Environmental Earth Sciences (2019) 78:494
https://doi.org/10.1007/s12665-019-8463-1

ORIGINAL ARTICLE

# Impact assessment of sea level rise over coastal landforms: a case study of Cuddalore coast, south-east coast of India

**S. Dhanalakshmi**[1] · **R. S. Kankara**[1] · **S. Chenthamil Selvan**[1]

Received: 16 August 2017 / Accepted: 9 July 2019 / Published online: 3 August 2019

## Abstract

Densely populated south-east coast of India is susceptible to disasters such as tsunami, coastal flooding storm-surge and shoreline erosion. Apart from episodic events, the gradual sea-level rise (SLR) has got more attention to coastal researchers recently relating to the potentially impacted coastal zone, its anthropogenic/environment associations, and the possible future scenarios. Global average SLR rate has increased in recent decades from 1.7 mm year$^{-1}$ 1901 to 2010, 3.1 mm year$^{-1}$ from 1993 to 2003 and 3.12 mm year$^{-1}$ from 1993 to 2012. The present study is an aim to assess the impact of future sea-level rise along Pondicherry—Chidambaram coast using Bruun Rule and Modified Bruun Rule. Eight satellite-derived data sets were used to study the shoreline change trends during 1990–2015. 25 years of shoreline change trend reveals that ~49% of the coastline is under erosion. Shoreline retreat to an increase in local sea level was also mapped by Bruun Rule. Bruun Rule has some limitations, and hence Modified Bruun Rule was used to analyze the inundation factor. The horizontal inundation of the study area was estimated as ~1.1 km (Bruun Rule) and ~1.6 km (Modified Bruun Rule). The impacts of SLR in the study area were determined by integrating inundation data with geomorphological and land use/land cover data. The study reveals that about 16.08 sq.km area of geomorphological features is likely to be highly affected, while 17.5 sq.km of the area likely to be affected on land use/land cover features. This study provides an interactive means to identify the vulnerable zone. The output maps can be used to visualize the affected areas spatially.

**Keywords** Bruun Rule · Modified Bruun Rule · Shoreline change analysis · Digital shoreline analysis system (DSAS) · Sea-level rise · Impact assessment · GIS

## Introduction

Coastal zones are of great importance as zones of settlement and play a vital role in the economic well-being of many nations. The coastal regions are densely populated due to developmental opportunities such as ports, harbours, estuaries of ecological importance, monuments of international heritage, tourist locations and pilgrimage centers. The coastal hazards such as tropical cyclones, storm surges, sea-level rise, and coastal erosion expose more than 250 million people living within 50 km (Saxena et al. 2013). Many scientists consider global warming-forced climatic change as one of the most pressing environmental threat facing the world today (IPCC 2007). There is an increasing consensus that an accelerating sea-level rise (SLR) scenario due to climate warming will have significant impacts on the coastal zone (Marzeion et al. 2012; Church et al. 2013). The projected rise in sea level due to climate change will result in coastline receding worldwide through accelerated erosion impacting the inlets, rivers/estuaries mouths, lagoons, etc. (Cutter et al. 2003). Al-Nasrawi et al. (2018) have used the future sea-level rise of Intergovernmental Panel on Climate Change (IPCC) hydro-scenarios to assess its impact on the eco-geomorphic aspects of coastal ecosystems. Rising sea level also inundates low-lying areas, converts wetlands to open water, erodes beaches, exacerbates flooding and increases the salinity of estuaries and aquifers (FitzGerald et al. 2008). About 90% of the damage is due to the inundation of land by sea water (Dube et al. 2009). Therefore, the existence of tools to evaluate the potential influence of sea-level rise on the shoreline is of prime importance. Statistical modeling usually involves projecting historical shoreline changes in the future (NRC 1990; Fenster et al. 1993; Douglas et al. 1998).

---

✉ R. S. Kankara
kankara@nccr.gov.in

[1] National Centre for Coastal Research, Chennai 600100, India

The NRC (1990) refers to this approach as "Historical Trend Analysis." This response-based approach uses time as a surrogate for processes, and the coastal response is measured by trend delineation of historical shoreline positions. Leatherman et al. (2000); Zhang et al. (2004) expanded the concept that a direct relationship exists between sea-level rise and shoreline recession over centennial to decadal time scales only to meet resistance (Sallenger et al. 2000; Cooper and Pilkey 2004). At a time scale useful for long-term management purposes (50–100 years, e.g., Esteves 2014), quantitative approaches have been dominated by the Bruun conceptual model (Davidson-Arnott 2005) and to a lesser extent, by the inundation model or historical trend analysis (Brunel and Sabatier 2007).

Generically, vulnerability is a set of conditions and processes resulting from physical, social, economic and environmental factors that increase the susceptibility of a community to the impact of hazards (O'Keefe et al. 1976; Wisner et al. 2004; Adger 1999). In 2004 Indian Ocean tsunami, the northern part of Tamil Nadu coast, particularly the Nagapattinam–Cuddalore coast was severely affected due to the higher run-up heights of about 5.2 m in Nagapattinam, which could lead to inundation extending up to 800 m in some of the low-lying areas. The Cuddalore coastal belts often prove to be the hot spots of severe impacts associated with frequent inundation in low-lying areas due to extreme weather events which affect beaches, coastal properties, and community. (Nicholls and Cazenave 2010; EC 2005; EEA 2006; Klein et al. 2003). In recognition of risks, there is a need to develop methodologies to assess coastal vulnerability to ensure efficient hazard management and mitigation (Cooper and Mckenna 2008; McFadden et al. 2007). The study using Geomatic technology has brought out comprehensive information on the impact of projected sea-level rise of 1 m over a Cauvery deltaic coastal region (Saravanavel 2018). Hence, the present study is aimed to assess the present trend of shoreline changes along Cuddalore coast and estimation of shoreline retreat due to future sea-level rise (SLR) and its impact along the coast using remote sensing and GIS tools. The study provides an interactive means to identify the vulnerable zone, and the output maps can be used to visualize the affected areas spatially. Thus, the susceptibility of this region to natural hazards and their devastating effects highlights the need for an impact assessment.

## Geographical setup of the study area

The coastal stretch of the study area is about 82 km from Pondicherry on north and Chidambaram region on the south lies between 12°03′30″N and 79°33′55″E and 11°17′48″N and 80°05′52″E (Fig. 1). The total area of investigation is approximately 1675 km$^2$. The coastal zone is often affected by various coastal disasters (erosion, cyclone, storm surge, flooding, etc.). The coastline is a part of a massive concave coast. The coast experiences both north-east and south-west monsoonal seasons annually. The average elevation of the study region is 1 m (3 ft.) above mean sea level (Saxena et al. 2013). Gadilam and Pennaiyar rivers in the north, Vellar, and Coleroon in the south are the major rivers draining into the Bay of Bengal along the coast. All these rivers are ephemeral and carry floods during monsoon. They generally flow from west to east, and the pattern is mainly sub parallel. Ponniyar is one of the significant seasonal rivers which drain the northern part of the study area during monsoon (north-east monsoon). Large parts of the Cuddalore coast are low lying with a gentle slope which increases the vulnerability of the region (Murthy et al. 2006).

The study area mainly consists of Tertiary Cuddalore formation and recent alluvium deposits, whereas Archaean/Cretaceous rocks cover the western part. The rocks of this formation consist of argillaceous sandstone, pebble-bearing sandstones, mottled sandstone, ferruginous sandstone, grits, and clay beds and lignite. The absence of garnet grains helps to distinguish them from the older group of rocks. The "Mount of Copper west" of Cuddalore comprises mainly fragments of rounded quartz bounded by the ferruginous contact.

Geomorphic features are the prime responsible for coastal changes and play an important role in determining the impact of sea-level rise. Every landform offers a certain degree of resistance to erosion. For example, rocky coast and wave cut benches offer maximum resistance. On other hands, soft sandy beach, sand dunes, mudflats, etc., show the least resistant to sea-level rise. Thus, the study of geomorphology enables to identify the coastal areas vulnerable to hazards under present circumstances and is likely to become exceedingly susceptible because of global climate change. Satellite data (Resourecesat-2, LISS-IV sensor) was used for the interpretation of various geomorphic landforms in ArcGIS (version 10.3) environment. A detailed map of the geomorphological landforms of the region is shown in (Fig. 2). Some of the geomorphological features of study area are sandy beach (covers nearly 7.45 sq.km), beach ridges (33.04 sq.km), swale (25.206 sq.km), backwater (7.49 sq.km) pediment (494.09 sq.km), pedi-plain (700.21sq.km), etc.

Timely information about the changing pattern of land use/land cover plays a significant role in land use planning and sustainable land development. Therefore, it is necessary to understand the area of land use/land cover patterns affected by natural calamity such as sea-level rise. Visual interpretation technique was adopted for demarcating the land use/land cover features of the study area. The land use/land cover features were manually digitized for the entire study area using satellite image (Resourcesat-2, LISS-IV sensor) (Fig. 3). Some of the features interpreted are mudflats (120.12 sq.km), salt pan (45.91

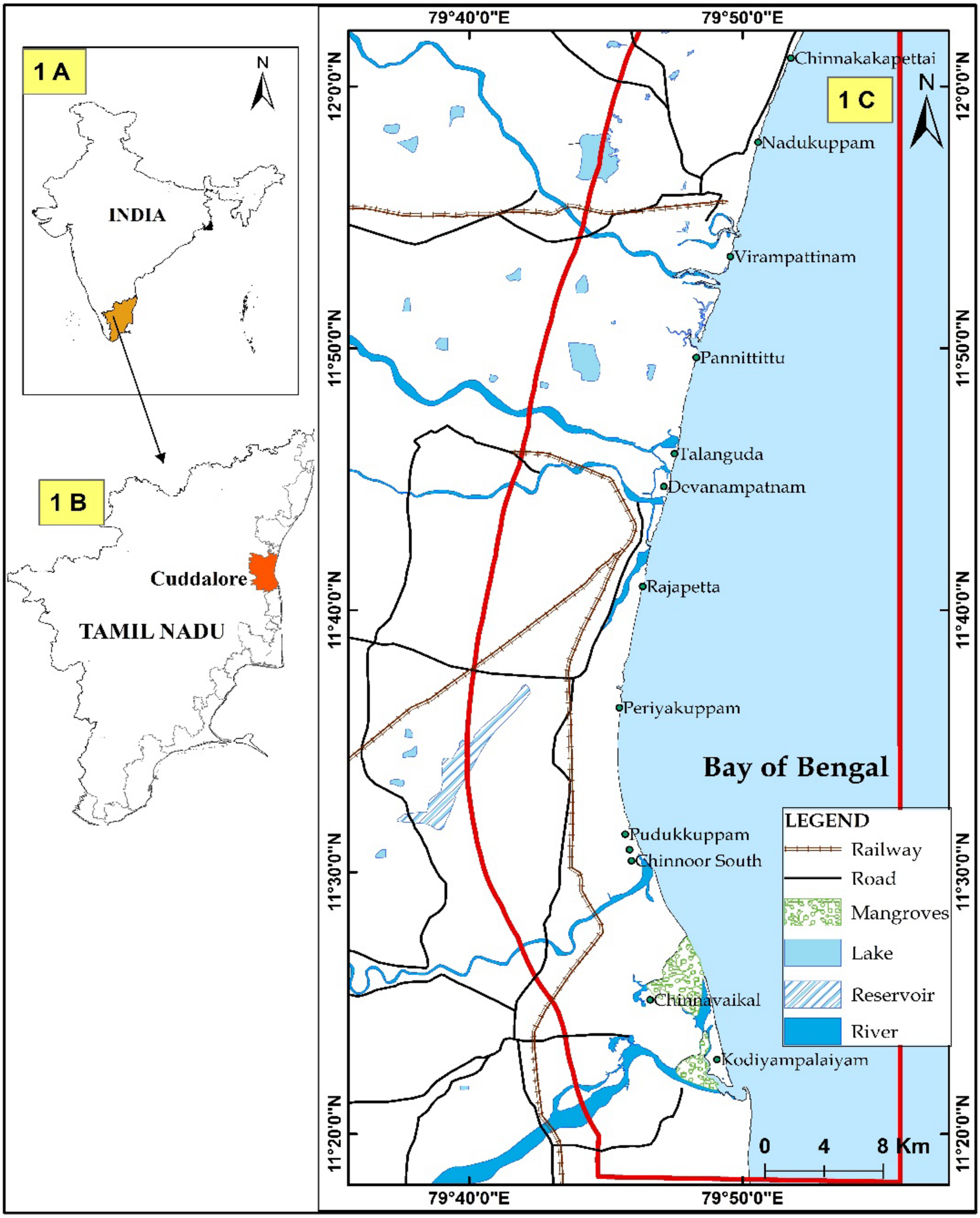


**Fig. 1** Map showing the location of the study area. (1A): India map, (1B): Tamil Nadu map with study area location, (1C): Base map for Cuddalore study region

sq.km) aquaculture (20.53 sq.km), mangrove (130 sq.km), cropland, vegetation, plantation, mining/industrial waste (320 sq.km), settlements (520.99 sq.km), water bodies (240 sq.km), etc.

## Materials and methods

In the present study, three different components such as shoreline change analysis, inundation mapping and

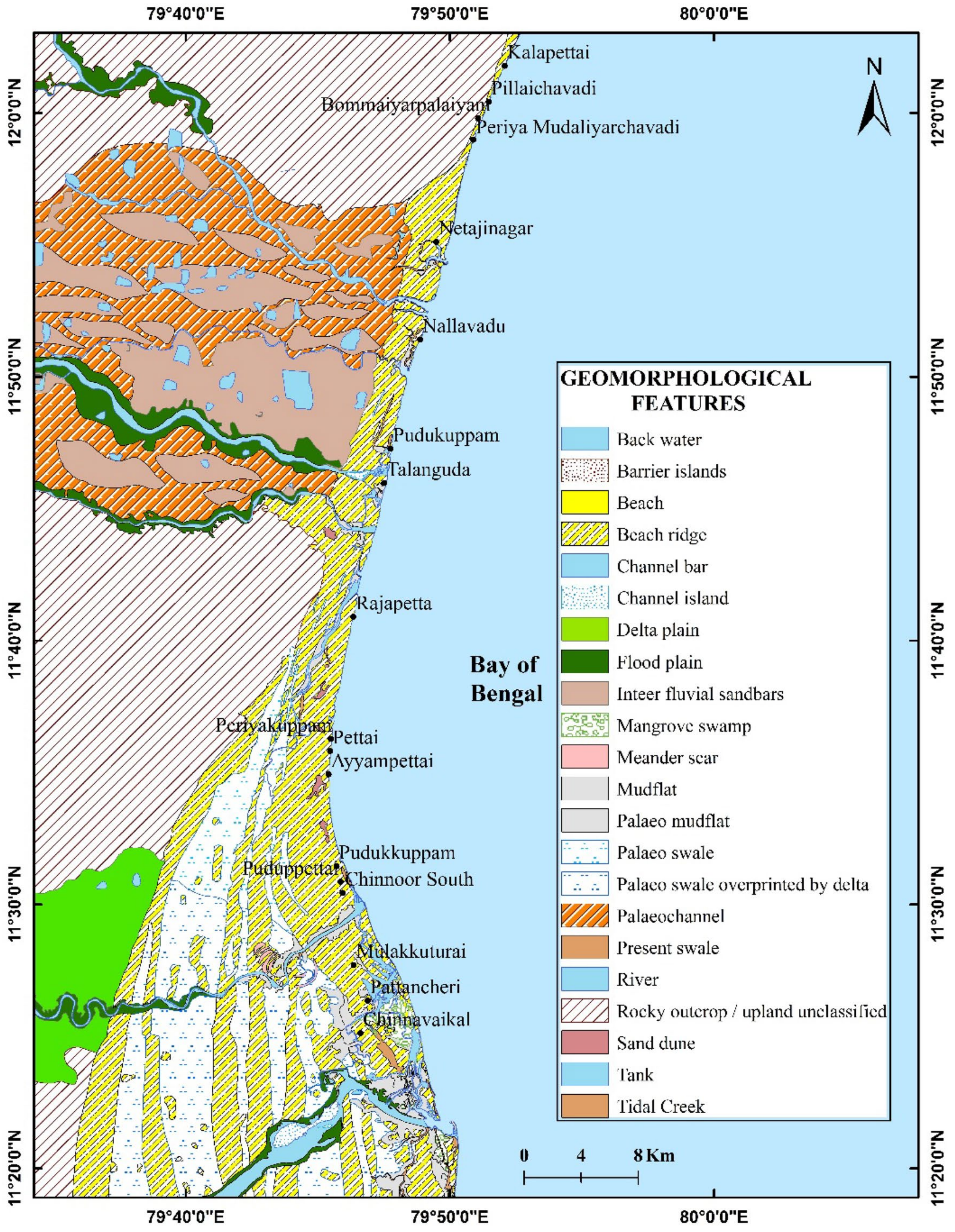


**Fig. 2** A detailed description of geomorphological landforms along Cuddalore region

impact assessment (overlaying the inundation with land use/land cover and geomorphology) were studied comprehensively to understand the impact of sea-level rise. The overall methodology is shown in Fig. 4.

## Shoreline analysis

To understand the coastal dynamics, present and past positions of shoreline and ground conditions must be mapped.

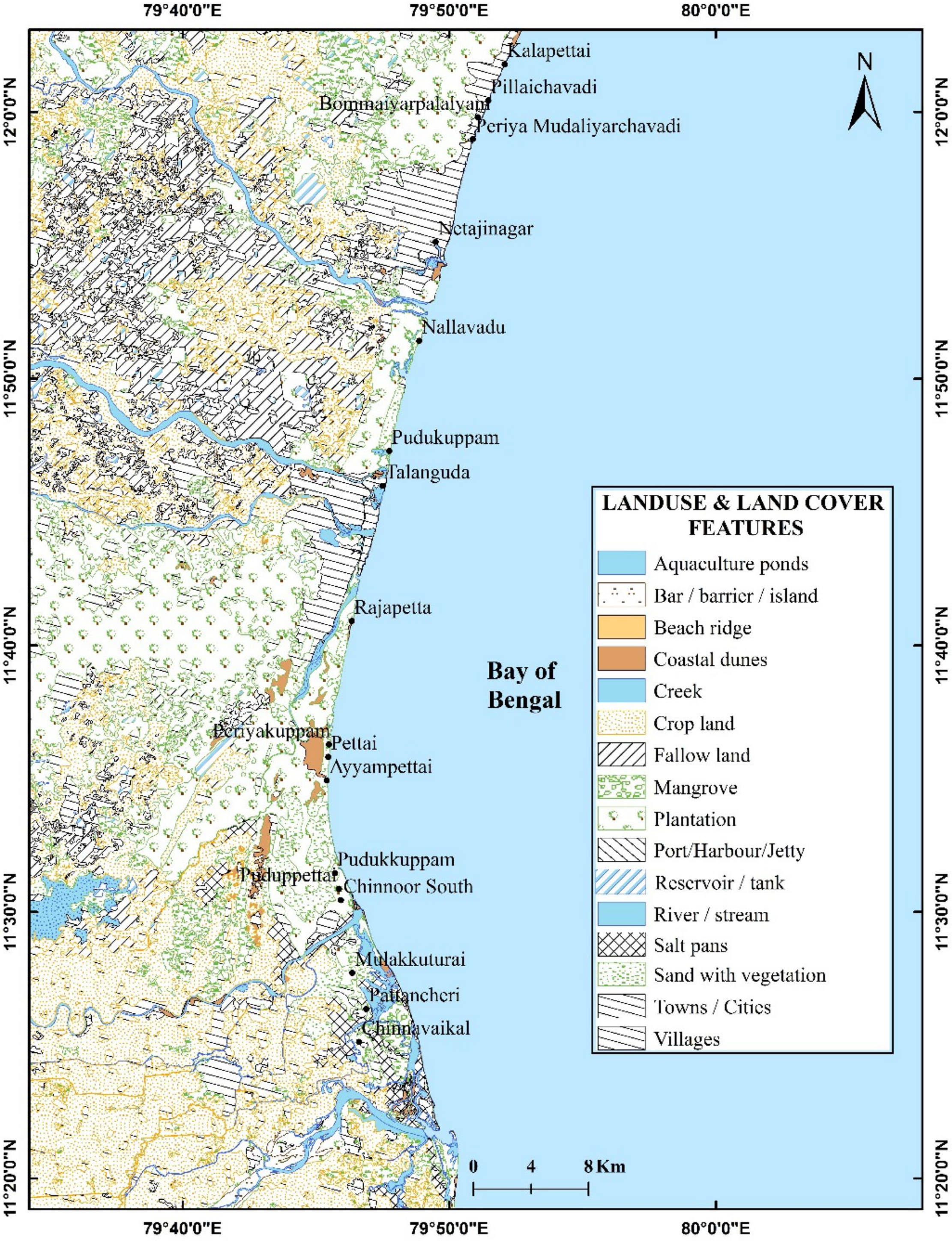


**Fig. 3** A detailed description of land use/land cover features along Cuddalore region

Satellite data are used as a primary data source for shoreline interpretation. Ground morphology in the present stage and any other man-made alterations (Anthropogenic activity) in the mainland were interpreted using visual interpretation techniques. Multi-dated satellite images of different periods were used as a primary data source for shoreline analysis. The details of different satellite data used in the study are given in Table 1.

Ground Control Points (GCP's) such as road intersection, building corner, rail–road intersections, etc. were collected

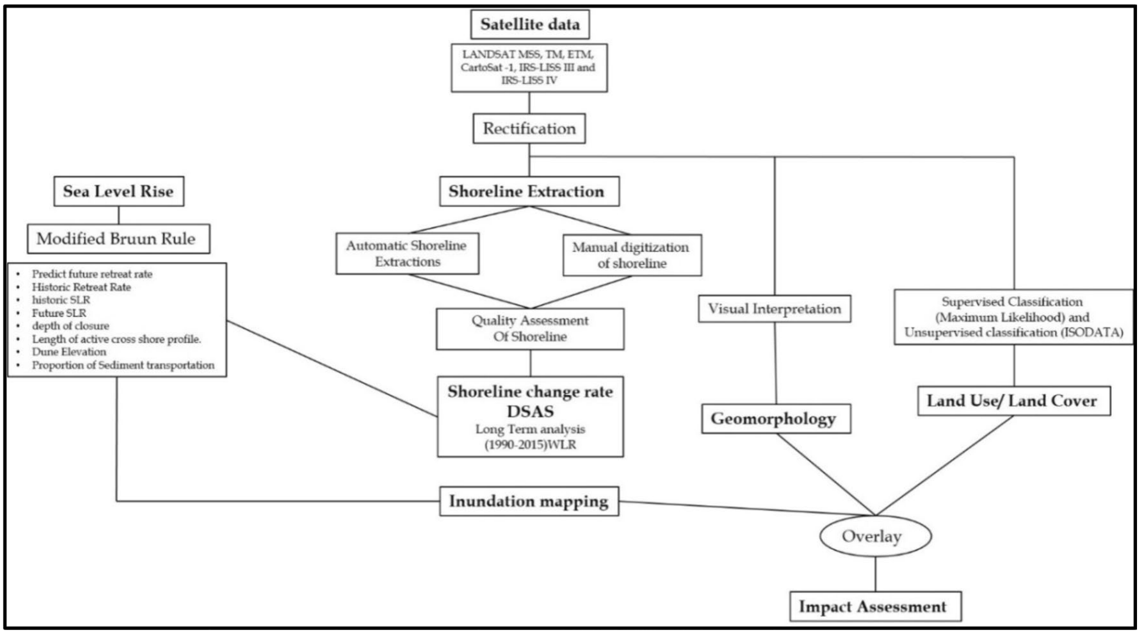


**Fig. 4** Simplified flowchart methodology adopted to study the impact assessment along Cuddalore coastal region

**Table 1** Details of satellite data used and its date of acquisition with cyclone details in the respective years

| Sl. no. | Satellite/sensor | Spatial resolution | Path/row/sub-scene | Date of image acquisition | RMSE (m) | Cyclone Details |
|---|---|---|---|---|---|---|
| 1 | Landsat (TM) | 30 m | P142/R52 | 25 April 1990 | ~18 | BOB 09 |
| 2 | Landsat (ETM+) | 30 m | P142/R52 | 28 March 2000 | ~16.7 | BOB 06, BOB 03, 08B, BOB 05 |
| 3 | Cartosat-1 (PAN) | 2.5 m | P559/R343<br>P558/R342<br>P558/R341<br>P558/R340 | 01 July 2006<br>01 July 2006<br>01 July 2006<br>01 July 2006 | ~2 | Fanoos |
| 4 | Resourcesat-1 (LISS III) | 23.5 m | P102/R65 | 29 March 2008 | ~15 | Nisha |
| 5 | Resourcesat-2 (LISS-IV) | 5.8 m | P102/R65/B<br>P102/R65/D | 18 March 2012<br>18 March 2012 | ~4 | Thane, Nilam |
| 6 | | 5.8 m | P102/R65/B; P102/R65/D | 24 May 2013; 24 May 2013 | ~2 | Madi |
| 7 | | 5.8 m | P102/R65/B<br>P102/R65/D | 01 April 2014<br>12 June 2014 | ~1.4 | |
| 8 | | 5.8 m | P102/R65/B<br>P102/R65/D | 01 July 2015<br>01 July 2015 | ~1.4 | |

The RMSE error obtained from image rectification are shown in the table

from the field using handheld GPS (Global Positioning System). The GCPs were collected covering the entire area of the images. The distortion and edge matching in the image can be minimized, and the accuracy of the images can be emphasized. ERDAS Imagine 2013 software was used for rectifying the satellite images (projection: UTM, Datum: WGS-84). Second-order polynomial transformation method was applied for each image. In the present study, Resourcesat-2, LISS-IV (2015) data was rectified initially. Then, this rectified image serves as a base image to rectify all other satellite images using an image to the image rectification process. Root Mean Square Error (RMSE) was maintained within a pixel. The RMSE obtained from each rectified image is shown in Table 1.

Shoreline changes are analyzed using eight different datasets from 1990 to 2015 (25 years). Landsat-5 (1990), Landsat-7 (2000), Cartosat-1 (2006), Resourcesat-1 (2008), Resourcesat-2 (2012–2015). 25 years of shoreline change was carried out using all eight satellite images from 1990 to 2015. Whereas, for short-term trend analysis, four different periods (1990–2000, 2000–2006, 2006–2012 and 2012–2015) were analyzed separately.

The shoreline changes and its position are an essential parameter in the prediction of the future trend of shoreline shift. Interpretation of a shoreline position in satellite data is a subjective topic. This may be due to the difference in tide variability, variations in meteorological conditions, inequalities in data resolution, seasonal setup and scaling of remote sensing data during different periods of data acquisition. Some of the shoreline proxies used by the researchers include the high water line (HWL) (Shalowitz 1964), line of vegetation (Hwang 1981), the toe or crest of the sand dune (Moore and Griggs 2002), low water line (Fletcher et al. 2003), mean high water (MHW) (Morton et al. 2004), wet–dry line (Moore et al. 2006) and cliff base or top (Hapke and Reid 2007). Therefore, after considering the field conditions, coastal features and data limitations, high water line (HWL) mark from each image was used as shoreline proxy which is equivalent to the previous wet/dry line identifiable on the sandy beach (Kankara et al. 2014, 2015). Visual interpretation method was adopted for shoreline extraction from each image. These extracted shorelines are then taken into ArcGIS for change calculation study. Digital Shoreline Analysis System (DSAS) version 4.0, (Thieler et al. 2009), an extension of ESRI ArcGIS (10.3) software was used to calculate the shoreline change rate using statistical methods with multiple shoreline positions.

Totally, 160 transects at 200-m spacing were generated to calculate the shoreline change rates over different periods of analysis. Two different statistical methods i.e., End Point Rate (EPR) and Weighted Linear Regression Rate (WLR) were used for shoreline change calculation. For the short-term trend, EPR method was considered as the best method for rate calculation (Kankara et al. 2014). Whereas, for long-term trend, WLR method was considered as it takes into account the uncertainty field to calculate the long-term rates of shoreline change. The weight ($w$) is defined as a function of the variance in the uncertainty of the measurement ($e$) (Genz et al. 2007):

$$w = \frac{1}{e^2}, \tag{1}$$

where $e =$ shoreline uncertainty value.

There are many measurement and positional uncertainties/errors associated with each extracted shoreline positions. These uncertainties affect the accuracy of shoreline change results. Therefore, in the present study, seasonal error, digitization error, rectification error, tidal error, and pixel errors are determined in each shoreline separately. The uncertainties values for each shoreline positions used in this study are shown in Table 2.

**Table 2** Measurement and positional uncertainties/error used in weighted linear regression (WLR) rate method

| Sl. no. | Satellite data | Total uncertainty Et (m) |
|---|---|---|
| 1 | Landsat-5 (TM) | 15 |
| 2 | Landsat-7 (ETM+) | 15 |
| 3 | Cartosat-1 (PAN) | 1.25 |
| 4 | Resourcesat-1 (LISS-III) | 11.5 |
| 5 | Resourcesat-2 (LISS-IV) | 2.9 |
| 6 | Resourcesat-2 (LISS-IV) | 2.9 |
| 7 | Resourcesat-2 (LISS-IV) | 2.9 |
| 8 | Resourcesat-2 (LISS-IV) | 2.9 |

## Shoreline retreat with response to sea-level rise

The rising and spreading of water over usually dry land are referred to as an inundation. The datasets required for this approach are shoreline change and bathymetry of the study area. Using Arc-GIS (10.3) tools, the trajectory line was drawn for 500-m intervals horizontally along the coast, and 10-m interval of contour map was prepared. Length, depth, and heights were used to measure for analyzing inundation using Bruun Rule. Due to the limitations in Bruun Rule, the Modified Bruun Rule (Bray and Hooke 1997) was also used with additional parameters such as future SLR, shoreline change results and sediment transportation for inundation map preparation for next 100 years. Modifications of the Bruun Rule were attempted to account for greater accuracy in representing the beach profile's response, or zone of active sediment transport, to sea-level rise.

The analysis by Bruun assumes that with a rise in sea level, the equilibrium profile of the beach and shallow offshore moves upward and landward. The Bruun Rule estimates the response of the shoreline profile to sea-level rise. The Bruun Rule can be applied to correlate sea-level rise with eroding beaches.

$$l_1 = \frac{l}{h + d} a \tag{2}$$

The distance "$l$" is calculated from the shoreline to the 10-m bathymetry contour of coastal data. "$a$" is the predicted sea-level rise. The Depth "$d$" (average height of beach) is calculated for the shoreline from comprehensive DEM. The Height "$h$" is calculated from the comprehensive DEM data (for below MSL). "$l_1$" is defined as the total predicted shoreline due to sea-level rise from the present MSL level and the predicted rise of sea level (0.59 m) reported as per the global sea-level rise in future by the IPCC report.

The Bruun Rule of shoreline response to sea-level rise was formulated for shorelines where all sediment is assumed to remain within the active profile and applies to low-lying shores with sediment covered shore platform (Bruun 1962). The Bruun Rule appears to provide shoreline positions that underestimate retreat by more than an order of magnitude (Nicholls and Stive 2004; Ranasinghe et al. 2007), even for the coastal landforms such as dune and barrier coasts etc with low sediment transportation in alongshore direction (Chandramohan and Nayak 1992). Obstructive assumptions were overwhelmed by adding parameters like sand dune elevation (*B*) and proportion of sand dune sediment, which is sufficiently large and remains within the active profile (*P*) (Weggel 1979; Hands 1983). This is defined as the percentage of sand and gravel within the retreating materials, since material of this size is difficult to mobilize and, unlike silt–clay materials, remains within the active profile rather than being lost offshore and where sediment is released, a Modified Bruun Rule (Dean 1991) appears more suitable for predicting shoreline response (Bray and Hooke 1997). Shoreline retreat rate derived from eight shorelines response model was tested to know the rates of historical shoreline retreat. This historical shoreline retreat provides a baseline for retreat rate between 1990 and 2015, with accelerating sea-level rise could be predicted. The model was applied in full spatial mode and was utilized to evaluate future shoreline change. Using ArcGIS tools, the inundation map was prepared, and the vulnerability assessment was carried out along the Cuddalore sector.

$$R_2 = R_1 + \frac{\left(S_2 - S_1\right)L}{P(B + h)}, \tag{3}$$

where $R_2$—Predict future shoreline retreat rate (ma$^{-1}$), $R_1$—Historic Shoreline retreat rate (ma$^{-1}$), $S_1$—Historic sea-level rise (mma$^{-1}$), $S_2$—Future sea-level rise (mma$^{-1}$), $L$—Length of active cross shore profile (m), $h$—Depth of closure (m), $P$—Proportion of sediment that remains within the active profile (m$^3$/year) and $B$—Elevation (m).

### Impact assessment

The overall goal of this study was to model the potential effects of sea-level rise and establish their vulnerabilities (Esteves 2014). The potential loss of land area in the study area poses a severe and potentially catastrophic problem (Frykman and Seiron 2009). The most dramatic inundation scenarios were projected using Modified Bruun Rule. The impact assessment along the study area concerning geomorphological and land use/land cover features has been estimated. Quantification of potential habitat loss can be estimated by merging the land use/land cover with the digital elevation model. Using the intersect tool in Arc-GIS 10.3, the impact assessment was determined by overlying the thematic maps (land use/land cover and geomorphology) with inundation output.

## Results

Shoreline change analysis, inundation mapping and impact assessment (overlaying the inundation with land use/land cover and geomorphology) due to sea-level rise were studied separately. Shoreline change pattern of past decades is essential to understand the future shoreline position and the impacts due to sea-level rise along the coast. Shoreline retreat with response to sea-level rise for 100 years is studied using both Bruun Rule and Modified Bruun Rule methods. Geomorphic features and land use/land cover patterns are prime responsible for coastal changes and play an essential role in determining the impact of sea-level rise.

### Shoreline change analysis

Shoreline change was analyzed for the past 25 years by appending eight different periods of shorelines. 1990–2015 (25 years) period of shorelines was analyzed using WLR method. Whereas, the shorter period of shoreline change was analyzed for four different periods, i.e., 1990–2000, 2000–2006, 2006–2012 and 2012–2015 using EPR method. A short-term period analysis is very much necessary to understand the behavior of the coast at different periods. It helps to understand the futuristic condition of the coast.

### Long-term shoreline change trend (1990–2015)

Shoreline change was calculated by taking eight different shoreline positions (1990, 2000, 2006, 2008, 2012, 2013, 2014 and 2015). Shoreline change pattern for long-term trend was calculated by weighted linear regression (WLR) rate method. The significant advantage of WLR method is that it not only gives the shoreline change result but also provides additional information such as standard error of the estimate (WSE), confidence interval (WCI) value and the *R*-squared value (WR2). In the present study, 85% confidence interval was used to calculate the rate. The final rate obtained from the analysis is then classified into seven different categories (high accretion, moderate accretion, low accretion, stable, high erosion, moderate erosion, and low erosion).

From the analysis, it was observed that 4.77% of the coast falls in high erosion category. Pattanacherri, Chinnavaikal region was noticed with high erosion. Whereas, Chinnor South and Melakkuturai were noticed with moderate erosion (6.15%). About 38.15% of coast falls under low eroding coast. Some of the regions noticed with low erosion are Pudukuppam, Talangada, Devanampattnam, etc. Kumaravel et al. (2013) have suggested a similar trend in his research study. About 22.71% of the coast falls in a stable state. Rajapettai, Chittiraipettai, Periyakuppam, and Ayyampettai are noticed with a stable condition. Low accretion (21.25%) was observed at Madavapallam, Reddiyapettai, Kumarapettai, Samipettai, and Pudupettai. Whereas, Vellingarayanpettai and Pudukuppam region were noticed with moderate accretion (6.75%). High accretion was very negligent amount (0.21%). Half of the study area (49.01%) was noticed with varying degree of erosion, and hence, it was necessary to investigate and analyze the coast periodically. Figure 5 shows the overall distribution of erosion/accretion pattern for the past 25 years along the coast.

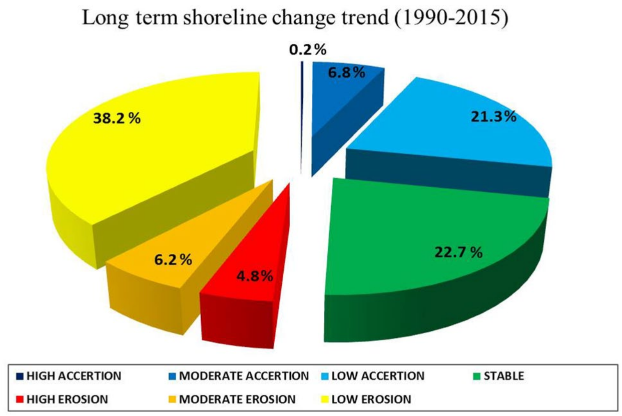


**Fig. 5** Pie chart showing the percentage distribution of long-term (1990–2015) shoreline change trend along Cuddalore region with seven different classes

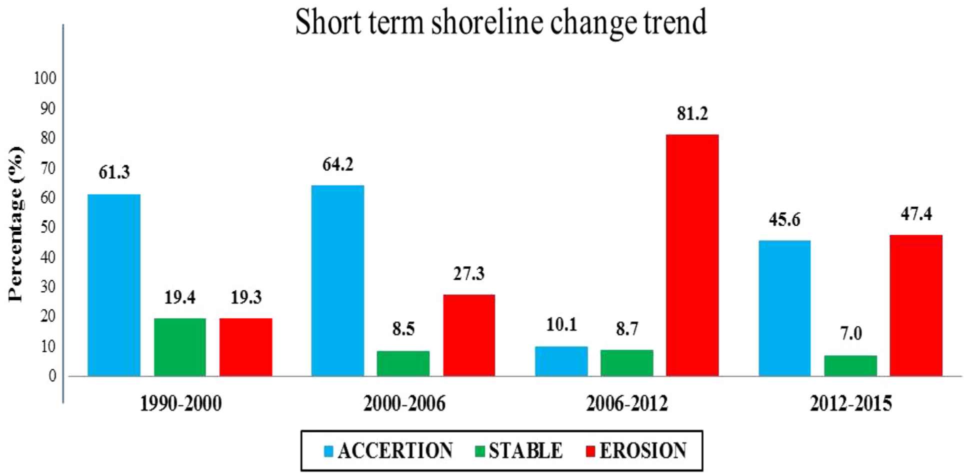
## Short-term shoreline change trend

Four different periods, i.e., 1990–2000, 2000–2006, 2006–2012 and 2012–2015 were analyzed to understand the periodic changes. The period between 1990 and 2000 shows 61%, 19% and 19% of accretion, stable and erosion, respectively. During 2000–2006, accretion has increased to 64% and erosion to 27%. Whereas, the stable condition decreased to 8%. However, during 2006–2012, erosion percentage increased drastically with 81% when compared to accretion and stable class. The natural calamity such as Thane cyclone made landfall at northern Tamil Nadu coast between Cuddalore and Puducherry on December 30, 2011. Other cyclones such as Fanoos (2006), Nisha (2008), Nilam (2012) could have altered the coast to a maximum extent. From 2012 to 2015, the coastal erosion was reduced drastically to 47%, and the accretion has shown an increasing trend with 45%. Figure 6 shows the shoreline change rate distribution for four different periods.

## Shoreline retreat with response to SLR (100 years)

Komar et al. (1991) have suggested that a three-dimensional sediment budget can improve shoreline retreat rate predictions as a function of sea-level rise. The sediment budget approach calculates sediment sources and sinks within a control volume, and therefore accounts for the long-shore transport gradient. However, sediment transportation was not included in Bruun Rule and therefore, Modified Bruun Rule was used for future SLR analysis (Turner et al. 2003). The Modified Bruun Rule includes additional parameters such as historical and future sea-level rise (IPPC report), historical shoreline changes and sediment transportation. The sediment transport of Cuddalore region was 0.895*106 m$^3$/year (Chandramohan and Nayak 1992). Usually, for studying the shoreline change, the satellite data collected should be in fair-whether condition (February to August). Taking this

**Fig. 6** Descriptive statistics of short-term shoreline change trend of all four different periods in the study area



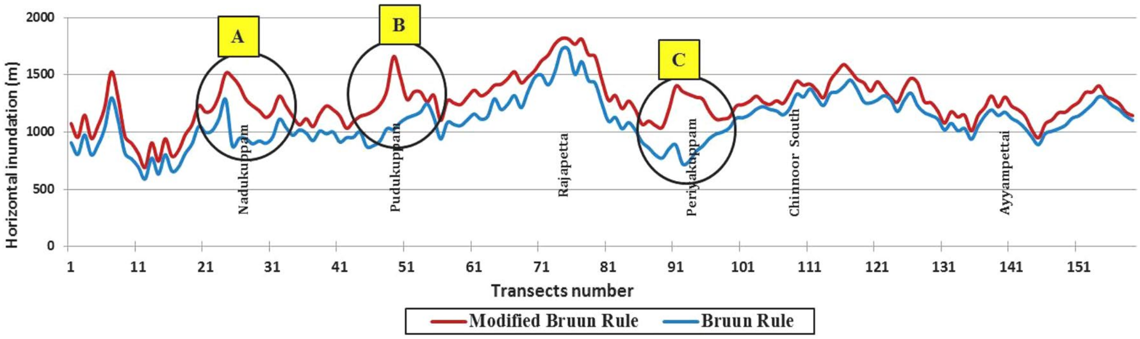


**Fig. 7** Extent of inundation (in meters) computed using Bruun Rule (blue line) and Modified Bruun Rule (red line). A (Nadukuppam), B (Pudukuppam) and C (Periyakuppam) are the locations where maximum variation is seen

into consideration, northerly long-shore sediment transport rate was considered in the model. The Modified Bruun Rule calculation was observed to be more accurate when compared to the Bruun Rule.

Figure 7 shows the horizontal inundation level of the study area (Bruun Rule and Modified Bruun Rule). The maximum inundation observed from both the analysis was 2000 m, and minimum inundation was 800 m. When compared with Bruun Rule, the horizontal inundation of Modified Bruun Rule was maximum (~ 200 m). From the graph, it shows that both the models suggest a similar trend of horizontal inundation. However, Modified Bruun Rule shows the higher end of inundation. Some of the areas which seem to be more inundated are Mudaliyarchavadi, Nadukuppam, Kattaikuppam, Pudukuppam, Devanampatnam, Talanguda, Nanjalingampettai and Periyakuppam.

## Impact assessment

In the present study, an attempt has been made to study the impact of sea-level rise on coastal geomorphology and land use/land cover features. This study shows the land features and areas at risk of erosion due to sea-level rise. Hence, it provides a comprehensive detail regarding the risk zonation mapping. Resourcesat-2 (LISS-IV, 2015) data were used to prepare the coastal landform.

## Impact over geomorphological features

Some of the coastal geomorphic landforms mapped along the coastal regions are the beach, beach ridge, pedi-plain, flood plain, sand dunes, pediment, tidal flat, etc. (Fig. 2). Arc-GIS (10.3 version) was used for geomorphic landform mapping, and intersection tool was used for overlay analysis study. The horizontal inundation due to Modified Bruun Rule was overlaid on geomorphic features. The study suggests that beach (2 sq.km), beach ridges (1.6 sq.km) and pedi-plain (0.8 sq.km) are the major landforms affected due to the sea-level rise. Nadukuppam, Pudukuppam, Periyakuppam, etc. are the coastal regions where the inundation was maximum (Fig. 8).

A similar study was made using the Bruun Rule. As suggested earlier, the horizontal inundation of Bruun rule was less when compared with Modified Bruun Rule method. Hence, the impact was minimal on the geomorphic landforms. Beach (1.4 sq.km), Beach ridges (1.1 sq.km) and pedi-plain (0.4 sq.km) are some of the landforms affected due to the rise in sea level in the Bruun Rule method.

## Impact over land use/land cover feature

Landuse and landcover are two different terminologies which can alter the regions and can contribute significantly to climate change. Arc-GIS (10.3 version) was used for land use/land cover mapping, and intersection tool was used for overlay analysis study. Sandy beach, aquaculture, cropland, plantation, mud flat, salt pan, and settlement are the features that are covered in the study area (Fig. 3). The horizontal inundation obtained from sea-level rise was overlaid on land use/land cover features (Fig. 9). The overlay of inundation obtained from Modified Bruun Rule suggests that sandy beach (2 sq.km), cropland (1.3 sq.km), aquaculture (1 sq.km) and plantation (0.6 sq.km) are mainly affected. However, inundation due to Bruun Rule indicates fewer regions are affected. Some of the features like beach (1.6 sq.km), cropland (1 sq.km), aquaculture (0.4 sq.km), plantation (0.2 sq.km) and structure (0.2 sq.km) are affected by sea-level rise. The horizontal inundation of Bruun rule was less when compared with Modified Bruun Rule method.

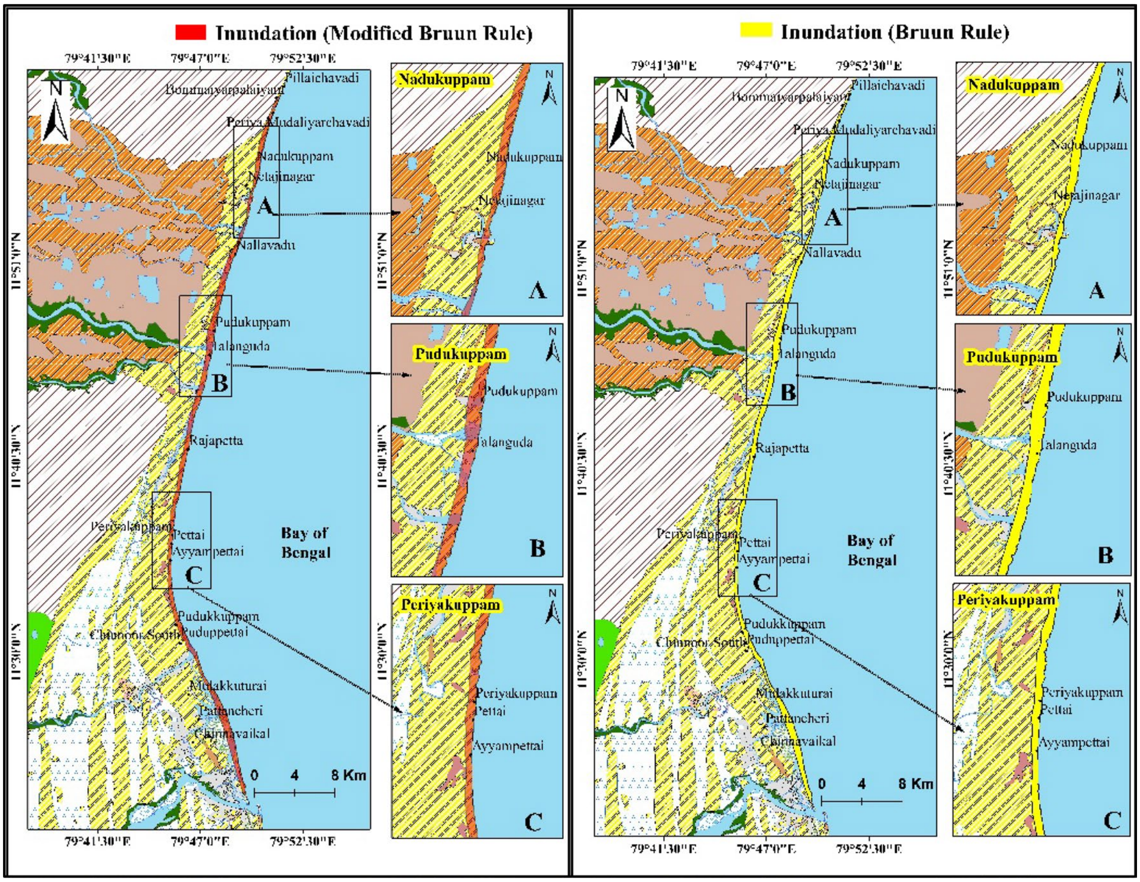


Fig. 8 The horizontal inundation obtained from Bruun rule and Modified Bruun rule was overlaid on geomorphological features. A (Nadukuppam), B (Pudukuppam) and C (Periyakuppam) are the locations which show more horizontal inundation

## Discussion

25 years (1990–2015) and short-term period (1990–2000, 2000–2006, 2006–2012 and 2012–2015) of shoreline change along Cuddalore coast were carried out using multi-resolution satellite images. It was necessary to understand the trend of coastal changes for shoreline management. Due to the developmental activities, changes in ocean flow pattern, wave climate and rise in sea level, coastlines are now more dynamic than ever and subjected to change its position continuously. 25 years of shoreline change trend indicates half of the study area (49.01%) was categorized with varying degree of erosion which suggests the necessity to monitor the coast periodically. Remaining 28% of coasts was seen with accretion and 22% of the coast is stable condition. Natural phenomenon such as a tsunami, storm surge, cyclone, etc. has a severe impact on the coast and its morphology. Murthy et al. (2006) reported extensive damage along the Cuddalore coast during the 2004 Indian Ocean tsunami.

From the short-term shoreline change trend, it is observed that the coastal regions are more dynamic and changes its position continuously. The result shows irregular patterns of shoreline change results. Therefore, it is necessary to examine the short-term variation along the coast. Short-term changes will provide the necessary information's regarding the dynamics of the coastal region. Shorelines are affected continuously by multiple interactions such as sea-level variations, geomorphology, sediment budgets, and human activities such as port, fishing harbours, etc.

The Bruun Rule estimates the response of the shoreline profile to sea-level rise. Bruun Rule has certain limitations in its calculation, and hence, Modified Bruun Rule was also used for shoreline retreat assessment. The model was applied in full spatial mode and was utilized to evaluate future shoreline change. Both methods suggest a similar trend of horizontal inundation. However, Modified Bruun Rule has maximum inundation due to sea-level rise. The coastal areas affected by inundation are Mudaliyarchavadi, Nadukuppam, Kattaikuppam, Pudukuppam, Devanampatnam, Talanguda, Nanjalingampettai and Periyakuppam.

Sea-level rise due to both Bruun Rule and Modified Bruun Rule methods were overlaid on geomorphic landforms and land use/land cover pattern along the study area. Sea-level rise due to the Modified Bruun Rule has a severe impact on the coastal landforms when compared with the Bruun Rule

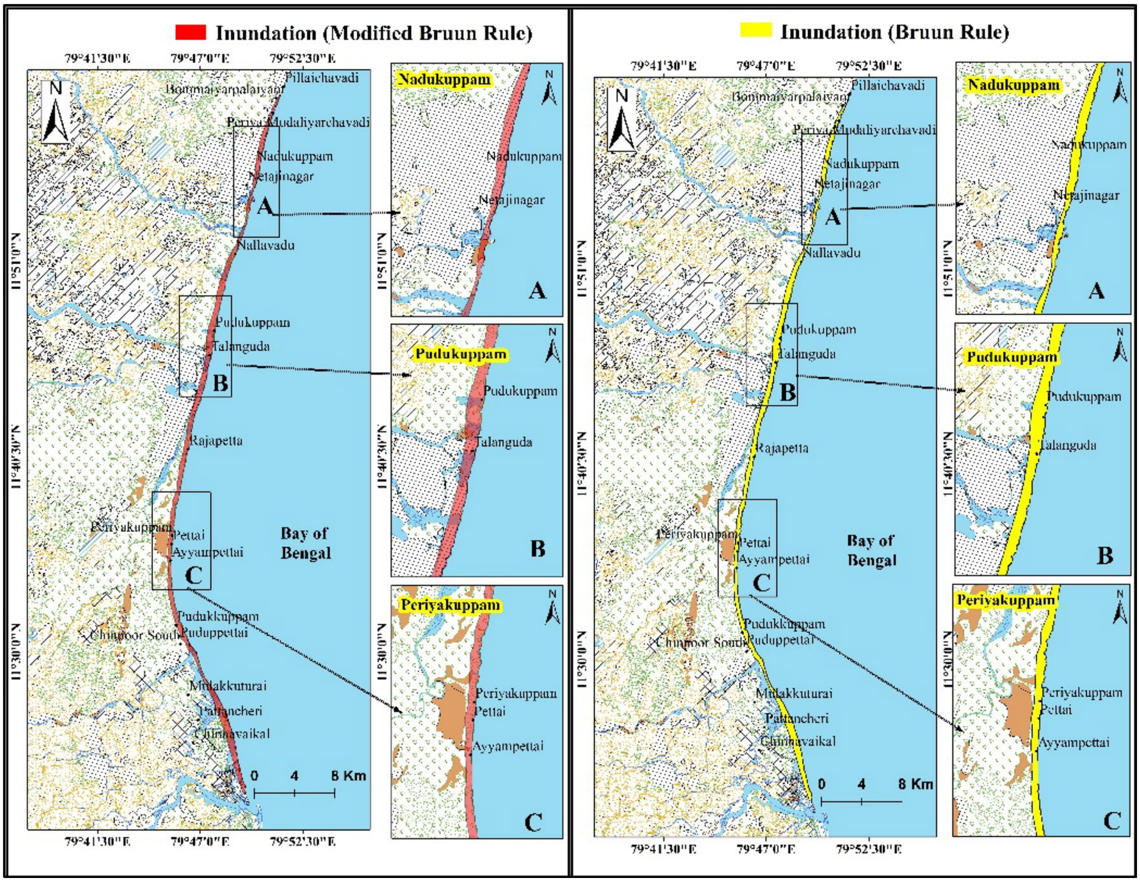


Fig. 9 The horizontal inundation obtained from Bruun rule and Modified Bruun rule was overlaid on landuse/landcover features. A (Nadukuppam), B (Pudukuppam) and C (Periyakuppam) are the locations which show more horizontal inundation

method. Some of the landforms affected by inundation are a sandy beach, cropland, aquaculture, and plantation. The geomorphic landforms such as the beach, beach ridges and pediplain are mainly affected due to the rise in sea level.

## Conclusion

The study emphasizes the shoreline change concerning sea-level rise and its impact on the coastal landforms and land use/land cover patterns. Historical shoreline positions were used to study the present and future shoreline position. From the 25 years of shoreline change analysis from 1990 to 2015, half of the coastal regions (49.01%) were noticed with varying degree of erosion. From the short-term trend, the result suggests that the coastline changes its position continuously. During 1990–2000 and 2000–2006 periods, accretion was the dominant class. However, during 2006–2012, erosion increased drastically. The area of horizontal inundation was estimated using both Bruun Rule and Modified Bruun Rule. The horizontal inundation is estimated as ~ 1.1 km (Bruun Rule) and ~ 1.6 km (Modified Bruun Rule) by considering the sea-level height from 0.59 m to 1.22 m. The horizontal inundation was overlaid on geomorphic landforms, and land use/land cover features to assess the impact. About 16.08 sq.km of geomorphic landform is affected by inundation. Whereas, 17.5 sq.km of land use/land cover area is affected by horizontal inundation. This study is useful for stakeholders, policymakers, coastal managers, scientists, and coastal livelihoods. This study provides an interactive means to identify the vulnerable zone. The output maps can be used to visualize the affected areas spatially.

**Acknowledgements** This work is the part of Coastal Processes & Shoreline Management (CP&SM) project of NCCR, Chennai. Authors sincerely thanks to Director, NCCR and entire CP&SM team for their keen interest and constant support for this work.We express our gratitude to the anonymous reviewers for their critical reviews and comments, which has helped us in improving the paper.

## References

Adger NW (1999) Social vulnerability to climate change and extremes in coastal Vietnam. World Dev 27:249–269

Al-Nasrawi AKM, Hamylton SM, Jones BG, Hopley CA, Al Yazichi YM (2018) Geoinformatics vulnerability predictions of coastal ecosystems to sealevel rise in southeastern Australia. Geomatics Nat Haz and Risk 9(1):645–661

Bray MJ, Hooke JM (1997) Prediction of soft-cliff retreat with accelerating sea-level rise. J Coast Res 13(2):453–467

Brunel C, Sabatier F (2007) Pocket beach vulnerability to sea level rise. J Coast Res SI 50:604–609 (Proceedings of the 9th International Coastal Symposium)

Bruun P (1962) Sea level rise as a cause of shore erosion. J Waterw Harb Div Proc Am Soc Civil Engg 88:117–130

Chandramohan P, Nayak BU (1992) Longshore sediment transport model for the Indian west coast. J Coast Res 8(4):775–787

Church JA, Monselesan D, Gregory JM, Marzeion B (2013) Evaluating the ability of process-based models to project sea-level change. Environ Res Lett 8:014051

Cooper JAG, McKenna J (2008) Social justice in coastal erosion management: the temporal and spatial dimensions. Geoforum 39:294–306

Cooper J, Pilkey H (2004) Sea level rise and shoreline retreat: time to abandon the Bruun rule. Glob Plant Change 43:157–171

Cutter SL, Boruff Bryan J, Lynn Shirley W (2003) Indicators of social vulnerability to environmental hazards. Soc Sci Q 84(1):242–261

Davidson-Arnott RG (2005) Conceptual model of the effects of sea level rise on sandy coasts. J of Coastal Res 21(6):1166–1172

Dean RG (1991) Equilibrium beach profiles: characteristics and applications. J of Coast Res 7(1):53–84

Douglas BC, Crowell M, Leatherman SP (1998) Consideration of shoreline position prediction. J of Coast Res 14:1025–1033

Dube SK, Jain I, Rao AD, Murty TS (2009) Storm surge modelling for the Bay of Bengal and Arabian Sea. Nat Haz 51:3–27

EC (2005) Climate change and the European water dimension a report to the European water directors. EU Report no. 21553. European Commission-Joint Research Centre, Ispra

EEA (2006) The changing faces of Europe’s coastal areas, EEA Report no 6/2006. European Environment Agency, Copenhagen

Esteves LS (2014) Managed realignment: is it a viable long-term coastal management strategy?. Springer, Berlin, p 136

Fenster MS, Dolan R, Elder JF (1993) A new method for predicting shoreline position from historical data. J of Coast Res 9:147–171

FitzGerald DM, Fenster MS, Argow BA, Buynevich IV (2008) Coastal impacts due to sea-level rise. Ann Rev Earth Planet Sci 36(1):601–647

Fletcher C, Rooney J, Barbee M, Lim SC, Richmond B (2003) Mapping shoreline change using digital ortho-photogrammetry on Maui, Hawaii. J of Coast Res Spec Issue 38:106–124

Frykman H, Seiron PO (2009) The effects of climate induced sea level rise on the coastal areas in the Hambantota district. A geographical study of Hambantota and an identification of vulnerable ecosystems and land use along the coast. Physical Geography and Ecosystems Analysis Lund University, Sri Lanka, Sölvegatan-12, Seminar series nr 173

Genz AS, Fletcher CH, Dunn RA, Frazer LN, Rooney JJ (2007) The predictive accuracy of shoreline change rate methods and alongshore beach variation on Maui, Hawaii. J of Coast Res 23:87–105

Hands EB (1983) The Great Lakes as a test model for profile responses to sea-level changes. In: Komar PD (ed) Handbook of coastal processes and erosion. CRC Press, Boca Raton, pp 176–189

Hapke C J, Reid D (2007) The National assessment of shoreline change: part 4. Historical coastal cliff retreats along the California coast: U.S. geological survey open-file report 2007-1133. https://pubs.usgs.gov/of/2007/1133

Hwang DJ (1981) Beach changes on Oahu as revealed by aerial photographs. Hawaii office of state planning. Coastal Zone Management Program, Honolulu, p 146

IPCC (2007) The physical science basis, summary for policy-makers. Contrib work group I Fourth Asses Rep Intergov Panal Climate Change. Cambridge University Press, Cambridge

Kankara RS, Selvan CS, Arockiaraj S (2014) An adaptive approach to monitor the Shoreline changes in ICZM framework: a case study of Chennai coast. Indian J Mar Sci 43(7):1271–1279

Kankara RS, Selvan CS, Markose VJ, Rajan B, Arockiaraj S (2015) Estimation of long and short-term shoreline changes along Andhra Pradesh coast using remote sensing and GIS techniques. Procedia Eng 116:855–862

Klein RJT, Nicholls RJ, Thomall F (2003) Resilience to natural hazards: how useful is this concept? Environ. Haz 5:35–45

Komar PD, Lanfredi N, Baba M (1991) The response of beaches to sea-level changes: a review of predictive models. J of Coast Res 7(3):895–921

Kumaravel S, Ramkumar T, Gurunanam B, Suresh M, Dharanirajan K (2013) An application of remote sensing and GIS based shoreline change studies—a case study in the Cuddalore district, East Coast of Tamilnadu, South India. Int J Innov Technol Explor Engg 2(4):211–215

Leatherman SP, Zhang K, Douglas BC (2000) Sea level rise shown to drive coastal erosion. EOS Trans Am Geophys Union 81:55–56

Marzeion B, Jarosch AH, Hofer M (2012) Past and future sea-level changes from the surface mass balance of glaciers. Cryosphere 6:1295–1322

McFadden L, Penning-Rowsell E, Nicholls RJ (2007) Setting the parameters: a framework for developing cross-cutting perspectives of vulnerability for coastal zone management. In: McFadden L, Nicholls RJ, Penning-Rowsell E (eds) Managing coastal vulnerability. Elsevier, Oxford, p 262

Moore LJ, Griggs GB (2002) Long-term cliff retreat and erosion hotspots along the central shores of the monterey bay national marine sanctuary. Marine Geol 181(1–3):265–283

Moore L, Ruggiero P, List J (2006) Comparing mean high water and high-water line shorelines: should proxy-datum offsets be incorporated in shoreline change analysis? J of Coast Res 22(4):894–905

Morton R A, Miller T L, Moore L J (2004) National assessment of shoreline change: part 1, historical shoreline changes and associated coastal land loss along the U.S. Gulf of Mexico. U.S. geological survey open file report 2004-1043, 44. https://pubs.usgs.gov/of/2004/1043

Murthy KSR, Subrahmanyam AS, Murty GPS, Sarma KVLNS, Subrahmanyam V, Mohana Rao K, Suneetha Rani P, Anuradha A, Adilakshmi B, Sri Devi T (2006) Factors guiding tsunami surge at the Nagapattinam—Cuddalore shelf, Tamil Nadu, east coast of India. Curr Sci 90(11):1535–1538

Nicholls RJ, Cazenave A (2010) Sea level rise and its impact on coastal zones. Science 328:1517–1520

Nicholls RJ, Stive MJF (2004) Society and sea level rise requires modeling. Sci E Lett 303:5665

O’Keefe P, Westgate K, Wisner B (1976) Taking the naturalness out of natural disasters. Nature 260:566–567

Ranasinghe R, Watson P, Lord D, Hanslow D, Cowell P (2007) Sea level rise, coastal recession and the Bruun Rule. Coasts and ports 2007. CD ROM published by Engineers Australia, Melbourne, p 8

Sallenger AH, Stockdon H, Haines J, Krabill W, Swift R, Brock J (2000) Probabilistic assessment of beach and dune changes. In: Proceedings of 27th international conference on coastal engineering. ASCE, New York, pp 3035–3047

Saravanavel J (2018) Climate change and impact of projected sea level rise along Cauvery Delta, Tamil Nadu, India—a geomatics approach. Int J of Adv Rem Sens GIS 7(1):2703–2711

Saxena S, Geethalakshmi V, Lakshmanan A (2013) Development of habitation vulnerability assessment framework for coastal hazards: Cuddalore coast in Tamil Nadu, India—a case study. Weather Clim Extrem 2:48–57

Shalowitz AL (1964) Shore and sea boundaries with special reference to the interpretation and use of coast and geodetic survey data (publication 10-1). US Government Printing Office, US Department of Commerce, Coast and Geodetic Survey, Washington, DC, p 484

Thieler ER, Himmelstoss EA, Zichichi JL, Ergul A (2009) Digital shoreline analysis system (DSAS) version 4.0, an ArcGIS extension for calculating shoreline change: U.S. geological survey open-file report 2008–1278. Accessed Feb, Sept 2015

Turner BL, Kasperson Roger E, Matsone Pamela A, McCarthyf James J, Corellg Robert W, Christensene Lindsey, Eckley Noelle, Kasperson Jeanne X, Luerse Amy, Martellog Marybeth L, Polskya Colin, Pulsipher Alexander, Schillerb Andrew (2003) A framework for vulnerability analysis in sustainability science. Proc Natl Acad Sci 100(14):8074–8079

Weggel JR (1979) A method for estimating long term erosion rates from a long term rise in water level. Coast Engineering Tech Aid (CETA) 79-2. U.S. Army Coastal Engineering Research Center, Fort Belvoir, VA

Wisner B, Blaikie P, Cannon T, Davis I (2004) At risk: natural hazards, People's Vulnerability and Disasters. Routledge, London

Zhang K, Dougles BC, Leatherman SP (2004) Global warming and coastal erosion. Clim Change 64:41–58