ORIGINAL ARTICLE

Impact of 2004 co-seismic coastal uplift on the mangrove cover along the North Andaman Islands

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Abstract

The December 2004 earthquake and the subsequent tsunami have incurred devastating impacts on vital habitats along the Indian coastal region, where few of them are irreversible. The earthquake has uplifted the northern Andaman coast, resulting in a drastic reduction of tidal water influx into the adjoining mangrove-laden mudflats. Satellite images of the period from 2003 to 2019 were used to assess the impact of coastal upliftment on the northern Andaman mangroves. Through satellite data analysis, we report a loss of 6500 ha of northern Andaman mangroves. Tidal hydrodynamics simulation under the post-earthquake scenario showed a vast area of mudflats deprived of tidal influx. This reduction in the tidal inundation has incurred a gradual and permanent mangrove area degradation. The earthquake impact on the mangroves was not spontaneous, but a gradual process, where the mangroves were intact until Mach 2006. The earthquake and the resultant coastal uplift have significantly altered the coastal geomorphology as well as the plant demography of the study area. Field visit revealed the terrestrial vegetation growth along the erstwhile mudflats, and vast areas of mangrove peat are observed, surrounded by successions of marshy and terrestrial plants. As mangroves are preferred habitat for diverse marine and terrestrial organisms and act as a vital food source and juvenile shelters for various fish species, the extensive loss of mangrove area may adversely affect a large scale biological ecosystem.

Keywords Mangrove habitat · 2004 Sumatra earthquake · Coseismic uplift · Andaman Islands

Introduction

Mangroves are defined as trees or bushes growing in the zone between the spring high water line and just above the mean sea level (Macnae 1968). These salt-tolerant plants help to regulate coastal flooding and erosion, thus protecting the inland coastal communities from natural hazards. Mangroves are self-generating and self-perpetuating littoral formation, which plays a major role in the global cycle of carbon, nitrogen, and sulfur (Romanach et al. 2018). They act as a habitat, supporting the life of a diverse group of flora and fauna. Moreover, mangroves are recognized for their economic functions that contribute toward a sustainable livelihood of coastal folks by providing forest products and fish resources (Anneboina and Kumar 2017). Despite its immense ecological importance, the mangrove forest around the world is facing threat from both natural extremes and anthropogenic influences.

Mangroves are often viewed as climate change indicators, owing to its sensitiveness to any disturbance in the environmental settings. The mangrove forest occurs in the tropical warm belt, with occasional subtropical extensions. Under the gradual changes in climatic conditions, mangrove forests undergo a spatial shift from their traditional domain. Reductions in the severity and frequency of discrete freezing events have favored the poleward shift of mangrove forests (Cavanaugh et al. 2014). Another climatic-driven range shift is the gradual conversion of the salt marsh into mangroves, primarily driven by regional warming (Coldren et al. 2019). The prehistoric climate-driven mangrove range shift is evident from the stratigraphic samples of present flood plains, where mangroves have been flourishing during the mid-Holocene times (Woodroffe et al. 1985).

Even though the mangroves are sensitive to climatic changes, they are also reported to show resilience. The mangroves

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exhibit a strong ability to modify their environment and promote habitat persistence under a sea-level rise scenario through surface elevation change processes and landward migration of successive generations (Krauss et al. 2014). Natural calamities like cyclones and tsunami have sometimes severely damaged the mangrove area, where it has been permanently transformed into a different ecosystem (Smith et al. 2009), while mangroves destroyed during cyclones are also reported to have recovered gradually by regenerating the lost area. According to Paling et al. (2008), the cyclone Vance had removed an approximate 5700 ha mangrove area along the eastern Exmouth Gulf, north western Australia however, 1500 ha of mangroves have regenerated during 6 years.

The gradual climatic changes and its interaction with extreme events have permanently changed the environmental conditions at several places that have resulted in the degradation of mangroves. Press and pulse associated with climate change and extreme events are attributed to the extensive mangrove dieback in the northern Australia (Harris et al. 2018). Ecosystem response under the changing climatic trends is not immediate, rather it is considered as a cumulative response to long-term stresses. A review of the recent climatic change impact on mangrove forests is carried out by Ward et al. (2016). The tropical cyclones, tsunami, and extreme cold or drought and flooding events are listed as the major natural forces by Sippo et al. (2018) that affect the mangrove mortality. These natural events have degraded 0.2% of the total mangrove cover of 2011. Tropical cyclones have caused 45% of the global area mangrove mortality. Even though the tsunami frequency is 10% less than the cyclonic events, the tsunami accounts for 18% of historical mangrove area loss (Sippo et al. 2018). The tsunami waves at Phang Nga, Thailand are reported to uproot the whole tree and at places, the waves have torn the mangrove leaves and branches resulting in the devastation of the mangrove forests (Kamthonkiat et al. 2011).

Remote sensing technology augments the monitoring studies of mangroves and its temporal changes. With the availability of free satellite data sets of high temporal and spatial resolution and sophisticated computation facility, Cardenas et al. (2017) reasoned to enhance the program skills for developing an automated mangrove monitoring system. Satellite images are widely used to map the mangrove extent and have brought out its temporal changes over decadal time frames (Ibharim et al. 2015; Son et al. 2015; Quader et al. 2017; Sumiko et al. 2017).

As the mangrove area degrades, it significantly affects the biodiversity of the region. The mangrove area is a preferred breeding ground for diverse marine and terrestrial organisms. Juvenile sharks and many reef fishes prefer the mangrove as their nursery grounds because of its abundance in prey and acts as a shelter from the predators (Morrissey and Gruber 1993). A recent study by Carugati et al. (2018) has reported

a loss of benthic biodiversity at degraded mangrove areas and highlighted the need to preserve the mangrove forests to maintain the functioning of the tropical ecosystem. In the present study, we report slow and vast scale mangrove forest deterioration along the northern Andaman due to the coastal uplift during the December 2004 earthquake.

Study area

The Andaman and Nicobar archipelago consists of 572 scattered islands, located broadly parallel to the subduction zone trench known as the Sunda trench (Curray 2005). The Islands are located in the torrid zone with a tropical climate, where the annual rainfall is around 3000 mm (Kumar et al. 2012). These islands are bestowed ecological reserves of the rich biodiversity of flora and fauna. The dense mangrove forest fringing the coast and over the tidally inundated regions is one of the most important florae of the Andaman and Nicobar Islands (ANI).

The ANI mangroves are relatively secluded with negligible anthropogenic influence compared to the Indian mainland. Among the Indian mangrove forests, they are considered best for its density and growth (Saxena et al. 2013). ANI has 35 mangrove species out of the 39 reported from India (Kathiresan 2018), where family *Rhizophoraceae* represents the major mangrove vegetative component followed by *Acanthaceae*, *Lythraceae*, and *Malvaceae* (Bharathi et al. 2014; Ragavan et al. 2015). The December 2004 earthquake and the associated tsunami have extensively devastated the vegetation, specifically the mangrove forest along the coastal region.

Several studies are carried out to assess the post-tsunami status of the ANI mangroves. In most cases, the studies have assessed the changes due to the tsunami impact and the submergence at the South Andaman and the Nicobar Islands (Chatterjee et al. 2008; Sachithanandam et al. 2014; Roy 2016). The 2004 Indian Ocean tsunami has damaged around 50% of the South Andaman mangroves, where a vast area has submerged under the seawater (Dharanirajan et al. 2007). The subsidence at the Nicobar Islands has resulted in an estimated 97% mangrove forest degradation (Nehru and Balasubramanian 2018). Nehru and Balasubramanian (2018) also have reported the transformation of erstwhile terrestrial land to inter-tidal zone forming potential sites for mangrove colonization.

The present study has focused on the extensive mangrove lose within the northern Andaman Island (93° 73'E - 92° 47'E and 13° 15'N - 13° 40'N). The region comes within the Diglipur forest division (Fig. 1), where *Rhizophora apiculata* is the dominant vegetative component of mangrove followed by *Bruguiera gymnorrhiza*, *Rhizophora mucronata*, *Ceriops tagal*, and *Bruguiera* sp. (Ragavan et al. 2015). Unlike the
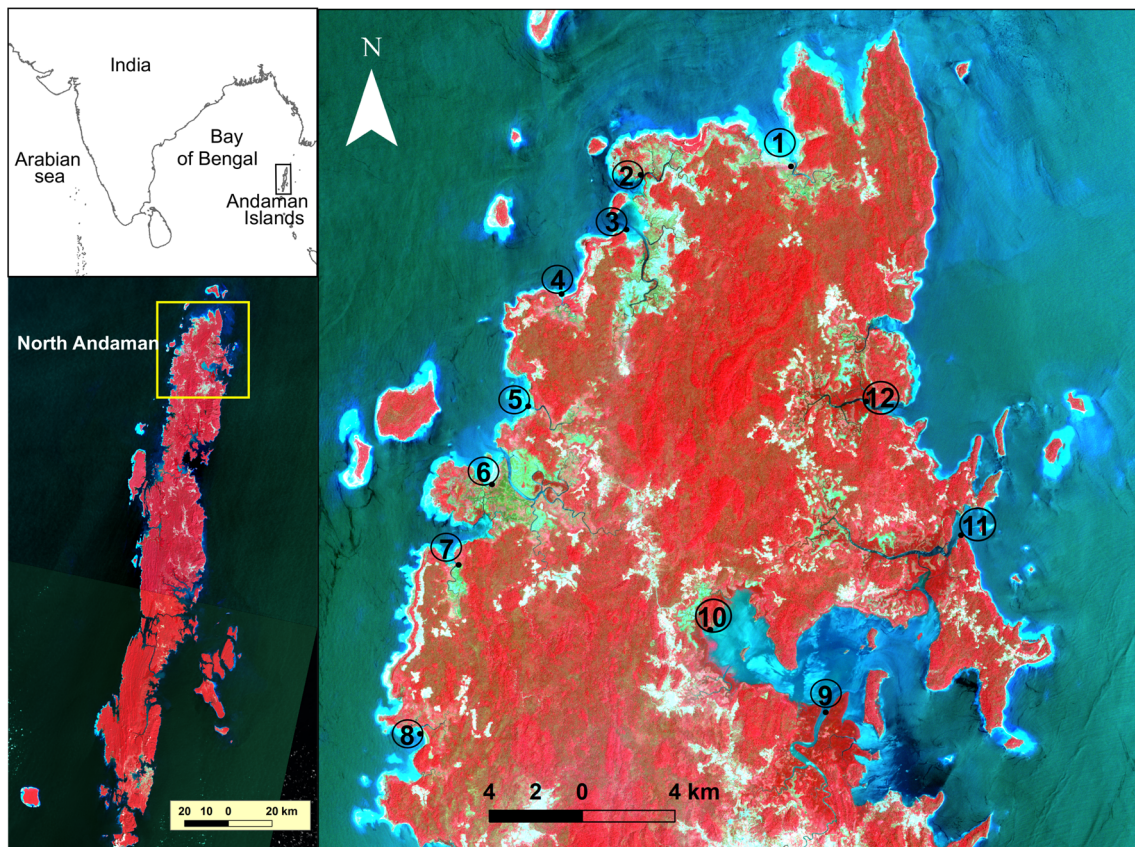
Fig. 1 Resourcesat-2 LISS4 FCC image of March 20, 2014 showing the study region of northern Andaman Islands; 1) Beele Bay, 2) Buchanan Bay, 3) Elizabeth Bay, 4) Jerotong Nala (Stream), 5) Ducan Bay, 6) Radhanagar Nala, 7) Burma Nala, 8) Hudson Bay, 9) Aerial Bay, 10) Blair Bay, 11) Terapa River, 12 Paichtar River

South Andaman and the Nicobar Islands, the northern Andaman Islands have uplifted during the coseismic land-level changes associated with the December 2004 earthquake. Roy and Krishnan (2005) have carried out field investigations along the northern Andaman Islands, and they reported the apparent mangrove degradation. Even though studies have reported mangrove mortality at northern Andaman Island (Ragavan et al. 2015, Saxena et al. 2013, Ray and Acharyya (2011)), they were confined to particular tidal swamps, and comprehensive analysis of the change in the area and the succession are however lacking.

Data and methodology

Datasets used

Cloud-free surface reflectance data of Thematic Mapper (TM) (Landsat 4 and 5) and Operational Land Imager (OLI) (Landsat 8) of the period from 2003 to 2019 (path number 134 and row number 51) were acquired from USGS website (http://earthexplorer.usgs.gov). Resourcesat-1 LISS-3 images are used to overcome the data gap of Landsat for 2012 and 2013. Table 1 shows the list of satellite data used.

Mangrove classification

The preserved mangrove forests are located in inaccessible regions, and remote sensing finds its importance as an additional tool in monitoring the mangrove area (Gupta et al. 2018). Over the last few decades, remote sensing data have provided spatiotemporal information on mangroves, species wise differentiation, and have aided in monitoring its health conditions (Kuenzer et al. 2011).

The present study has used Combined Mangrove Recognition Index (CMRI) developed by Gupta et al. (2018) to estimate the temporal changes in mangrove cover from the satellite image. The method incorporates outputs from NDVI and NDWI indices that classify the mangroves based on its greenness and water content. CMRI is the difference between NDVI and NDWI that assimilates the mangrove property of high water content using NDWI and the greenness using NDVI.

The spatial coherence of CMRI estimated mangrove cover is evaluated using the existing mangrove database of Coastal Zone Information System (CZIS) prepared by Space Applications Centre (ISRO) (SAC 2012) and submitted to the Ministry of Environment, Forest and Climate Change, Government of India. CZIS database is prepared by visual

Table 1 List of satellite data used

Date	Satellite	Spatial resolution (m)	Tidal elevation (m)
December 8, 2003	LANDSAT 5	30	0.032
March 13, 2004	LANDSAT 5	30	1.018
February 12, 2005	LANDSAT 5	30	0.255
March 3, 2006	LANDSAT 5	30	0.211
March 6, 2007	LANDSAT 5	30	-0.041
March 24, 2008	LANDSAT 5	30	-0.018
March 11, 2009	LANDSAT 5	30	-0.246
February 26, 2010	LANDSAT 5	30	0.434
February 13, 2011	LANDSAT 5	30	1.017
February 11, 2012	Resourcesat-2	25	-0.176
March 13, 2013	Resourcesat-2	25	1.383
March 09, 2014	LANDSAT 8	30	0.761
March 12, 2015	LANDSAT 8	30	0.306
March 14, 2016	LANDSAT 8	30	1.008
March 17, 2017	LANDSAT 8	30	0.42
January 31, 2018	LANDSAT 8	30	0.631
February 19, 2019	LANDSAT 8	30	0.045

interpretation of the 2004 LISS-4 data and is the baseline data for the Indian coastal land use land cover.

Field observations

Limited field observations are carried along the erstwhile intertidal zones at Radhanagar Nala, Elizabeth Bay, and Blair Bay. We have taken the GPS locations and identified the present-day vegetation along the region.

Hydrodynamic simulation

`The tidal hydrodynamics at Elizabeth Bay is simulated using Telemac-2D to understand the tidal influx changes after the December 2004 earthquake. Telemac-2D is an ideal modeling framework for the creek environment due to its finite element grid, which allows graded mesh resolution (Lang 2010). Shallow water Saint-Venant equations of momentum and continuity, derived from the Navier Strokes equations form the basis of the 2D depth-averaged model (Hervouet 2007). The simulation is carried out for the Elizabeth Bay where the domain is represented by a mesh with 18,666 nodes (Fig. 2). The bathymetry of the domain is prepared using the integration of available National Hydrographic Office (NHO) charts and ETOPO-1 data sets. As no values are present along the creeks, -3 m depth is assigned to the mouth, and the values are linearly reduced along the channel to -0.5 m at the creek head. The major difficulty is in assigning the topographic values of the tidal mudflat since the available DEM gives erroneous values. 2003 LANDSAT data is used to delineate the creek boundary and the tidal mudflat periphery. The creek boundary is

assigned an elevation of 0 m, and the tidal mudflat boundary is taken as 1.9 m that represents the maximum spring high tide of the region. The contours are then interpolated to obtain the topography and are integrated with the bathymetry to prepare the geometry of the domain.

Pre-earthquake earthquake hydrodynamic conditions are simulated by forcing the domain with tidal elevation data of February 2004 obtained from TPXO 7.0 data sets. A constant viscosity coefficient of 10^{-6} m^2 s^{-1} and a bottom friction coefficient of 0.35 m are used. The December 2004 earthquake has uplifted the northern Andaman Islands by 1.2 m (Malik and Murty 2005) and considering this, the post-earthquake hydrodynamics is simulated by raising the domain geometry by 1.2 m and forcing with tidal elevation data of February 2005. Tidal inundation at each element is computed for both the scenarios to estimate the inundation change under post-earthquake condition.

Results

CMRI is used to estimate the mangrove cover area using temporal satellite data listed in Table 1. The CMRI based classification of the mangrove is reported to produce higher classification accuracy compared to the other indices (Gupta et al. 2018), where the mangrove forest at Andaman is classified with an accuracy of 86.72%.

Accuracy of the CMRI is assessed by estimating the spatial coherency of CMRI mangrove cover with the CZIS mangrove database. Mangroves from CMRI result covered an area of 8591 ha, while the CZIS mangroves covered an area of about

Fig. 2 Bathymetry overlaid with grid for Elizabeth Bay along the west coast of northern Andaman Island
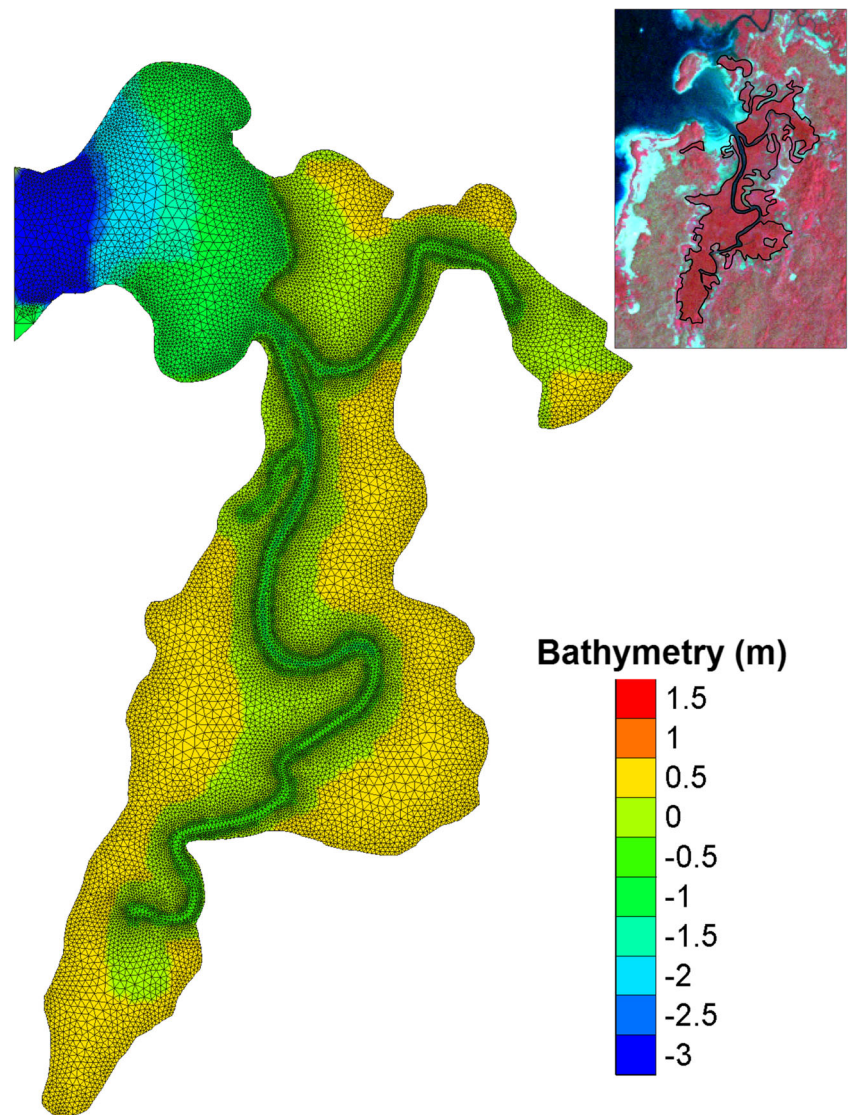

8020 ha. An area of 15% is under the commission error, and the error of omission is 9%. Over 84% of the CMRI estimated mangrove region overlap spatially with the CZIS database. Fig. 3 shows the comparison of CMRI estimated mangrove area with the CZIS database for the mangrove area for Radhanagar Nala (stream).

Table 2 shows the CMRI estimated mangrove area during 2003 and 2019 for the selected 12 sites. Fig. 4 shows the mangrove cover change and succession at Elizabeth Bay. The mangrove cover change can be viewed as disastrous since 97% of the Elizabeth Bay mangrove has disappeared from 2003 to 2019. Interestingly, a direct earthquake or tsunami impact is undetected from the satellite images. Until March 2006, 550 ha was under mangrove cover. A subsequent change is observed, where the mangrove area reduced to around 290 ha during December 2006. During 2008, the mangrove area got significantly reduced to 43 ha. Mangrove trees located further from the creek were affected first, while those fringing the tidal channel peripheries have survived.

Changes in the mangrove area at the Radhanagar Nala are shown in Fig. 4b. Fig. 5 shows the trend in the reduction of mangrove cover over the period. Until March 2006, the mangrove area remained almost constant to about more than 1500 ha and reduced to 950 ha during December 2006. The region had suffered a loss of about 93% of the mangrove habitat area (Table 2). Patches of mangroves are still observed along the tidal channel periphery.

Fig. 4c shows the mangrove cover change at Blair Bay. The temporal pattern in the mangrove cover change is presented in Fig. 5. The mangrove area at Blair Bay reports a gradual decrease, where the area has remained almost unchanged until March 2013. The CMRI estimated mangrove cover shows a gradual decrease in the mangrove area, and the total loss of mangrove forest is 72%. A pertinent observation along the region is incipient
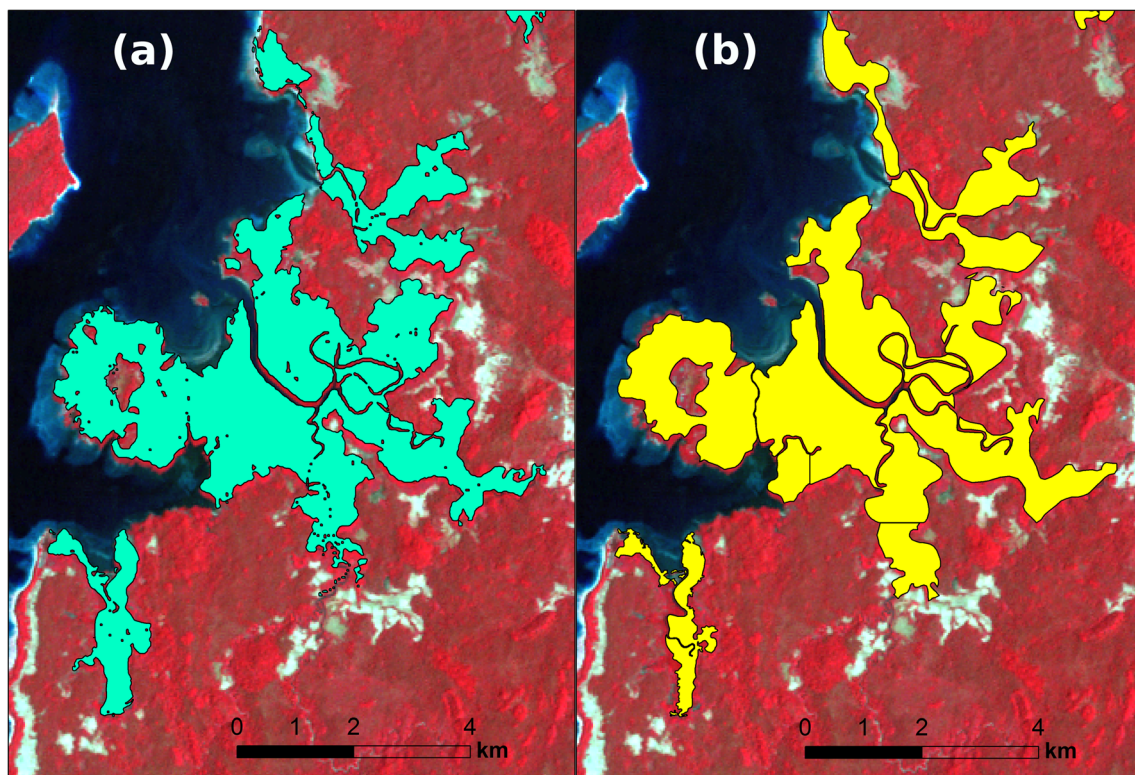
Fig. 3 Comparison of CMRI estimated mangrove cover from 2004 image with existing CZIS database of 2004 for the mangrove area along the Radhanagar Nala

mangrove over the newly-formed mudflat, emerged during the earthquake.

Field observations are carried out along the selected locations at the Elizabeth Bay, Radhanagar Nala, and Blair Bay. At Elizabeth Bay, two or three rows of mangrove trees fringing the creek periphery are intact (Fig. 6a), while complete degradation of mangrove trees within the mudflat has happened, leaving exposed peat of the dead mangroves surrounded by a succession of marshy

and terrestrial vegetation (Fig. 6b). A pattern of succession is apparent along the southern side of the creek. Adjacent to the intact mangroves, barren land having isolated growth of mangrove associates like *Acrostichum aureum* is observed, followed by grassland dominated mainly by *Dimeria* sp. Toward the landward side, the region once a thick mangrove forest is presently covered with shrubs and bushes comprising primarily by *Chromolaena odorata* and species of Primulaceae. The northern bank does not show

Table 2 Change in the mangrove are over the period of study

| Mangrove region	Mangrove area 2003 (ha)	Mangrove area 2019 (ha)	Percentage loss of mangrove cover
Beele Bay	280	16	94
Buchanan Bay	368	34	90
Elizabeth Bay	568	13	97
Jerotong Nala	123	-	99
Ducan Bay	264	4	98
Radhanagar Nala	1518	97	93
Burma Nala	163	4	97
Hudson Bay	259	7	97
Aerial Bay	1325	771	41
Blair Bay	756	209	72
Terapa River	1291	462	64
Paichtar River	831	254	69

Fig. 4 Change in mangrove cover area and pattern of succession at A) Elizabeth Bay, B) Radhanagar Nala, C) Blair Bay
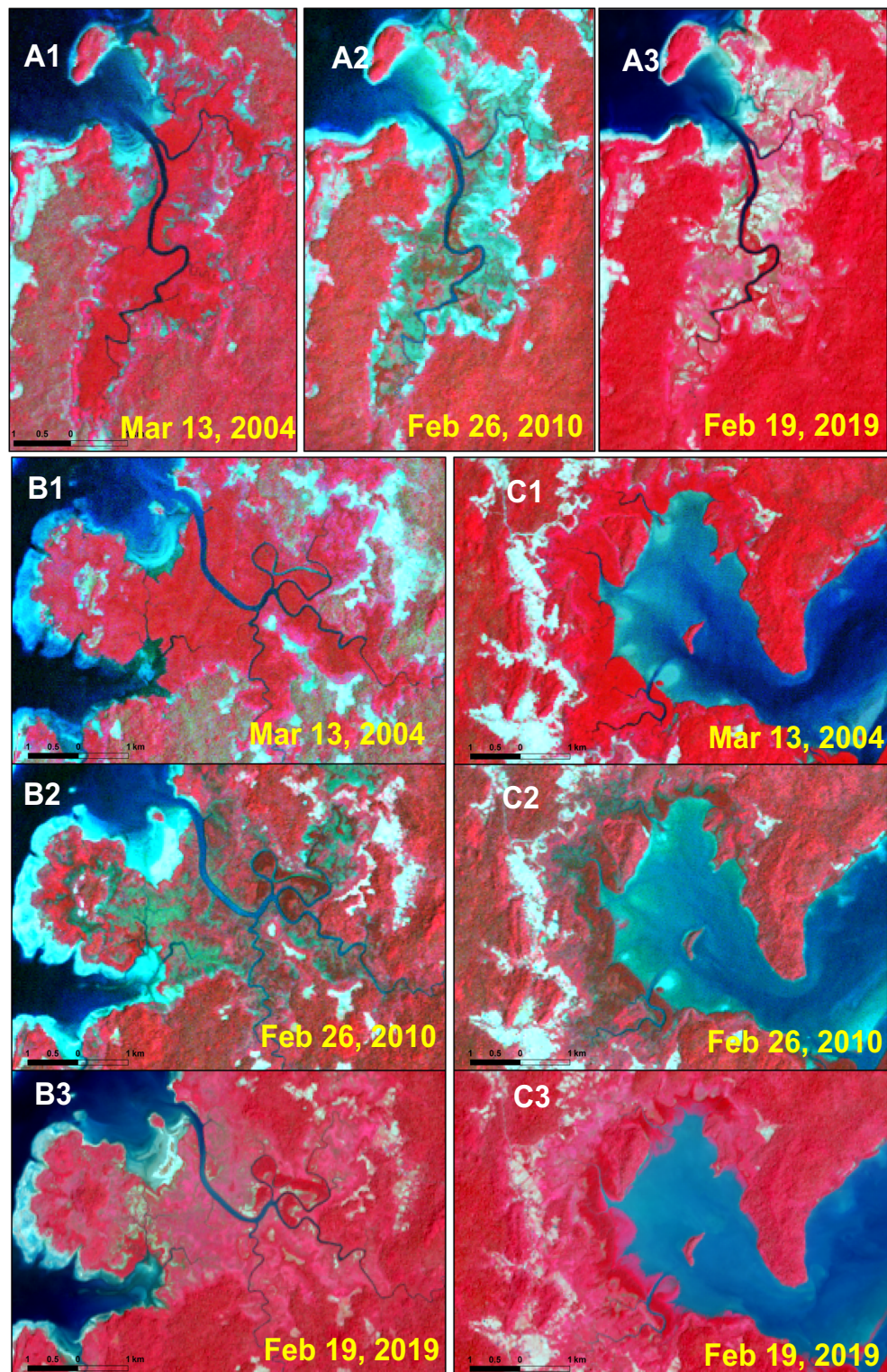
such patterns, and the growth of successive plats is randomly spaced *A. aureum*. An interesting observation on the northern bank is the presence of *Avicennia* sp. in patches located farther from the creek (Fig. 6c).

The mangroves fringing the Radhanagar Nala creek are also unharmed. The tidal mudflats at either side are presently a lush forest of terrestrial vegetation. The peat of dead mangrove trees got buried under exuberant creepers like *Mikania* sp. (Fig. 6d). The erstwhile mangrove forest

Fig. 5 Temporal changes in the CMRI estimated mangrove cover from 2003 to 2019

Legend:
- Average (total)
- Average (western coast)
- Average (eastern coast)
- Radhanagar Nala
- Blair Bay
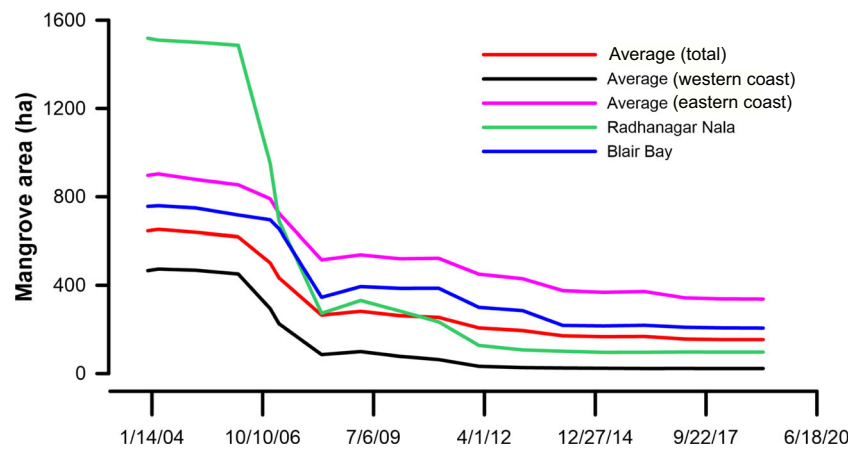
toward the land area of Radhanagar and Blair Bay also shows a similar succession of native terrestrial vegetation like *Pluchea* sp. and *Calophyllum* sp.

Tidal hydrodynamics at Elizabeth Bay is simulated for 1 month considering the two scenarios of pre and post-earthquake conditions. The total inundation hour at each model element is computed from the simulated results (Fig. 7). The post-earthquake condition shows that the mudflat located away from the creeks is devoid of any tidal inundations. Flooding at the tidal channel also reduced significantly, and tidal channels are inundated only during the high tidal conditions.

The total mangrove cover estimated from 2003 and 2019 satellite images is around 8600 and 2100 ha respectively, which includes mangroves fringing the coast and are not shown in Table 2. 150 ha of mangrove area is newly formed and are primarily located along the Blair Bay region. 6500 ha of the mangrove forest area got destroyed which accounts for

around 75% of the 2003 mangrove cover. The western coast lost 95% of the mangrove forest area, while the mangrove loss at the eastern coast is around 60%. This large-scale mangrove disappearance along the northern Andaman region is significant to cause a regressing state of the biological ecosystem. Fig. 5 depicts the mangrove reduction trend. Mangrove cover area has decreased until 2007, and thereafter a slight increase in area is observed up to 2012, where Radhanagar Nala mangroves show maximum change rate. Aerial Bay shows the minimum mangrove lose, while from 2015, at the Jerotong Nala, hardly 7 pixels of CMRI estimated mangroves are observed (Table 2).

Discussions

The mangrove forest along the northern Andaman Island has significantly reduced since the December 2004 earthquake,

Fig. 6 Field photographs of Elizabeth Bay and Radhanagar Nala; **a**) mangroves along the periphery of the creeks, **b**) peats of the dead mangroves surrounded by succession of marshy and terrestrial vegetation **c**) patches of *Avicennia* that have survived at northern bank of Elizabeth Bay **d**) peats of dead mangrove trees buried under creepers at Radhanagar Nala
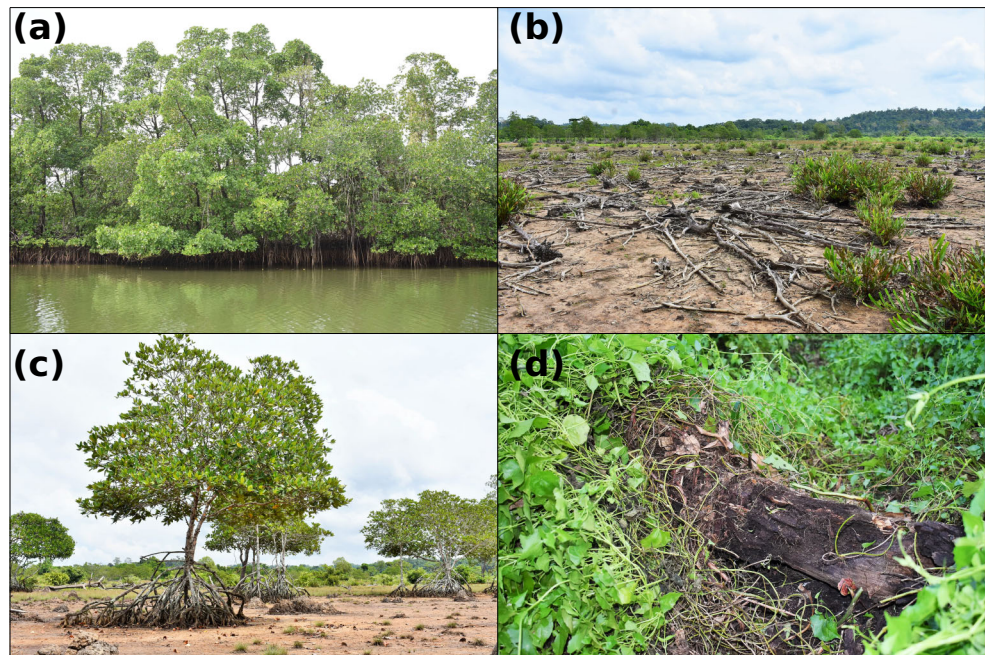
Fig. 7 Simulated inundation scenarios under pre-earthquake and post-earthquake conditions

Inundation hours during high tide

675
600
525
450
375
300
225
150
75
0

a) Pre earthquake
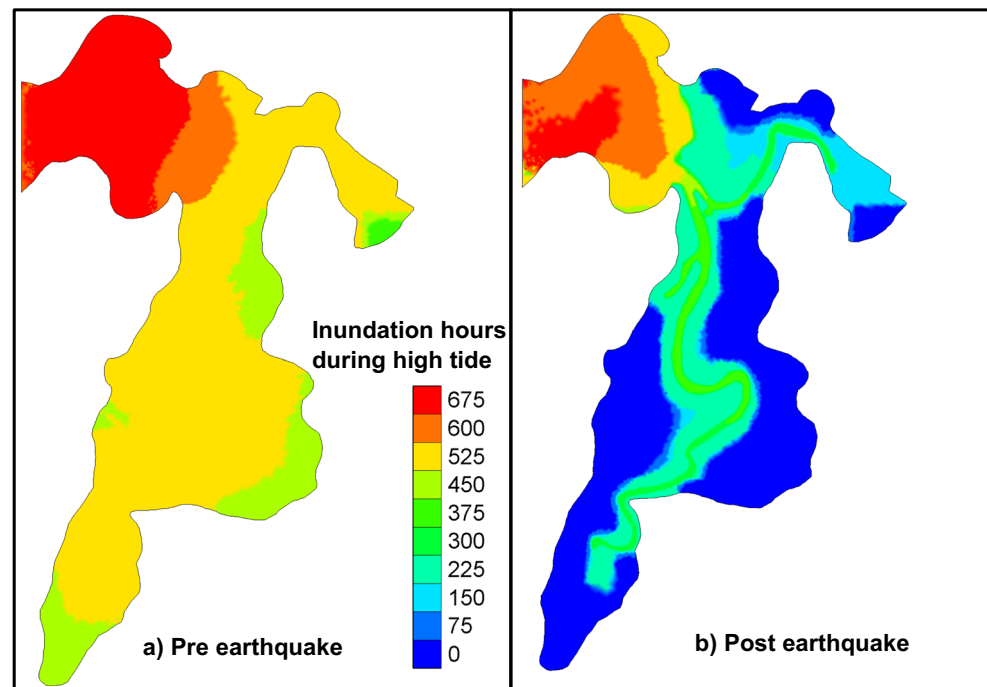
b) Post earthquake

where the reduction in area is about 6500 ha. The earthquake uplifted the islands to about 1.2 m (Malik and Murthy (2005)) and has prohibited the influx of tidal water reaching the mudflats. The tidal hydrodynamic simulation results with post-earthquake conditions indicate a significant reduction in the tidal inundation, and the mudflats to the landward side are devoid of tidal inundations.

Roy and Krishnan (2005) have presumed the mangrove degradation at Andaman due to the land uplift and the subsequent reduction of the tidal water flow into the mudflat. Ray and Acharyya (2011) have adduced desiccation as one of the causes of mangrove mortality at the Kishorinagar area of the northern Andaman. Desiccation is observed at Elizabeth Bay, where a considerable area is barren with *A. aureum* patches, while at Radhanagar Nala, lush terrestrial vegetation had grown along the region where once mangrove forest used to thrive. The Andaman Islands comes under the torrid zone, receiving 3000 mm of annual rainfall (Kumar et al. 2012). Depletion in the tidal inflow into the mudflat and the subsequent geomorphological changes associated with the change in hydrological conditions could have caused the large-scale mangrove devastation. The cease of tidal waters has likely reduced the soil salinity and nutrient availability for the mangrove and has led to its vast mortality.

The mangrove mortality, however, was a gradual process rather than any direct consequence of the earthquake or associated tsunami. Ray and Acharyya (2011) have conducted a field study during 2005 and reported the presence of dense mangrove forests at a tidal swamp of the northern Andaman. The findings corroborate with our study that the mangrove forest has sustained till 2006 pre-monsoon. The mangroves are reported to have survived on the moisture, salinity, and nutrients retained in the soil.

Mangrove forests located on the western coast of the northern Andaman have incurred severe damages than those located to the eastern coast. The mangrove forest degradation along the western coast is 95%, whereas only 60% of the mangrove is destroyed along the eastern coast. The islands have uplifted with a tilt toward the east (Meltzner et al. 2006), which made the western coast to uplift more. This probably has made the mudflats along the western coast completely deprived of tidal inundation resulting in mangrove growth merely along the creek periphery. At the eastern coast, only the mangrove trees located farther landward of the creeks are affected, implying a substantial inundation into the mudflats in comparison with the western coast.

The post-earthquake land that has emerged at Blair Bay is presently covered with mangrove forests, and the new mangrove area is around 150 ha. Why new mangrove patches had grown only at Blair Bay may be an intriguing question. However, the landform of the emerged substrate may be the probable reason for the new mangrove growth observed only at Blair Bay. The December 2004 earthquake has resulted in the coral bed exposure (Malik and Murty 2005) along the main shoreline, whose hard substrate prohibits mangrove growth. Unlike the other mangrove area, the Blair Bay is located away from the main shoreline and toward the head of Aerial Bay, which may have sufficient deposition of mud materials. The earthquake might have exposed these mud depositions with a porous substrate where mangrove growth is possible.

The coastal geomorphology as well the plant demography had changed significantly since the tide ceased to inundate because of the coastal uplift. Satellite data analysis shows that a vast area of the erstwhile mangrove forest had changed to barren area and subsequently to terrestrial vegetation. Field observations also affirm the succession at the Radhanagar area and Blair Bay. The region is presently covered with shrubs, creepers, and isolated tropical trees like *Macaranga* sp. that has grown during the period. Mudflats adjoining the Elizabeth Bay creek are still barren, with isolated growth of *A. aureum* and *Dimeria* sp. The succession of terrestrial vegetation at Elizabeth Bay is visible from the satellite images while the pace of succession is gradual in comparison to the Radhanagar and Blair Bay.

Rhizophora sp. might be the most affected mangrove species since the zonation pattern reported by Ragavan et al. (2015) observes the dominance of long stands of *Rhizophora* sp. along the tidal swamps of Andaman Islands. These swamps at the northern part of the island are presently dried up leaving mangrove peat. Along the tidal swamp of Elizabeth Bay creek, *Avicennia* sp. has survived in patches surrounded by peat of dead mangrove trees. *Avicennia* sp. is considered a resilient mangrove species and at the northern Andaman also they have survived, while other mangrove species have degraded.

Aerial Bay located along the eastern coast accounts for a loss of only 41% of mangrove forest area. Ariel Bay is located between the 0.5 m and 0 m contour of vertical ground movement reported by Ray and Acharyya (2011) that makes the region the least vertically uplifted area within the northern Andaman Islands. This might be the possible reason for the minimum mangrove damage at Aerial Bay compared to the other places. Mangrove at Jerotong Nala on the western coast has disappeared completely, where the locals have reported a complete closure of the stream mouth.

The present study reports a 6500 ha reduction in the northern Andaman mangroves since the earthquake. However, even while considering the whole Andaman and Nicobar Islands, Forest Survey of India (FSI) (FSI 2017) have reported 5400 ha decrease in the mangrove area from 2004 to 2013, whereas considering only the Andaman Islands, FSI (2013) have reported only 1300 ha decrease in the mangrove area. The figure is an underestimate even to the approximation carried out by Ray and Acharyya (2011) who have assumed 4000 ha decrease in the northern Andaman mangroves based on the assessment for a single tidal swamp.

Conclusions

Remote sensing technology significantly supplements the monitoring studies of, in particular, inaccessible areas like mangrove forests and to assess its temporal changes. The interesting aspect of the present study is to substantiate how natural processes can induce changes leading to widespread mortality of the vital ecosystem like mangrove forests. The substantial loss of mangrove forests has already indicated its impact on marine species, where the fishermen have reported a significant decrease in fish catch especially the crabs and shrimps.

The study specifically assents to the importance of tidal water for mangrove sustainability. As the seawater inundation ceased, the biogeochemical conditions of the mudflats have transformed and are presumed to cause hostile conditions for the mangroves to sustain. Tides help in the mangrove growth by exclusion of other vascular plants, distributing the nutrients, flushing the salt and other wastes, and maintains the geomorphology of the region thereby making the substrate porous for nourishment and mangrove reproduction. Simulation of the tidal hydrodynamics shows that, after the earthquake, tidal inundation has ceased over substantial areas of the mudflat. The reduction in the tidal inundation is an immediate consequence of the earthquake, while deterioration of the mangrove forest has certainly lagged for more than a year.

As mangroves form a vital habitat for diverse marine and terrestrial organism, the mangrove mortality at this scale would incur large and prolonged impact on the biological ecosystem.

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