6.62	− 3.74	− 10.36	5.75	4.54	3.87
Mangroves degraded	–	9.49	0.74	9.49	− 8.75	0.74	0.00	1.73	0.14
Mudflat	259.37	249.58	190.1	− 9.79	− 59.49	− 69.28	47.32	45.47	34.69
River	6.37	5.88	5.88	− 0.49	− 0.01	− 0.49	1.16	1.07	1.07
Salt pan	15.46	37.26	57.13	21.80	19.88	41.68	2.82	6.79	10.43
Sandy area	3.63	2.76	2.08	− 0.87	− 0.68	− 1.55	0.66	0.50	0.38
Sandy beach	3.31	2.46	2.70	− 0.84	0.24	− 0.60	0.60	0.45	0.49
Settlement with vegetation	21.65	24.19	30.35	2.55	6.16	8.70	3.95	4.41	5.54
Total area	546.90	547.72	546.46				100	100	100

areas into salt pans, aquaculture farms and tourists amenities. The Salt Corporation of the Government of India owns 13 out of the 14 salt pans, whereas the Tamil Nadu Salt Corporation Ltd., owns one salt pan (ICMAM 2005). The salt pans located on the western part of the Muthupet mangroves wetland draw seawater from the Palk Strait through canals for salt production. Increased salt pan area in the region between 1978 and 2017 is about

19.88 km^2. The spatial extent of aquaculture farms increased from 0.19 to 7.74 km^2 during the period of 1978–2017. These activities resulted in decrease of mangrove areas from 31.54 to 21.18 km^2 from 1978 to 2017, while 10.36 km^2 resulted in failure due to increasing infrastructure, namely salt pan, and aquaculture and tourism activities. However, degraded mangrove reduced after this gradual increase in planted mangroves (afforestation mangroves) by the Tamil Nadu Forest Department.

In view of such constraint, the Tamil Nadu Forest Department and other public and private institutions undertook afforestation and reforestation of mangroves since 1998 all along the lagoon area. Of the total afforestated/reforested mangrove areas of about 62.26 km^2, new mangrove areas of about 21.18 km^2 flourished as on 2017 indicated by the study. Afforested areas included mudflats also which caused a 35% decrease in total mudflat extent in the study area as of 2017. Siltation of tidal openings has decreased the spatial extent of the water bodies to 11% over the years. Prolonged siltation has converted most of the lagoon areas as dry salt-affected areas, and along with increased aquaculture and salt pan activities, the area has become non-suitable for mangrove ecosystems over the years (Lieth and Al Masoom 1993; Noor et al. 2015). The sediment-based morphological features such as sand dunes and sandy areas including sandy beach indicated a 0.91 km^2 and 2.15 km^2 loss in the last four decades, respectively. The water body along the coast includes lagoon, creek, backwater and rivers covering 14% of the total area.

5.2 Shoreline changes

The historical shoreline change statistics were calculated from the end-point rate (EPR) and net shoreline movement (NSM). NSM gives the distance between the oldest (1978) and the youngest (2017) shorelines, denoting the net horizontal movement of the shoreline with respect to time and EPR calculates the rate of change. The study reveals that the mean rates of shoreline change vary from -1.97 to 18.16 m year^{-1} (end-point rate) and -43.05 to 369.07 m NSM (net shoreline movement). EPR result showed that 80% of the coast is accreting in nature at the rate of about 7.68 m year^{-1} and 18% of the coast undergo erosion at about -1.53 m year^{-1}, while 2% of the coast is stable (Figs. 4 and 5).

Vegetated areas such as Thuraikadu RF (Reserved Forest), Muthupet RF, Kodiyakarai and Vedaranyam recorded high accretion rates, while Serttaikadu creek and Kodiyakadu RF in the lagoon recorded severe erosion due to tidal influence and a cumulative effect of the physical parameters such as wind, wave and sea-level rise.

The coastal stretch from Narasingapuram to Muthupet RF shows accretion due to the formation of dense mangrove and coastal dunes along the coastline, while coastal stretch north of Muthupet to Vedaranyam shows patches of erosion of different magnitude mainly due to seasonal opening and closure of lagoon mouth on either ends (Fig. 6a).

5.3 Changes in vulnerability parameters

In the recent decades, the coastal stretch of Vedaranyam swamp is considered as a major 'Vulnerable Hotspot', due to episodic hazards, namely Tsunami (2004), Nisha (2008), Thane (2011), Nilam (2012), Mahasen (2013) and Gaja Cyclone (2018) and increased land-based infrastructures and associated landforms. The result revealed that the study area faces severe threat due to rapid changes in alteration of geomorphological features, shoreline changes, sea-level change, wind, wave exposure and associated storm surge. Coastal vulnerability index (CVI) was calculated as the square root of the product of the
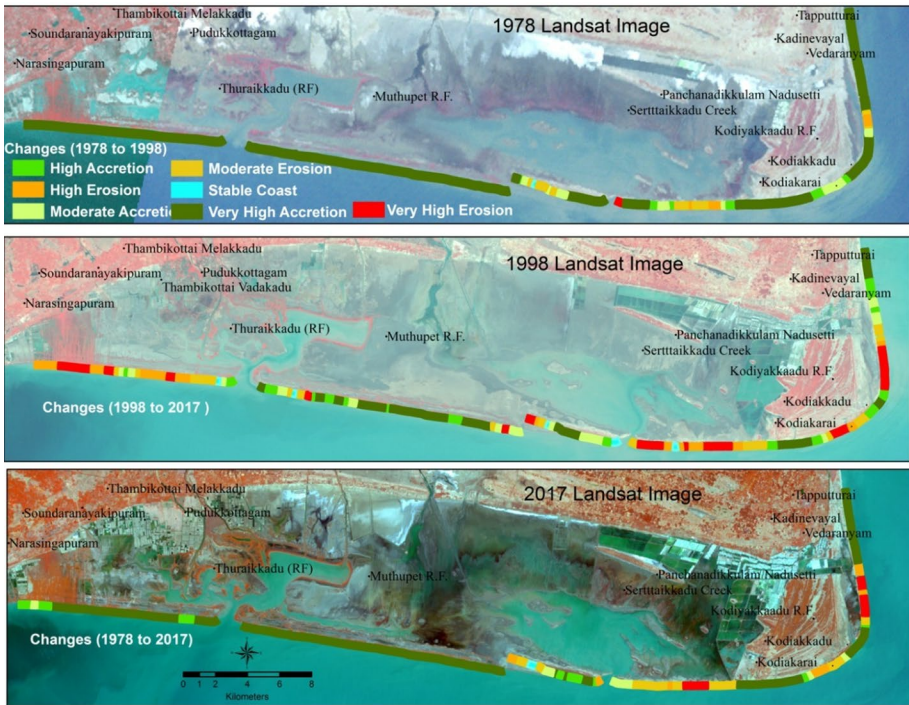
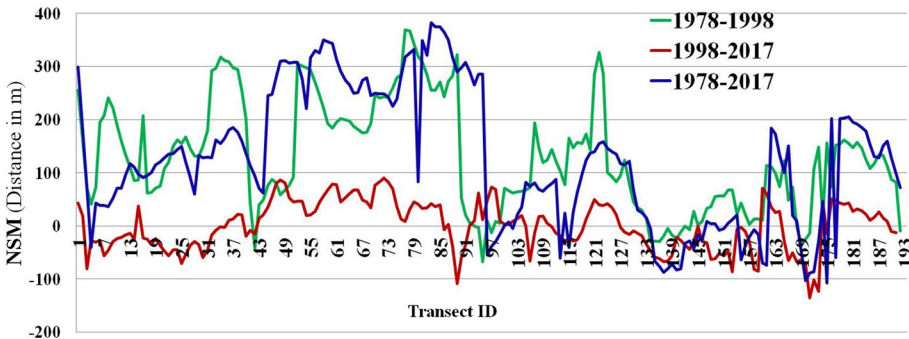**Fig. 4** Erosion/accretion mapping for Vedaranyam swamp coast

Fig. 5 Net shoreline movement (NSM) trend for Vedaranyam swamp coast

ranked variables divided by the total number of variables. The results of Vedaranyam swamp coast experience periodic coastal flooding due to extreme storm surges, as well as storm surges riding over tides and cyclones. Significant changes were found in Serttaikadu creek due to equally contributed all physical parameters and seasonal opening of the lagoon mouth. (Table 4 and Figs. 6a and 7). The sea-level rise is a major phenomenon that combines global and regional processes that affect climate change-induced coastal vulnerability along the coastal region (Unnikrishnan and Shankar 2007). Therefore, storm surge inundation damages the soil through penetration of saltwater into the
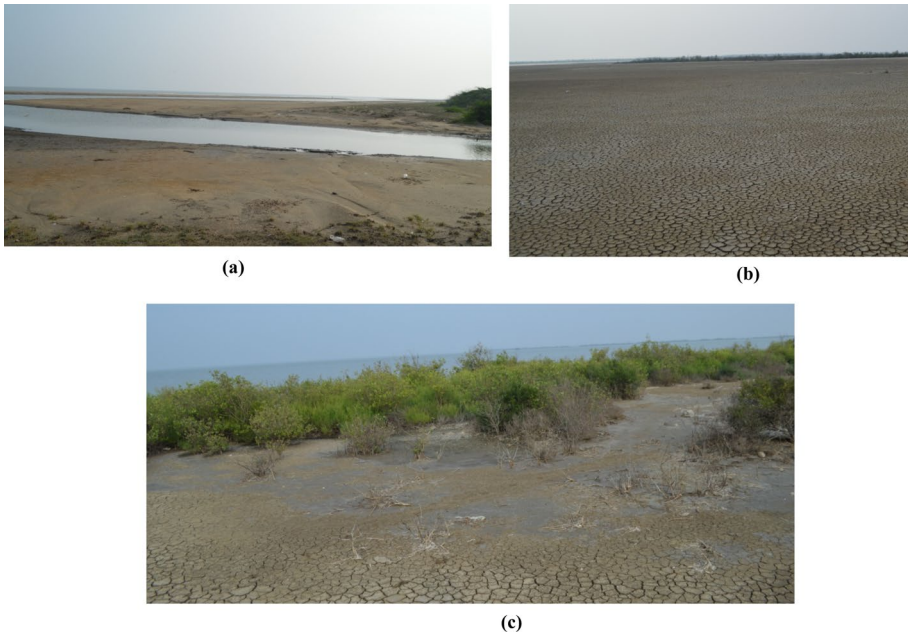
Fig. 6 **a** Very high vulnerability site at Serttaikadu creek due to tidal influence and a cumulative effect of the physical parameters. **b** Sun-dried mudflats, crackled and punctuated by salt pan at Muthupet area. **c** Afforestation mangroves affected by Gaja cyclone 2018
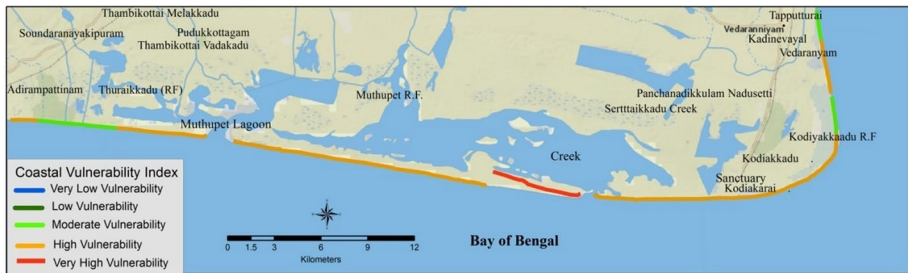

Fig. 7 Vulnerability map for Vedaranyam swamp coast

coastal upper water level and extents to agricultural and coastal ecosystems along the coastal stretches (Fig. 6a–c).

5.3.1 Identified risk zones

The results revealed that the accreting coastline in 1978 was higher than those in 1998 and 2017, as a consequence of conversion of natural ecosystems to human induced activities. Therefore, the seven key indicators were ranked from very low vulnerable to very high vulnerable coastal area (Table 2 and Fig. 7). The indices 'very high vulnerability' (>4.5), towards the southern part of Serttaikadu creek dominated by mudflat, salt pans and sandy

beach, indicate it as a very high erosion prone area and equally contributed all physical parameters.

Conversion of mudflats to salt pans and disturbances to coastal dunes are the major stress factors responsible for the 'very high vulnerable' status of this coastal stretch. The future sea-level rise along the coast may further worsen the stability of this coast (Rani et al. 2015). Beside this, most of the coastal stretches such as Adirampattinam, small stretches of Muthupet lagoon and northern part of Kodiyakarai and Vedaranyam region were assessed as high vulnerable (3.5 to 4.5) areas. Thus, it is evident that the depletion of the coastal natural resources plays a dominant role in high and moderate erosion stretches and highly exposure of physical parameters. As a consequence of rapid depletion of these natural resources, the Vedaranyam coast is vulnerable to numerous disasters such as tropical cyclones and storm surges. The Vedaranyam coast is vulnerable to several disasters like tropical cyclones and storm surges, and was also hit by the tsunami in 2004 due to the rapid depletion of natural resources; the local population of about 116,966 (2011 census) are affected by these hazards in the recent years (Pradeep et al. 2014).

5.3.2 Identified safe zones

The accreting coast of moderate vulnerability (2.5 to 3.5) was observed near Kodiyakadu, and Thopputhurai and Thuraikadu RF, which could be attributed to presence of dense mangroves, coastal forest and agriculture land. It is highly exposed to the sea-level rise and lower wave exposure and geomorphological changes. M. S. Swaminathan Research Foundation and the Tamil Nadu Forest Department planted mangroves in Vedaranyam swamp coast to about 62.26 ha from 1998 to 2017 according to multitemporal satellite images. This effort acts as ecological seawalls (i.e. mangroves), which can dissipate wave energy, beach nourishment, restore the natural properties of beaches and reduce the coastal vulnerability to erosion which may subsequently change the status of the coast from moderate vulnerability to low vulnerability.

6 Conclusion

Vulnerability assessment of Vedaranyam swamp coast to multihazards on the basis of land use changes, shoreline dynamics, geomorphology and physical parameters using weighted ranking method was attempted in the study. Understandings in view of vulnerability were the shifting land use practices, shoreline dynamics and physical parameters activities of the study. Major commercial activities such as salt pans, aqua farms and tourism spots along the coast in place of effective coastal natural protectors such as mangroves, natural and manmade plantations, dunes, sand areas and mudflats indicate an increasing trend of coastal erosion. The continuous natural hazards due to high exposure of sea-level rise, wind and wave activities and its impacts on the coastal zone have gradually changed the coastal stretches from Vedaranyam to north of Muthupet lagoon to different degree of vulnerability ranging from very high to high vulnerability. On the other hand, the coast south of Muthupet lagoon to south of Adirampattinam indicates a moderate vulnerability coast due to relatively less human interventions to the green corridors of the coast and small stretches of Tapputurai, Thuraikadu RF and Kodiyakadu RF observed moderate vulnerability due to agricultural plantation and forest area are protected from physical parameters effects.

This deteriorating coastline will affect the complex interaction of the coastal ecosystems, agricultural activities, habitations and combined action of waves, wind, variations in sea level, and storm affect the vulnerability to long term and further increase the vulnerability of the coast. Preservation of wetlands and non-conversion of agriculture, mudflat and scrubland into aquaculture and salt pans should be the prioritized actions to be taken for the sustainability of this swamp coast. Awareness programmes on the heritage of the coastal resources, environmental management, encouragement for afforestation mangroves activities, and raising environmental alertness with the local population may add support to protect the coast from further deterioration.

From coastal legal policies point of view, the Coastal Regulation Zone (CRZ) notification of 2011 and the recent CRZ notification 2019 may further strengthen the conservation of natural land forms in the coast and will prevent loss of life and property from increased storms, tides and floods. These regulations will result in positive, collaborative management and policy development for controlled and appropriate coastal activities which protects eroding/low lying areas and sensitive coastal resources including archaeological and heritage areas of the coast.

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