Impact of sea level rise and shoreline changes in the tropical island ecosystem of Andaman and Nicobar region, India

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Abstract
We report here a four decades of shoreline changes and possible sea level rise (SLR) impact on land use/land cover (LULC) in Little Andaman Island by using remote sensing (RS) and Geographic Information System (GIS) techniques. A total of six remote sensing data sets covering years between 1976 and 2018 were used to understand the shoreline changes. Moreover, a Digital Shoreline Analysis System (DSAS) was used to estimate short- and long-term shoreline changes from ArcGIS environment. Besides, the island vulnerability due to SLR was studied through using digital elevation model (DEM). As a result of Sumatra earthquake (2004), the results were showed a significant variation in shoreline upliftment and subsidence. The land subsidence was noticed in the range of 1042–3077 ha with sea level rise between 1 and 5 m. Hence, we conclude that Little Andaman Island is vulnerable to SLR and overwhelm low-elevation coastal zone.

Keywords Andaman and Nicobar Islands · GIS · Remote sensing · Sea level rise · Shoreline changes

1 Introduction
Coastal zone is a transition area between land and sea, and it signifies a relatively small area with extremely productive and diverse ecosystems (Maselli 2004). Moreover, it is very important economic zone due to rich natural resources and 10% of worldwide population reside within 10 m low-elevation area (Jiang et al. 2016; McGrananhan et al. 2007). Besides, anthropogenic activities from this population lead to oceanic pollution, global warming and climate change. The climate change can cause increase in the sea surface temperature, sea level rising, larger variability in rainfall pattern and intensity of storm (IPCC 2007; Thornton et al. 2014). According to a report by Intergovernmental Panel on Climate Change (IPCC), the global average of SLR was 3.2 mm year⁻¹ during 1993 and 2010. However, the SLR will not be stable across global during the twenty-first century.
and will remain increase in future years (Jayanthi et al. 2017). According to small island developing states (SIDS), the small islands nations are most vulnerable to climatic change, which impacts resulting in limited freshwater and land availability, food scarcity and energy stocks (Schwerdtner Mánez et al. 2012; Borges et al. 2014). The SLR threatens were happened in various small island nations such as Tuvalu and Maldives, which were relatively flat and even less than 2 m elevation from the mean sea level (Brown 2001). Several works reported that the impact of disasters on small islands were more vulnerable than non-island nations (Meheux et al. 2007). The increase in the ocean surface temperature may impact severely on coral reef ecosystem and associated flora and fauna diversity (Mondal et al. 2014). Besides, the contribution of greenhouse gas from islands is insignificant to global climate change (Mimura 1999); they bear the maximum but get affected severely form the natural disasters.

An increase of 1 m sea level in Indian coast results in loss of 5764 sq.km land with displacement of seven million people (Ministry of Environment and Forests (MoEF) 2009). The 2004 Sumatra earthquake and subsequent tsunami resulted in unprecedented loss of life, property damage and morphological changes in the coastal zones of Indian Ocean rim countries (Ramachandran et al. 2005; Choowong et al. 2009; Paris et al. 2009; Meilianda et al. 2010). Besides, the Andaman and Nicobar Islands (ANI) of India was significantly damaged by the earthquake and subsequent tsunami (Ramanamurthy et al. 2005). The damage include land uplift, subsidence, destruction of coral reef, beach erosion, sediment transport deposition, damage of dunes and mangroves (Nirupama et al. 2006; Dharanirajan et al. 2007; Bahuguna et al. 2008; Prerna et al. 2014; Mageswaran et al. 2015). The geomorphic changes in ANI were studied by using pre- and post-earthquake remote sensing data and quantified their areal extents (Narayana, 2011). In addition, the subsidence and emergence of north and middle Andaman districts were reported from South Andaman group of Islands (Rajendran et al. 2007). Recent study from Cuddalore coast of India has reported that around 16.08 km² area of geomorphological features and 17.5 km² of LU/LC are expected to be affected in future years (Dhanalakshmi et al. 2019). However, the impacts of SLR and shoreline changes in the coastal area of ANI are not studied in detail. Hence, we made an attempt to estimate the potential impacts of SLR in the coastal area of ANI and its historical shoreline changes by using geospatial techniques.

1.1 Study area

Little Andaman is the southernmost and fourth largest island (10° 30’ to 10° 54’ N and 92° 29’ to 92° 31’ E) among the Andaman group Islands (Fig. 1). This island covers a coastline area of 110 km with its aerial extent of 734 sq.km. According to Indian census 2011, the total population of the island was 18,823 which include 16 inhabited villages that consist of 4 g panchayats and residence of Onge aboriginal tribe. Moreover, this island is considered as tribal reserve area since 1957. The topography of this island is highly undulating with the highest elevation of 210 m in the central region, where the north and northwestern portions show lesser elevation (0–12 m). The island consists of ecologically sensitive ecosystems such as mangrove, coral reef, sand dune, sandy beach and turtle nesting sites. The tourist attractions of this island including White Surf and Whisper Wave waterfalls, Palm oil plantation, Bala reef, Netaji Nagar, Butler Bay beach and dams in Ramakrishnapur and Vivekanandapur are significantly important. Besides, Hut Bay and Dugong Creek are the two main Ports of Little Andaman island. According to the Government of India (Ministry
of Home Affairs 2005), this island was significantly affected by the 2004 tsunami and claims a death toll up to 37 people.

2 Materials and methods

2.1 Data

In the present study, Landsat imagery of different periods from US Geological Survey (USGS) were obtained and utilized to study shoreline changes. Besides, the Google Earth imagery (digital globe) 2018 was used to update the LULC features. For land elevation, Shuttle Radar Topographic Mission (SRTM) data of 90 m resolution were downloaded from www.earthexplorer.usgs.gov website and Survey of India Toposheet (87B/5, 87B/9, 87B/6, 87B/10) of 1:50,000 scale was used to extract the topographic contours to create a DEM (Table 1).

3 Methods

3.1 Shoreline change mapping

The multi-temporal satellite data are frequently used to extract shorelines from different periods (Umit Duru 2017). Initially, the 2004 satellite image was rectified using 20 ground
| S. no. | Data type    | Satellite/map/in situ measurements | Date of acquisition | Spatial resolution (m) | Source                                      | Purpose         |
|-------|--------------|------------------------------------|---------------------|------------------------|---------------------------------------------|-----------------|
| 1     | Remote sensing | Landsat-8/ETM+                      | 30/10/2018          | 30                     | www.earthexplorer.usgs.gov                 | Shoreline change|
|       |              | Landsat-5/TM                        | 26/02/2010          | 30                     |                                             |                 |
|       |              | Landsat-5/TM                        | 20/02/2005          | 30                     |                                             |                 |
|       |              | Landsat-5/TM                        | 13/03/2004          | 30                     |                                             |                 |
|       |              | Landsat-5/TM                        | 21/11/1989          | 30                     |                                             |                 |
|       |              | Landsat-2/MSS                       | 18/03/1976          | 60                     |                                             |                 |
| 2     | Remote sensing | Landsat-8/ETM+                      | 30/10/2018          | 30                     | National Remote Sensing Centre             | LULC            |
|       |              | Digital globe                       | 2018                | 1                      | Google Earth imagery                       | LULC            |
| 3     | Remote Sensing | SRTM                               | 2011                | 90                     | www.earthexplorer.usgs.gov                 | DEM             |
| 4     | Map          | Toposheet                           | 1979                | 1:50,000 scale (25 m)  | Survey of India                            | DEM             |
| 5     | In situ      | Handheld GPS                        | 2016                | ±3                     | NCSCM                                       | Field survey    |
control points (GCPs) collected randomly in the field by using Trimble handheld Global Positioning System (GPS). Then, the other set of images were geocoded using image to image rectification method and projected all the images to Universal Transverse Mercator (UTM) Zone 46 N and World Geodetic System (WGS) 84 Datum by using Earth Resources Data Analysis System (ERDAS) imagine software.

In this study, we have adopted the wet–dry boundary as shoreline, and using visual interpretation technique, shorelines were manually digitized in ArcGIS 10.2.1 software for different periods. The extracted shorelines of different periods were fed into digital shoreline analysis system (DSAS) to estimate the change rate. The DSAS is a freely available software, which runs as an additional tool within ArcGIS software and calculates statistical methods using various shorelines. Moreover, the DSAS generates transect lines perpendicular to the shoreline and the transect spacing and length are set at 100 m and 1 km, respectively (Fig. 2).

A total of 1285 transects were built to estimate the erosion/accretion rates along the study area. However, three methods were used to estimate the rate of shoreline changes, viz. end point rate (EPR), linear regression rate (LRR) and weighted linear regression (WLR). In EPR method, the change rate is estimated by the time elapsed between the oldest and the youngest shoreline positions. In LRR method, the rate of change was calculated by fitting a least-squares regression to all shoreline points for particular transects (Theiler et al. 2003). The LRR method is having its own advantage which includes all shoreline data’s are taken into consideration, easy to employ, irrespective of changes in trend or accuracy, and estimates the variations based on proven statistical concepts (To and Thao 2008). The WLR technique uses a linear regression, considering the account weight of uncertainty errors to determine a best-fit regression line (Fletcher et al. 2012). The uncertainty errors (both positional and measurement) considered in the study were digitizing error, rectification error, pixel error, tidal fluctuation and seasonal error. Based on the results obtained from the DSAS, the shoreline is classified into three classes, i.e., erosion (< – 1), stable (– 1 to + 1) and accretion (> + 1). The present study adopted the stable coast (− 1 to 1 m/year) classification criteria used by Mahapatra et al. (2015).

### 3.2 Land-use and land-cover mapping

The Landsat-ETM+ (2018 image) was used to prepare the land-use/land-cover (LULC) map. Though the Landsat image is ortho-rectified, the satellite was geometrically corrected by ERDAS IMAGINE software with available ground control points (GCPs) which were collected randomly by using Trimble handheld GPS. The satellite image was projected to UTM Zone 46 N and Datum WGS84. The false color composite (FCC) was applied in the satellite image to classify the features. Then using visual interpretation technique, the features were manually digitized based on the visual interpretation keys in ArcGIS software and LULC map was prepared. Further, it was updated with the recent (2018) Google Earth imagery. A field verification was carried out with the help of handheld GPS for checking accuracy of the generated LULC map, and modifications were made accordingly.

### 3.3 Inundation mapping

The most apparent effect of SLR is the everlasting inundation of coastal region. The inundation refers to the gradual submersion of the low-lying coastal lands by sea waters. In this study, we created a DEM by using Shuttle Radar Topographic Mission (SRTM) data and
Survey of India’s topographic contours. Besides, the SRTM image was used for a spatial resolution of 90 m, with horizontal and vertical accuracies of less than 45 m and 15 m, respectively, and the relative accuracy to the coastline was less than 1 m (Demirkesen et al. 2008). However, the both the data sets were having different resolution; therefore, we

Fig. 2  Baseline, transects and different shoreline constructed along Hut Bay
applied kriging interpolation method to merge the data in ArcGIS for producing a seamless topographic DEM. In addition, the DEM data were used to generate three different inundation scenarios (viz., 1 m, 3 m and 5 m) through the spatial analyst tool in ArcGIS software. As a result, we could assessed the areas of submergence easily and the impact of projected SLR by overlaying three different inundation scenarios on LULC map.

4 Result and discussion

4.1 Assessment of short-term shoreline changes

Generally, the shoreline of Andaman and Nicobar Islands (ANI) has not observed any large-scale variation in the past (prior to 2004 earthquake). But, the 2004 Sumatra earthquake event made significant changes in the coastal morphology of ANI (Anu and Rajendran 2006). So, to address the impact of 2004 earthquake event, we assessed the pre- (2004) and post- (2005) shoreline changes to Little Andaman. In the present study, the EPR method was used in DSAS for assessment of short-term shoreline change covering three different periods such as 1976–2004; 2004–2005 and 2005–2018. During the period 1976 to 2004, the shoreline migration change rate was varied from −8.8 to 7.7 m/year and the average rate was −0.27 m/year (Fig. 3a). The average shoreline change rate in eroding coast was −2.8 m/year, and in the accreting coast, the change rate is 2.42 m/year (Table 2). Moreover, the majority of the coastal areas showed a stable coast (58.4 km) followed by

![Graphical representation of shoreline change rate.](image)

**Fig. 3** Graphical representation of shoreline change rate. a EPR: 1976–2004, b EPR: 2004–2005, c EPR: 2005–2018, d WLR and LRR: 1976–2018
Table 2  Shoreline change statistics using different statistical methods

| Method | Period     | Mean Shoreline change (m/year) | Erosion | Accretion |
|--------|------------|--------------------------------|---------|-----------|
|        |            |                                | %       | Max (m/year) | Min (m/year) | Mean (m/year) | %       | Max (m/year) | Min (m/year) | Mean (m/year) | Stable % |
| EPR    | 1976–2004  | −0.27                          | 30.35   | −8.8       | −1.01       | −2.89       | 24.2    | 7.78       | 1.01       | 2.42       | 45.45    |
|        | 2004–2005  | 97.87                          | 27.6    | −232.2     | −1.01       | −34.46      | 68.9    | 900.1      | 1.02       | 155.9      | 3.5      |
|        | 2005–2018  | 0.90                           | 24.6    | −17.56     | −1.01       | −3.72       | 42.6    | 60.96      | 1.01       | 4.24       | 32.8     |
| LRR    | 1976–2018  | 2.64                           | 12.9    | −5.53      | −1.02       | −2.63       | 58.3    | 23.86      | 1.01       | 5.10       | 28.8     |
| WLR    | 1976–2018  | 3.36                           | 9.9     | −4.22      | −1.01       | −2.19       | 60.3    | 30.06      | 1.01       | 5.92       | 29.8     |
erosion (39 km) and accreting (31.1 km; Table 3). These results indicate that erosion was recorded in the coast of Hut Bay and south of Onge Tikry Island (Fig. 4a).

In order to assess the morphological changes occurred due to 2004 earthquake, we used pre-earthquake (2004) and post-earthquake (2005) satellite images. The analysis result showed that around 27.6% eroded coast, 3.5% stable coast and 68.9% accreting coast (Fig. 5). The erosion was recorded along Dugong Creek, Vivekanandpur, Hut Bay and South Bay (Fig. 4a). The improved accretion areas are due the December 26, 2004, earthquake event, which resulted in upliftment of the western side of Andaman. The graphical shoreline changes for the period 2004–2005 is shown in the Fig. 3b. Meltzner et al. (2006) analyzed the pre- and post-satellite images and a tidal model for mapping the 2004 earthquake associated extent upliftment and subsidence in ANI. They found that the southern and eastern areas were gone down, whereas the northern and western Andaman Islands were uplifted. Besides, they reported that islands falling on the east of the pivot lines were subsided and the western side was uplifted. Moreover, Bilham et al. (2005) studied the impact of 2004 earthquake by using aerial photograph of ANI and reported that the north-west coast of the North Sentinel island was actually uplifted in range of 1–2 m.

The morphological changes in Trinkat Island was studied by Yunus and Narayana (2015), the images of pre-tsunami and post-tsunami showed that 2.31 sq.km of the land area got submerged. This result showed that the island is dynamic after the tsunami and around 464 ha of beach area got lost during the period of 2004–2013. During 2005 to 2018, the majority of the coastal areas showed accretion around 42.6% and erosion in the range of 24.6% (Fig. 3c). The stable coastal area was noticed over 42.2 km, which was 32.8% of the total shoreline (Fig. 5). The average accretion was 4.2 m/year and erosion was −3.7 m/year, and the major erosion was noticed between the north of Jackson Creek and Apl island, and south of West Bay and Sandy point (Fig. 4a, Table 2).

4.2 Assessment of long-term shoreline changes

The long-term shoreline change rate for 42 years (1976 to 2018) was studied by using LRR and WLR methods (Fig. 4b). The LRR method change rate was varied from -5.5 to 23 m/year, and erosion and accretion were found in the rate of 12.9% and 58.3%, respectively. The stable coast was recorded in 28.8% of the coast and exhibited with 370 transects. The average shoreline change rate in the eroding coast was −2.6 m/year and that in the accreting coasts was 5.1 m/year (Figs. 3d, 5; Tables 2, 3). Through WLR method, accretion was recorded along 60.3% of the coast, while the stable and eroding coast reported were 29.8% and 9.9%, respectively (Fig. 5). The average shoreline change rate in the eroding coast was −2.2 m/year and accreting coasts was 5.9 m/year. The overall mean change rate (3.3 m/year) obtained by WLR was higher than the average change rate of LRR (2.6 m/year) method (Table 2). In general, the long-term shoreline changes showed more accretion than erosion (Fig. 4b).

Malik and Murty (2005) studied the pre- and post-earthquake water levels in Diglipur and Mayabunder jetties, and the results showed that the Andaman Islands were vertically uplifted by 1.2 m. Island got submerged around 2.5–3.0 m in Great Nicobar Island (Malik et al., 2006). Chini et al. (2008) used Synthetic Aperture Radar (SAR) images to identify the upliftment of the entire west coast of Little Andaman. Anu and Rajendran (2006) used GPS measurements to measure the upliftment/subsidence along ANI and found that Little Andaman island and northeastern part of Andaman Island were uplifted to 36 cm and 63 cm, respectively, whereas Port Blair was subsided to 87 cm. Yunus et al. (2016)
| S. no. | Period       | Statistical method | Eroding coast                                                                 | Accreting coast                                                                 | Stable coast                                                                 | Transects records erosion/accretion/stable coast |
|--------|--------------|--------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------|
| 1      | 1976–2004    | EPR                | Between Kalapathar and Indira bazar, Onge Tikry, Ekiti Bay, north of Jackson Creek | Between Burmila Creek and Dugong Creek, Sandy point, south of West Bay           | Between Dugong Creek and Butler Bay, West Bay                                    | ![Chart](image1.png)                          |
| 2      | 2004–2005    | EPR                | Dugong Creek, Vivekanandpur, between Kalapathar and Indira bazar, South Bay     | Entire western part of Little Andaman, between Bumila Creek and north of Dugong Creek, Onge Tikry, Sandy point | Few transects north of Onge Tikry                                                  | ![Chart](image2.png)                          |
| 3      | 2005–2018    | EPR                | Between south of West Bay and Sandy point, between Jackson Creek and Apl island | Dugong Creek, between Kalapathar and Indira bazar, between South Bay to Sandy point, West Bay, south of Ekiti Bay | Between south of Dugong Creek and Butler Bay, Onge Tikry                         | ![Chart](image3.png)                          |
| 4      | 1976–2018    | LRR                | Between Kalapathar and Indira bazar, Onge Tikry                                | Entire western and northern part (except Jackson Creek), Dugong Creek            | Between north of Vivekanandpur and Kalapathar, few transects in north of Onge Tikry and Jackson Creek | ![Chart](image4.png)                          |
| S. no. | Period  | Statistical method | Eroding coast                                                                 | Accreting coast                                                                 | Stable coast                                                                 | Transects records erosion/accretion/stable coast |
|-------|---------|--------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------|
| 5     | 1976–2018 | WLR                | Between Few transects in Hut Bay, Onge Tikry                                 | Entire western and northern part (except Jackson Creek), Dugong Creek           | Between north of Vivekanandpur and Hut Bay, few transects in north of Onge Tikry and Jackson Creek | ![Chart](image_url)                              |
Fig. 4  a Short-term shoreline change status, b long-term shoreline change status

Fig. 5  Statistics of shoreline change status in different periods
reported that the landform changes in the Katchal Island and its western part is constantly eroding at a lower rate even after 10 years of 2004 earthquake event and it could be due to strong wave and tidal currents prevailing in monsoon periods. The beach recovery in Banda Aceh was noticed after six months of tsunami event. An accretion in the western and beach loss in the northwest coast were noticed. The Phang-nga beach was recovered completely within 2 years from the tsunami event (Melianda et al. 2010; Choowong et al. 2009). However, Thailand coast was not restored to its original form due to natural erosion and anthropogenic activities (Szczuciński 2012). The shoreline changes in the Little Andaman were connected to natural factors such as waves, tidal action, long and cross-shore currents, tsunami and storm surges. The newly constructed jetty and breakwater (after tsunami) in Hut Bay Island lead to a negative impact on coastal morphology (Roy 2017). Besides, the construction of dams at Vivekanandpur and Ramakrishnapur caused less supply of sediment to the coast and drawn in shoreline configuration.

The shoreline variations are associated with repeated cyclonic storms and the SLR and disturb with shore sediment transport by human activities such as harbors, groins or breakwaters and are obstruct to natural sediment movement and reducing the sediment deposit in the coast (Morton 2008). The satellite image were showed that fringing reefs were very limited at eastern side and few patches in western side of Little Andaman. Earlier studies on coral reef suggest that declining in coral covering area in ANI was triggered owing to tsunami waves in 2004, and coral bleaching events were documented during 2005, 2009, 2010, 2012 (Mondal et al. 2013; Dam-Roy et al. 2014). The decline in coral cover area directly increases the erosion in the coast by invading strong waves. Besides, illegal sand mining in the coastal area also may affect the coastal morphology (Cherian et al. 2012).

4.3 Estimation of land use and land cover (LULC)

The LULC map for Little Andaman was derived from the Google Earth imagery (2018) and categorized into 13 classes with aerial extent (Fig. 6; Table 4). The reserve forest covered a largest component of LULC, which covered 58,414.28 ha (79.64%) followed by mangroves 3933.43 ha (5.36%), settlement with vegetation 3220.6 ha (4.39%) and plantation 2111.31 ha (2.88%; Table 4). In previous study, nearly 237.13 ha of reserve forest was reported as lost due to 2004 tsunami and further reduced to 681 ha between 2003 and 2010 due to expansion of settlements area (Shankar et al. 2013). However, recent study reported that the forest cover reduced from 623.65 sq.km (1976) to 593 sq.km (2017) and most prominent changes were noticed after the tsunami (Mahapatra et al. 2019). The mangroves of Little Andaman were found along creeks and intertidal mudflats in the northeast and northwestern parts of this island, especially in Jackson creek, Dugong creek and Bumila creek (Fig. 6). The present study estimated that mangrove covering area was 4130 ha during 2018 and the *Rhizophora* and *Bruguiera* species were the dominant species in the Little Andaman island. Due to tsunami, around 3400 ha of mangrove area was submerged, and 1700 ha and 140 ha were damaged and degraded, respectively (Shankar et al. 2013). After the tsunami, around 1973 permanent shelters were constructed in Little Andaman (Hut Bay and Netaji Nagar) with the help of government and non-governmental organization (NGO) (http://www.and.nic.in/shelterP/islandwise.htm). Besides, a large number of infrastructure setup were brought in to this island, which includes community buildings (community hall, health subcenter, schools, etc.), sanitary systems and road network.
However, some infrastructures and tsunami houses were expanded with deforestation of reserve forest in some locations. From the literature study, we understand that settlement with vegetation is increased gradually due to increasing population and associated infrastructural development, establishment of permanent tsunami shelter and tourism development. Plantation in Little Andaman was estimated as 2111.31 ha (2.88%) in 2018, and
Table 4  Extent of inundation (ha) in various LULC categories

| S. no. | LULC class                  | Area in 2018 (ha) | % of area in 2018 | Area of inundation at 1 m SLR (ha) | % of inundation at 1 m SLR | Area of inundation at 3 m SLR (ha) | % of inundation at 3 m SLR | Area of inundation at 5 m SLR (ha) | % of inundation at 5 m SLR |
|--------|----------------------------|------------------|------------------|-----------------------------------|--------------------------|-----------------------------------|--------------------------|-----------------------------------|--------------------------|
| 1      | Degraded forest            | 443.81           | 0.61             | 192.71                            | 43.42                    | 291.67                             | 65.72                    | 336.64                             | 75.85                    |
| 2      | Degraded mangroves         | 196.63           | 0.27             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| 3      | Exposed rock/reef          | 401.73           | 0.55             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| 4      | Jetty                      | 4.05             | 0.01             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| 5      | Mangroves                  | 3933.43          | 5.36             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| 6      | Plantation                 | 2111.31          | 2.88             | 1.72                              | 0.08                     | 8.25                               | 0.39                     | 29.19                             | 1.38                     |
| 7      | Reserve forest             | 58,414.28        | 79.64            | 831.91                            | 1.42                     | 1696.99                            | 2.90                     | 2576.10                            | 4.41                     |
| 8      | Reservoir                  | 75.51            | 0.10             | 0                                 | 0                        | 0                                  | 0                        | 0                                 | 0                        |
| 9      | Sandy beach                | 351.91           | 0.48             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| 10     | Scrub land                 | 173.06           | 0.23             | 5.7                               | 3.29                     | 14.2                               | 8.2                      | 23.40                             | 13.5                     |
| 11     | Settlement with vegetation | 3220.60          | 4.39             | 10.72                             | 0.33                     | 37.98                              | 1.18                     | 72.38                             | 2.25                     |
| 12     | Submerged rock/coral reef  | 3621.29          | 4.93             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| 13     | Water body                 | 392.69           | 0.53             | NA                                | NA                       | NA                                 | NA                       | NA                                | NA                       |
| **Total** |                           | 73,340.3         |                  | 1042.76                           |                          | 2049.09                           |                          | 3077.71                           |                          |

NA—not applicable because it is located in the intertidal zone
agriculture is the backbone for local people in this island, despite tourism and fishing activities. The important agricultural crops are paddy, vegetables, coconut, areca nut, red oil palm, pulses and fruits. In 1979, the Government of India sanctioned a project for raising 2,400 ha of Red Oil Palm Project in this island, and under this program, around 1593 ha was allocated for plantation within the reserve forest area. A report by environment and forests stated that the plantation in Little Andaman was carried out within the reserve forest area in some places, which also could be a reason for the reduction in the forest cover (Forest Code 2011).

Coral reef of Little Andaman exhibits narrow, linear and extensively well-developed fringing reefs in all around the island, except at Hut Bay, West bay and Jackson creek (Fig. 6). The area covers around 3621.29 ha (4.9%) and comprises three important coral genera: Acropora spp., Psammocora spp. and Goniastrea sp. According to Coastal Ocean Research and Development in the Indian Ocean status report (Obura et al., 2008), an estimate of 12.85 sq.km of reef area was damaged in Little Andaman due to the 2004 tsunami. The island hosts white sandy beaches in Butler Bay, Hut Bay, Harminder bay, John Richardson Bay, South Bay, West Bay and Ekiti Bay which covers an area of 351.91 ha (0.4%). The Butler Bay and Hut Bay beaches of Little Andaman serve as tourist hotspots. The sandy beaches of Little Andaman also host nesting of turtles and the major turtle species of this island includes Hawksbill, green, olive ridley and Leatherback. The nesting site of green turtles is more than other turtles, which was reported in West Bay, South Bay, north of Hut Bay, Butler Bay, south of Bumila Creek, north and south of Jackson Creek (Andrews and Tripathy 2004). The field photographs of LULC and coastal features of Little Andaman are shown in Figs. 7 and 8.

4.4 Estimation of inundation due to SLR

Three different inundation scenarios, i.e., 1 m, 3 m and 5 m, were generated using the spatial analyst tool in ArcGIS software (Fig. 9). The projected SLR impact on LULC showed the level of inundation and the type of LULC to be affected (Table 4). If the sea level rises around 1 m, submerge may take place in an area of 1042 ha. Likewise, 3 m and 5 m rise may cause submerge around 2049 ha and 3077 ha, respectively. Under the 1 m SLR scenario, these study results show that some areas such as reserve forest (831.908 ha), degraded forest (192.7 ha), settlement with vegetation (10.7 ha), scrub land (5.7 ha) and plantation (1.7 ha) areas may be submerged (Table 4). Similarly, 5 m SLR scenario may cause submerge of reserve forest largely with an aerial coverage of 2576 ha, followed by degraded forest (336.64 ha), settlement with vegetation (72.3 ha), plantation (29.19 ha) and scrub land (23 ha). A related study from Andhra coast reported that rise of 0.6 m SLR may displace more than 1.29 million people from the coast. Moreover, the study mapped and categorized very high-risk areas such as mudflats, mangrove swamps and backwaters of Krishna, Godavari and Penner deltaic region (Rao et al. 2008). In the vulnerability point of view, coastal slope plays an important role in determining the extent of inundation for any coastal hazards (Dinesh Kumar 2006). The effect of SLR would be significant to a low-lying coast and conflicting to steeply sloping coast (Mani-Murali et al. 2013). During 2004 tsunami, the maximum inundation was taken place at Akkaraipettai (Nagapattinam district, Tamil Nadu) which was due to the low-lying and gently sloping topography (Ramanamurthy et al. 2005). However, the high-elevation and steep sloping coast of Kanyakumari and Kadiapattinam (south Tamil Nadu) were experienced only less inundation (Chandrasekar et al. 2007).
Fig. 7  Field photographs.  a cliff in Netaji nagar,  b Hut Bay jetty,  c beach view north of Hut Bay,  d coastal forest in the southern tip,  e beach view south of Hut Bay jetty,  f eroding site in Harminder Bay,  g mangroves in Dugong creek,  h coral debris near Bumila creek
Three primary coastal features of the present study area, viz. reserve forest, settlements with vegetation and plantation, suffer the maximum damage of inundation due to rising sea level. The major forest types in the study area include Andaman tropical evergreen, Andaman semievergreen, Andaman moist deciduous and littoral forests (Champion and Seth 1968). From this study, we found that around 1024 ha (44.84%) of forest land (includes both degraded forest and reserve forest) would be submerged due to 1 m SLR and for 3 and 5 m rise, and the submergence would be 1988.4 ha (68.6%) and 2912.7 ha (80.26%), respectively. The littoral forests (reserve forest) would be under severe threat of inundation due to 1 m and 5 m SLR, which covers between 150 and 200 m from the seashore, and are mostly dominated by endemic trees Manilkara littoralis, Terminalia catappa, Gyrocarpus americanus, Guettarda speciosa and Pongamia pinnata (Rasingam and Parathasarathy 2009). The coastal forest act as a defense mechanism to reduce the impact of tsunami and storm surges (Yanagisawa et al. 2009). During 2004 tsunami, the dense coastal vegetation reduced the height of the tsunami wave, whereas the absence of coastal forests caused the highest level of damage (Shuto 1987; Danielsen, 2005). The settlements with vegetation (LULC category) in Little Andaman island experience the second largest damage by the projected SLR. The settlement area is spread across five revenue villages of Little Andaman, viz. Vivekanda Pur, Rabindra Nagar, Ram Krishna Pur, Netaji Nagar and Hut Bay. Among this, Netaji Nagar and Hut Bay are located in the southeast of Little Andaman, which are highly vulnerable to SLR due to the gentle slope, low-lying coastal topography and population density. The settlements with vegetation category’s inundation to 1 m SLR are about 10.72 ha, and for 3 m and 5 m SLR, they are 37.98 ha and 72.38 ha, respectively. The Tsunami houses in Little Andaman are constructed at higher elevation (around 10 m) and located 1 km away from the coast, which show the safety and free from coastal hazards. Plantation in Little Andaman also has a considerable damage due to SLR, and around 1.72 ha (0.08%) of land would be susceptible to 1 m SLR. A 3 and 5 m rise, around 8.25 ha (0.39%) and 29.19 ha (1.38%), would be submerged, respectively. From the field survey, we noticed areca nut plantation in Vivekanandpur and Rabindra Nagar villages. Besides, coconut plantation is noticed in Hut Bay area (south).

The Rhizophora and Bruguiera species are the two dominant mangrove species in the Little Andaman. The SLR may have significant adverse effect on mangroves and it could alter to SLR to a certain degree by expanding landwards or seawards (Spalding et al. 2014). However, it does not survive in less rate of sediment formation than the rate of SLR (Gilman et al. 2008). The impact of SLR on mangrove ecosystems is based on the substrate type, marine processes, local tectonics, sediment and freshwater availability and salinity of soil and groundwater (Semeniuk 1994; Blasco et al. 1996). The SLR is expected to reduce the mangrove coverage and decrease in species diversity on small islands with micro-tidal sediment-limited environments (Raha et al. 2012). Coral reefs are highly sensitive and are particularly susceptible to SLR due to minor changes in environmental conditions. A slight increase in sea temperature (as little as 1–2 °C) can cause stress and leads to coral bleaching (Dodge et al. 2008). A large-scale destruction of coral reef in ANI was noticed due to tectonic activity and subsequent tsunami event (Kulkarni et al. 2008). Moreover, many bleaching events were reported from the Andaman Sea due to increase in the surface temperature in the years of 1991, 1995, 1997, 1998 and 2010 (Mondal et al. 2013). Previous study reported that around 80% bleaching occurred in Andaman coral reefs in the year 1998 (Pet-Soede et al. 2000). The loss of coral reefs indirectly affects the socioeconomic of the coastal communities through fisheries, commercial tourism, recreational opportunities and hazard proneness of the shore.
Fig. 8 Field photographs. a coastal forest and exposed rocks during low tide, b tsunami rehabilitation area in Hut Bay, c mangroves in Bumila creek, d areca nut plantation, e jetty area, f agricultural activity, g Butler Bay beach, h White Surf waterfalls
Sandy beaches in the Little Andaman are the important tourist destinations and breeding ground for sea turtles. These beaches were severely affected by the 2004 tsunami and later recovered substantially (Swaminathan et al., 2011). The sandy beaches are susceptible to the impact of rising sea level, which results in the vanishing of pristine beaches and subsequently affects the livelihood of the people and the country's economy. Moreover, it also causes loss of turtle breeding site and consequently in decline of turtle population.

4.5 Mitigation measures

The following are some of the mitigation measures to overcome climatic change and SLR impact (modified after Natesan and Parthasarathy 2010).

1. Special attention to the densely populated and low-lying coastal areas.
2. Avoiding new developmental activities near the coast (especially in predicted inundated areas).
3. Relocate the public facilities and infrastructure to safer zones.
4. Shield the highly vulnerable coast by suitable hard structures (jetties, groins or sea-walls).
5. Protect the coastal forest by proper monitoring and management.
6. Strengthen the coral reef ecosystem by monitoring and developing new coral reef restoration sites.
7. Protection of coastal sand dunes and its ecosystem.
8. Conserve and protect mangrove forest ecosystem.
9. Creating awareness on SLR and mitigation measures among the government officials and local community.
10. Enhancing the sea level monitoring techniques and develop realistic inundation scenarios.
11. To plan adaptive and risk reduction policies for the sustainable development of the coast.

5 Conclusion

We studied the shoreline changes occurred in the past and identified the vulnerable areas to the projected SLR. This shoreline change study shows that 2004 Sumatra earthquake altered the coastal morphology of Little Andaman. The results obtained by LRR and WLR methods were very similar; however, the WLR method takes into account the uncertainty errors. Hence, these two methods can be suggested for the shoreline management plan. Our study indicates that the coastal areas of Little Andaman are susceptible to flooding in various degrees resulting in permanent inundation, episodic flooding, aggravate erosion, seawater intrusion and destruction of important ecosystems (wetlands and forest). Moreover, about 1042 ha of the study area would submerge due to 1 m SLR, and it would be a slow onset phenomenon. Due to low-lying, gently slope and closeness to the coast, the Hut Bay and Netaji Nagar are more susceptible to SLR and other natural hazards (storm surges). The SLR is a potential hazard to these areas in near future and will affect coastal ecosystems and socioeconomic, hence which demands for protective measures to prevent the losses. This study would be useful to the Andaman and Nicobar administration to draw suitable disaster and mitigation management plans. Besides, this study proves that the combined usage of RS and GIS technique would be useful in monitoring the coastal ecosystem very effectively.

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Declarations

Conflict of interest No potential conflict of interest was reported by the all authors.

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