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Shoreline and Land Use Land Cover Changes along the 2004 tsunami-affected South Andaman Coast: Understanding Changing Hazard Susceptibility

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Abstract

The 2004-tsunami affected the South Andaman coast experiencing dynamic changes in the coastal geomorphology making the region vulnerable. We focus on pre-and post-tsunami shoreline and Land Use Land Cover changes for the period 2004, 2005, and 2022 to analyse the dynamic change in hazard. We used GEBCO bathymetry data to calculate Run-up (m), arrival times (Min), and inundation (m) at 13 different locations using the 2004 Sumatra Earthquake source parameters. The Digital Shoreline Analysis System is used for the shoreline change estimates. The Landsat data is used to calculate shoreline and LULC change in five classes, namely Built-Up Areas, Forests, Inundation areas, Croplands, and water bodies during the above period. We examine the correlation between the LULC changes and the dynamic change in shoreline due to population flux, infrastructural growth, and Gross State Domestic Product growth. India industry estimates the Andaman & Nicobar Islands losses exceed INR 10 billion during 2004 that would see a five-fold increase in economic loss due to a doubling of built-up area, a three-fold increase in tourist inflow, and a population density growth. The unsustainable decline in the forest cover, mangroves, and cropland would affect sustainability during a disaster despite coastal safety measures.

Keywords: Geomorphology, Land use Land cover, Shoreline, Tsunami, Remote sensing

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1. Introduction:

The Coastal shorelines are dynamic and highly vulnerable to erosion and accretion caused by hydrodynamic, tectonic, geomorphic, and climate forcing including tsunamis, cyclones, flooding, storm surges, wave action, wind and tide changes, and sea level variations (Nayak 2002; Boak &Turner 2005; Kumar et al. 2010; Mukhopadhyay et al. 2011). In addition to natural coastal processes, coastal resources are constantly under stress due to anthropogenic activities, such as industrialization, port construction, beach sand mining, garbage dumping, urbanization, trade, tourism, and recreational activities, which significantly impact the shoreline and results into damage to natural ecosystems (Yi et al. 2018; Davis, 2019).It is important to regularly monitor spatio-temporal along shorelines, Land use / Land Cover (LULC) and geomorphic features(Moran, 2003; Cooper et al.2004; Scheffers et al. 2005; Jayakumar & Malarvannan 2016). Several studies have been conducted to analyse various coastal processes, including the mapping of shoreline change, LULC change detection and analysis of geomorphological landforms using satellite data. The temporal multispectral satellite data allow for the identification of regions undergoing erosion or accretion change (Misra and Balaji, 2015; Kumari et al. 2012; Tonisso et al. 2012; Murali et al, 2013, Sudha Rani et al, 2015; Rowland et al, 2022, Thieblemont et al, 2021). The Indian Ocean tsunami of December 26, 2004 was triggered by a magnitude 9.3 undersea earthquake near the coast of Sumatra, Indonesia and Caused massive destruction of the coastal ecosystem in the Andaman region (Sheth et al. 2006; Ramalanjaona, 2011). Using remote sensing data and statistical techniques the shoreline & geomorphology changes caused by the 2004 Sumatra tsunami examined (Mouat and Lancaster 1996; Saraf and Choudhary, 1999; Reid et al. 2000; Chen 2002; Weng 2002; Siddiqui and Maajid 2004; Mujabar and Chandrasekhar 2011; Kumari et al. 2012; Tonisso et al. 2012; Jangir et al.2014; Yuvaraj et al. 2014; Yunus and Narayana, 2015; Yunus et al., 2016).

Since the 2004 Tsunami the Andaman and Nicobar Islands have experienced remarkable population growth, infrastructural development, and flourishing tourism activities progress over the past decade (Yuvaraj et al, 2014). The development is profound in the south Andaman region. This is a cause of concern for the tsunami vulnerability as the region is prone to very large earthquakes as it is a seismo-tectonically active plate boundary. In this study, we Compute Tsunami arrival times, run-up heights, and inundation extent along the south Andaman region. We also analyzed dynamic vulnerability using temporal and spatial changes in shoreline and LULC for the tsunami-affected areas (Velmurugan et al, 2006; Ghadamode et al, 2022). The analysis covers three time periods: 2004 (pre-tsunami), 2005 (post-tsunami), and 2022 (current status of shoreline and LULC) using multi-temporal Landsat data to map the extent of shoreline changes in the EPR (End Point Rate) & NSM (NET Shoreline Movement) Method. A relationship between LULC changes and vital socioeconomic factors such as population dynamics, tourism trends, and the Gross State Domestic Product (GSDP) is established to assess the potential future impacts of tsunamis in the region. The results would provide actionable insights to the policymakers, coastal planners, and stakeholders in disaster management and sustainable coastal development.

2. Study Area

South Andaman region with ~1,262 km² and a 413 km coastline is the southernmost island of the Great Andaman where most of the Andaman Islands' population and infrastructure are centrated. According to the 2011 Indian census, South Andaman has a population of 238,142 people, which increased to 266,900 in 2021 (estimate based on www.census2011.co.in). The most habitable areas in the eastern part of South Andaman are located on low lands at bay heads in addition to the higher slopes bordering bays and coastal flat lands (Ghosh et al. 2007). The South Andaman region experienced devastation and losses during the 2004 Tsunami and is vulnerable (Fig. 1). We selected 13 locations, namely South point in Port Blair, Rutland Island, Corbyn's cove Beach, Madhuban Bay, Brichgunj, Chidiyatopu, Thirupatti Temple, Wandoorjetty, Bamboo flat, Potatang, Shoal bay, Radha Nagar, and Govinda Nagar for vulnerability assessment in the present study.

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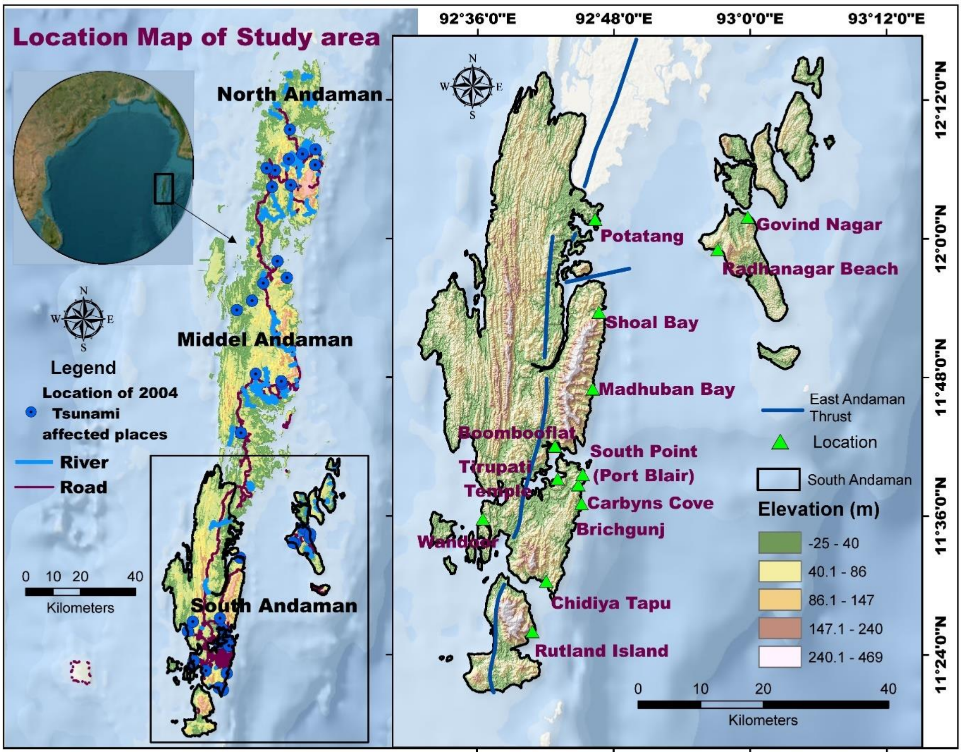

Figure 1 Location Map of the South Andaman Region (© Google Maps & © Google Earth).

The region's topography is primarily influenced by tectonic activity and weathering processes (Curray, 2005; Bandopadhyay and Carter, 2017). The East Andaman Thrust also called East Boundary Thrust is a linear/curvilinear ~500 km long fault zone and is the locus of ongoing convergent and crustal deformation along the Sunda-Andaman plates. This structure is pivotal in creating accretionary prisms within the outer-arc ridge of the Andaman and Nicobar subduction zones (Fig. 1; Bhat et al., 2023).

The structure-bound major geomorphological features in South Andaman include hills, valleys, beaches, mangroves, and coral reefs (Fig. 2a). The Younger coastal plain is a relatively flat and low-lying area adjacent to the coastline, which is formed through the accumulation of sediments brought by the ocean (2d). The highest peak on the island is Mount Harriet with approximately 1,200 meters (3,937 feet) (southandaman.nic.in). The north-western part of South Andaman is highly dissected whereas the North-eastern part is moderately dissected and the Southern part is most likely low dissected structural hills and valleys (Fig. 2 a and e). The island has a rough coastline with various bays, inlets, and headlands. A wave-cut platform is a flat or gently sloping rock surface found along South Point coastlines in Port Blair (Fig. 2f). It is formed through the erosive action of waves, which gradually wear away the rock over time.

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These platforms can be exposed at low tide and are often a unique feature of rocky coastlines. Coral reefs along the coast contribute to the formation of sandy beaches and barrier islands (Reguero et al., 2018). Mangrove forests are found on coasts in South Andaman Island, primarily in the brackish water and muddy sediments lagoons and tidal zone (Fig. 2g). Mangroves are crucial in stabilizing coastal ecosystems and providing habitat for various species. Wandoor, Chidya tapu, and Sippighat are some notable locations of mangrove forests in South Andaman coastal areas. The upper slopes of the region are covered with high dissected structural hills with dense pristine forest (Fig. 2a). The slope ranges between 0 to 44.9 degrees, with lower slopes in the coastal region mostly inhibited and undergoing rapid coastline modification and Land Use Change (Fig. 2 b and c). The North, Northeast, and Southern portions of South Andaman have the steepest slope and relief area, while the Eastern, Southeastern, and western parts have relatively lower slopes. The coastal plains in south Andaman are dynamic and prone to tsunamis due to their location and active plate boundary, therefore studying shoreline change and LULC change is especially important due to potential impacts on local communities and ecosystems.

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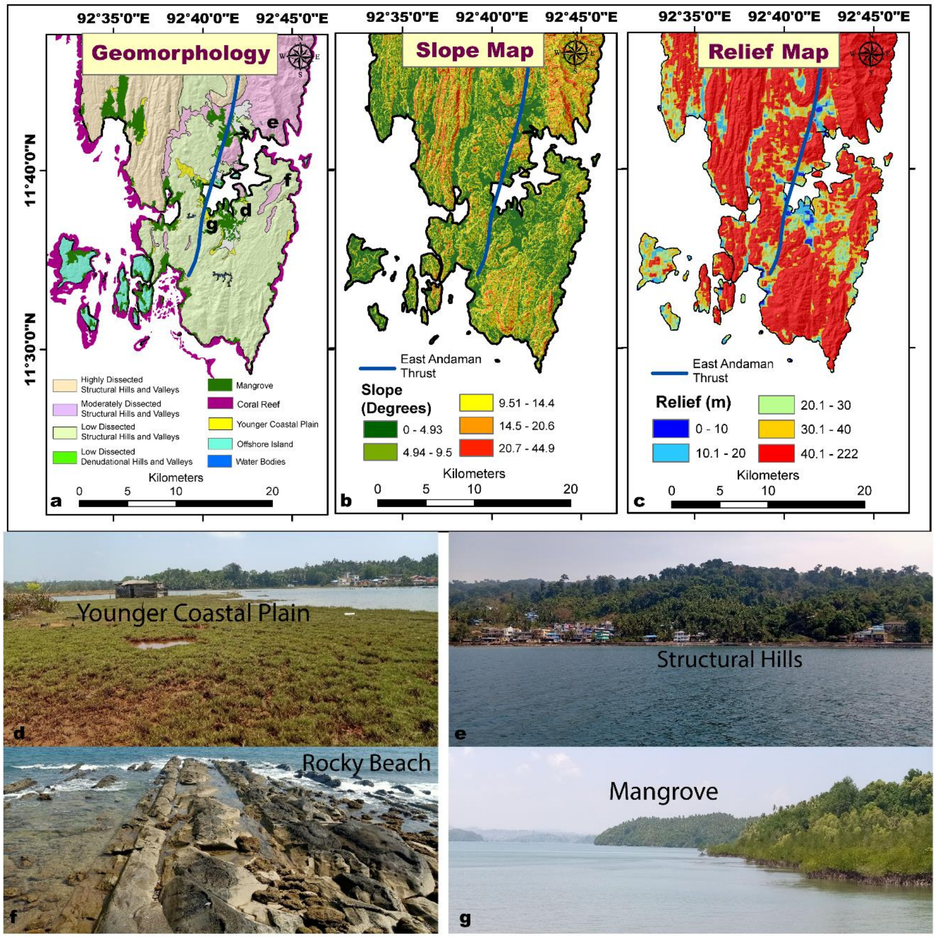

Figure 2 (a) *Geomorphology,* ***(b)*** *Slope map,* ***(c)*** *Relief Map,* ***(d)*** *the younger coastal plain,* ***(e)*** *Structural Hills,* ***(f)*** *Rocky Beach with a wave-cut platform near south point, Port Blair,* ***(g)*** *Mangrove.*

3. Materials and Methods

To assess the vulnerability, it is imperative to generate a spatial dataset that may have a bearing on assessing the dynamic changes.

3.1 Data Used

Landsat satellite data, such as Thematic Mapper (TM) and Operational Land Imagery (OLI) sensor for the years 2004, 2005, and 2022 is used in the present study. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) is used to prepare the study area's slope and relief map. This dataset analyzes shoreline and monitors the LULC changes along the South Andaman coast. We used the General Bathymetry Chart of the Ocean (GEBCO) for run-up and inundation studies along the south Andaman coastal areas (Table 1).

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Table 1: Data used in the present study region

Data	Purpose	Month & Year	Resolution	Sources
GEBCO bathymetry	Inundation and Run-Up	2022	90 m	GEBCO
Landsat 5 TM and Landsat 8 OLI	LULC and Shoreline Change Analysis	March-2004 January-2005 March-2022	30 m	USGS Earth Explorer
SRTM DEM	Slope, Relief	-	30m	USGS Earth Explorer
Geomorphology	Geomorphology	-	1:250k	bhukosh.gsi.gov.in
Socioeconomic data	Population, Tourism, Gross State Domestic Product (GSDP)	1991-2021 2001-2020	-	(censusindia.gov.in) (Directorate of economics and statistics) (Rbi.org.in)

3.2 Tsunami Run-ups and Inundation

The 2004 earthquake rupture zone is divided into five segments by Ioualalen (2007) to simulate all stages of the tsunami. The earthquake source mechanism involves the rupture process, and magnitude is essential for tsunami hazard assessment. There have been several attempts to model tsunamis, calculate run-up heights, and evaluate their impact and hazards along coastal areas (Rani et al. 2011; Srivastava et al. 2021). For the propagation and run-up models, we used GEBCO bathymetry data with 81 arc seconds and 3 arc seconds resolution. The 26th December 2004 Sumatra earthquake ruptured about 1400km in length. Considering different slip distributions for the five segments (Table 2) TUNAMI-N2 code is used to compute the four grids A, B, C, & D. The exterior grid (A) in a very large domain as the tsunami propagates transoceanic and is interpolated into the B, C, and D grids. After giving the required inputs the program is compiled and executed to get the directivity map, wave amplitudes at different tide-gauge locations, and run-up heights.

Table 2 Earthquake source parameters used to compute the deformation at the source along the Andaman-Sumatra Subduction Zone

Input Parameters	Seg1	Seg2	Seg3	Seg 4	Seg5
Longitude (DD)	94.57	93.90	93.21	92.60	92.87
Latitude (DD)	3.83	5.22	7.41	9.70	11.70
Focal Depth (km)	25	25	25	25	25
Strike angle (°)	323	348	338	356	10
Rake (°)	90	90	90	90	90
Slip (m)	18	23	12	12	12

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Fault Length (km)	220	150	390	150	350
Fault Width (km)	130	130	125	95	95
Dip (°)	12	12	12	12	12

3.3 Shoreline Analysis in DSAS

To estimate shoreline changes, the USGS's digital shoreline analysis system (DSAS) version 5.1 (an extension of ArcGIS) is used. The procedures are executed in 4 steps: shoreline digitization, baseline generation, transect generation, and computation of the rate of shoreline change (Nithu Raj et al. 2020; Natarajan et al., 2021). The digitized shorelines for 2004,2005and 2022 years are added to a personal geodatabase in a single shapefile. The shoreline image data is added to the attributes as MM/DD/YYYY, and the baseline is in the meter UTM projected coordinate system. To estimate rates of change, DSAS uses baseline measurements of a time series of shorelines and a shapefile (Leatherman and Clow, 1983). The process of generating transects involves initially choosing a predefined set of parameters from the personal geodatabase, including settings for the baseline and shoreline. Subsequently, we placed these transects perpendicular to the shoreline, extending 800 meters at intervals of 150 meters along the entire shoreline, originating from the baseline. To ensure a smoother outcome, a 50-meter smoothing distance was applied using the 'cast transects' tool within DSAS. In this study, we employ statistical methodologies such as the End Point Rate (EPR) and Net Shoreline Movement (NSM) to analyze the data.

3.3.1 Net Shoreline Movement (NSM)

NSM is a statistical parameter used to determine the net change in the shoreline position over a specific period. It is calculated by finding the actual distance between the most recent shoreline (in this case, 2022) and the oldest shoreline (2004) along each transect placed perpendicular to the shorelines. The formula for NSM can be expressed as:

$$NSM = \{d_{2022} - d_{2004}\}m$$

3.3.2 End Point Rate (EPR)

EPR is a statistical parameter used to quantify the rate of shoreline change over time. It is calculated by dividing the Net Shoreline Movement (NSM) by the time elapsed between the oldest and most recent shoreline measurements. The formula for EPR can be expressed as This calculation provides a measure of how much the shoreline has shifted per year, indicating the rate of erosion or accretion. It is important to have data from at least two shoreline dates (Dolan et al. 1991; Crowell et al. 1997).

$$EPR = \left\{ \frac{d2022 - d2004}{t2022 - t2004} \right\}$$

3.4 Land Use Land Cover Analysis (LULC)

The LULC map uses Landsat 5 TM (2004 and 2005) and Landsat 8 OLI (2022). False Colour Composite (FCC) satellite images combine near-infrared, red, and green bands to delineate five different classes Forest, built-up, Cropland, Water bodies, and Inundated area. (Prabhbir and Kamlesh, 2011). Tone, texture, size, shape, pattern, association, and other visual interpretation techniques also were used to interpret different land use classes. Maximum likelihood is a supervised classification method used in this study to detect LULC change. Each pixel in the classified Landsat images varies over time due to changes in land cover.

4. Results

An analysis of the 2004 tsunamigenic earthquake's impact on the South Andaman region, focusing on tsunami directivity, arrival times, run-up heights, shoreline changes, and LULC impact is examined in detail

4.1 Tsunami studies along the South Andaman Region

The 2004 tsunamigenic earthquake is modeled to quantify the tsunami propagation, arrival times, and run-ups at different locations along the South Andaman region. The initial deformation at the source is computed for the fault parameters (Table 2). The Directivity map shows that most of the energy propagation is in the East-West Direction (Fig. 3). The arrival times (Minutes), run-up height (meter), and Inundation extent (meter) at 13 different locations along the South Andaman region (Table 3) is considered for further analysis. The results show that the run-up heights range from 1 to 13 m, arrival times range from 27 to 58 min, and the inundation extent range from 90 to 950 m. This suggests a significant variability in the impact of the tsunami across the South Andaman Region. Shoal Bay recorded the highest inundation extent of 950 meters and experienced the highest run-up height of 13 meters, indicating significant wave impact (Fig. 3b; Table 3). Corbyns Cove Beach and Rutland Island experienced significant inundation distances, exceeding 700 meters (Fig.3b, Table 3). Potatang, Corbyns Cove Beach, and Brichgunj also recorded relatively high run-up heights that exceeded 9 meters (Table 3). The tsunami arrived at Thirupatti Temple after 38 minutes, suggesting a delayed impact compared to other locations. Most locations experienced arrival times between 27 and 58 minutes, indicating a relatively quick propagation of the tsunami wave. At some locations, however, the tsunami arrived early. Jain et al. (2005) have mentioned that tsunami waves arrived between 40 to 50 minutes in the Andaman and Nicobar

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Islands. Our results also agree with Cho et al. (2008) and Prerna et al. (2015) who computed the tsunami runup heights at a few of the locations considered in the present study.

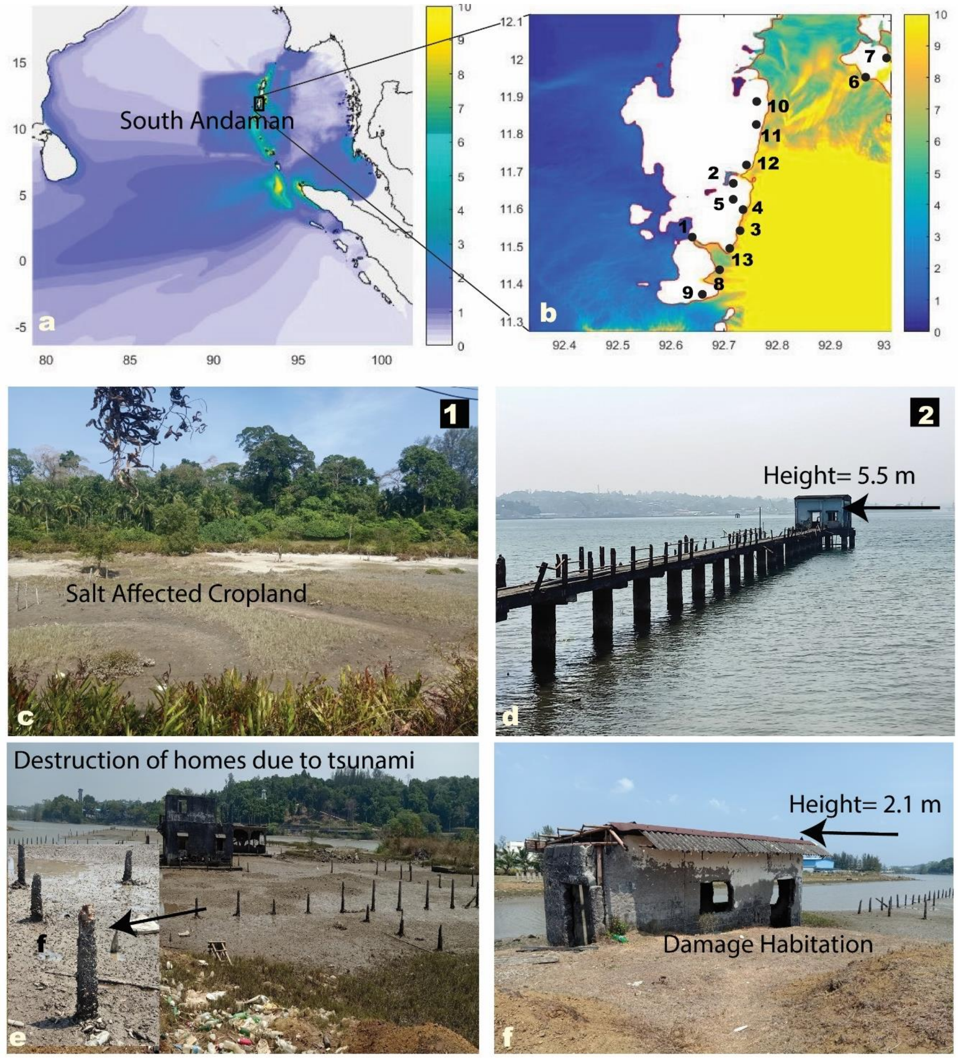

Figure 3 (a) Directivity of the tsunami Wave Propagation of December 2004 Sumatra tsunami (b) Run-ups at different locations along the south Andaman Coast (c) showing Stagnation of Tsunami water in the agricultural land and Low laying Area in Port Blair, (d) Fully damaged construction bridge in Bombooflat. (c, d) shows damage to the house near the Sippighat area (Photo: 01/03/2023).

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Table 3 Estimated Run-up heights, Arrival Times, and inundations at the study region from the Sumatra tsunami

SN	Locations	Longitude (DD)	Latitude (DD)	Arrival Time (Mins)	Runup (m)	Inundation (m)
1	Wandoorjetty	92.614750	11.581667	36.5	3.5	450
2	Bombooflat	92.715417	11.700722	42	5.5	90
3	Corbyns Cove Beach	92.770916	11.642372	33	12.7	900
4	South Point, Port Blair	92.702917	11.652389	31.5	9.6	550
5	Thirupatti Temple	92.703861	11.581694	38	1	200
6	Radha Nagar	92.951722	11.979306	54	2.6	156
7	Govinda Nagar	92.989139	12.030167	58	3.6	195
8	Chidiyatopu	92.716639	11.499306	36	3.9	585
9	Rutland Island	92.703818	11.431497	27	6	700
10	Shoal Bay	92.795963	11.934202	56	13	950
11	Potatang	92.801282	12.027380	58	12.5	210
12	Madhuban Bay	92.785534	11.782775	54	6.9	210
13	Brichgunj	92.770162	11.618980	30	10	585

4.2 Shoreline Change during Tsunami (2004-2005) and post-tsunami (2005-2021)

The south Andaman coasts are divided into seven zones based on proximity with the inundation studies to calculate Net shoreline movement (NSM), and End Point Rate (EPR) to understand the short-term and long-term changes impact of coastal erosion (Fig. 4, Supplement Fig. S1-S7). The NSM and EPR rates are calculated over two separate time frames to comprehend the damages caused by tsunamigenic and regular wind-wave-surge events in South Andaman Island. These zones were used to understand erosion and accretion rates between (i) 2004 - 2005 (Fig. 4a), and (ii) 2005-2022 (Fig. 4b). The EPR and NSM values from 2004 to 2005 indicate the direct effect of tsunami waves, whereas 2005 to 2022 values represent periodic wind-wave-surge dynamics. Periodic coastal shoreline changes refer to the regular and repeating fluctuations in the position of the shoreline along the coast. These changes can be influenced by natural and human-induced factors. A total of 1,083 transects are created at 50-meter intervals, distributed among the zones as follows: Zone 1 (339 transects), Zone 2 (147 transects), Zone 3 (89 transects), Zone 4 (74 transects), Zone 5 (137 transects), Zone 6 (73

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transects), and Zone 7 (220 transects). The shoreline variation rates indicate both positive accretion and negative erosion (Fig. 5, Table 4). The EPR rate Changes in meters per year (m/y) for the periods 2004-2005 show a higher erosion rate compared to 2005-2022, particularly in Zones 3, 4, and 5 (Fig. 5a). The NSM rates, focused on two distinct time frames, indicate the NSM rates during the tsunami, for the year of 2004-2005 (Fig. 5b), and the NSM rates over the extended 17-year period from 2005 to 2022 are measured in meters (Fig. 5c). The detailed analysis of the maximum (accretion), minimum (erosion), and mean shoreline changes for each of the seven zones that occurred during the tsunami event and the post-tsunami period are discussed below.

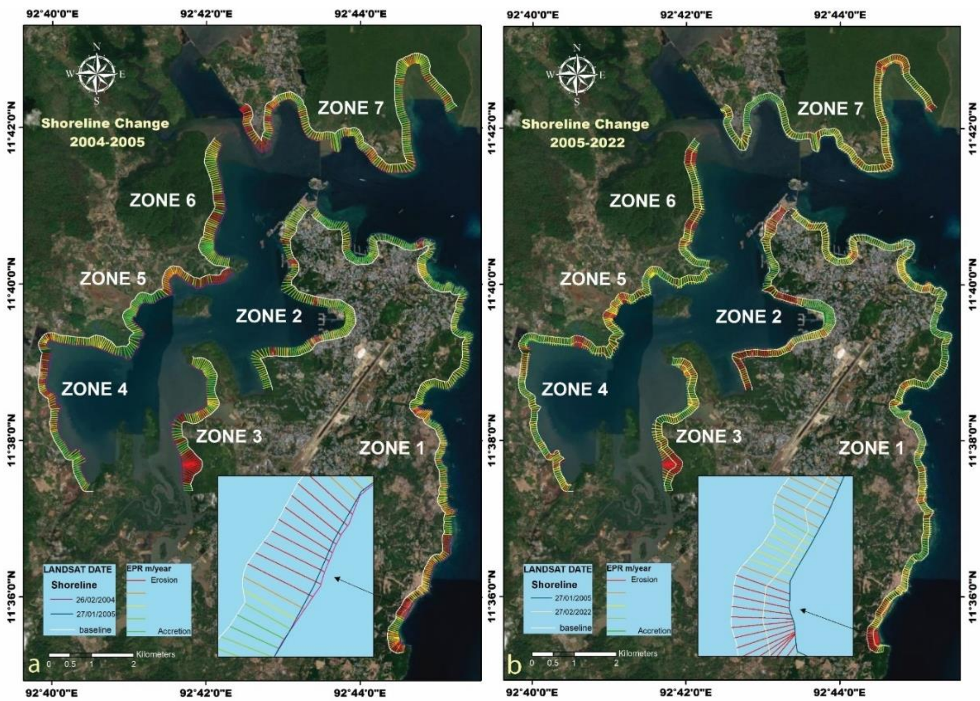

Figure 4: Shoreline changes observed (a) during 2004-05 due to the tsunamigenic process and (b) from 2005-2022 due to wind wave surges overlaid on Google Earth images (© Google Earth). The affected coastline is subdivided into seven distinct zones for detailed analysis.

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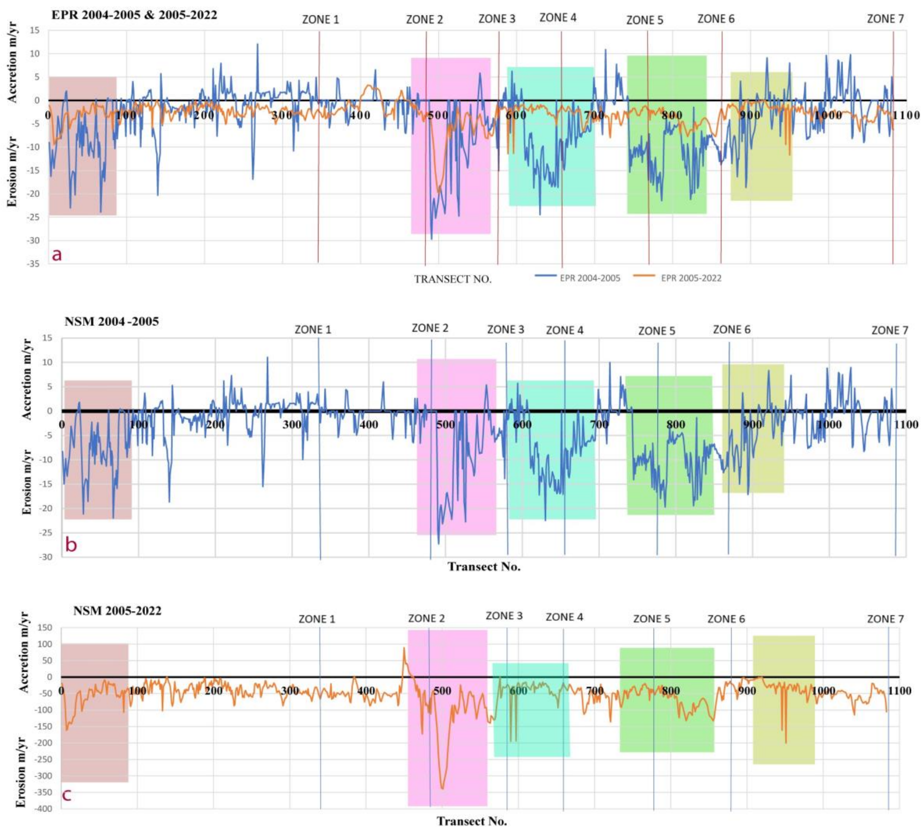

Figure 5: (a) The rates of erosion and accretion in seven distinct areas along the South Andaman shoreline using EPR methods, and (b, c) NSM have been conducted between the years 2004-2005 and 2005-2022. Highlighted color indicating high erosion zone

Table 4 Shoreline change in southern Andaman is observed for 2004-2005 and 2005-2022 using USGS's DSAS methods.

		2004-2005		2005-2022	
ZONE		EPR(m/y)	NSM(m)	EPR(m/y)	NSM (m)
ZONE 1	Mean	-2.85	-2.62	-2.55	-43.57
	Minimum	-23.9	-21.29	-9.44	-161.21
	Maximum	12.05	11.06	0	0
ZONE 2	Mean	-0.54	-0.50	-1.0639	-18.174
	Minimum	-7.17	-6.58	-4.56	-77.93
	Maximum	6.54	6	3.25	55.56
ZONE 3	Mean	-9.92	-8.11	-7.10	-121.51
	Minimum	-24.71	-23.27	-19.87	-339.51
	Maximum	5.58	4.37	-1.02	-17.42
ZONE 4	Mean	-7.92	-7.72	-2.24	-38.34
	Minimum	-24.47	-22.46	-11.42	-195.03

	Maximum	6.23	5.72	-0.79	-13.42
ZONE 5	Mean	-6.594	-6.05	-2.94	-50.26
	Minimum	-21.47	-19.7	-7.95	-135.83
	Maximum	10.88	9.99	-1.03	-17.54
ZONE 6	Mean	-9.74	-8.94	-4.92	-84.05
	Minimum	-21.18	-19.44	-7.75	-132.39
	Maximum	-1.46	-1.34	-1.86	-31.73
ZONE 7	Mean	-2.16	-1.986	-2.43	-41.56
	Minimum	-18.65	-17.29	-11.7	-199.96
	Maximum	9.77	8.97	-0.04	-0.61

ZONE 1: This zone experienced a combination of erosion and accretion between 2004-05 and 2005-21. The maximum erosion rates are observed at Megapoda, with an EPR of -23.9 m/y. and -9.44 m/y., NSM analysis shows the estimated erosion is -21.29m and -161.21m respectively (Fig. SM 1 a, b, Table 6). The southern part of South Andaman Island has more shoreline erosion rather than accretion, which can be attributed to the heightened impact of tsunamis on the southern region, a phenomenon that is more significant when compared to the northern part of South Andaman Island. These Sediments eroded from one coastline area are often transported along the shoreline by the longshore currents. The angle of wave approach creates these currents and is responsible for moving sediment parallel to the coastline.

ZONE 2: This zone experienced a combination of erosion and accretion between 2004-05 and 2005-21. The maximum rate of erosion is -7.17 m/y and -4.56 m/y (EPR) was recorded at IOC Colony, while the maximum accretion rate of 6.54 m/y and 3.25 m/y (EPR) was observed at Ashwin Nagar Respectively. The NSM analysis indicated a shoreline retreat of -6.58 m at IOC Colony and -77.93 m advancement at Ashwin Nagar. The jetties in the Jungli Ghat port played a role in controlling erosion and accretion at these sites (Fig. SM-2, Table 6).

ZONE 3: This zone experienced a combination of erosion and accretion between 2004-05 and 2005-21. The maximum erosion rate is -24.71 m/y and -19.87 (EPR) at Flat Bay, while the maximum accretion rate is 5.58 m/y and (EPR) at NLC Limited. The NSM analysis revealed a shoreline retreat of -23.27 m and -339.51 m at Flat Bey. High wave energy and exposure to strong currents, which are more common near Flat Bay, can lead to increased erosion of mangrove shorelines (Fig. SM 3, Table 6).

ZONE 4: This zone experienced a combination of erosion and accretion between 2004-05 and 2005-21. The maximum erosion rate is -24.47 m/y at Ferrargunj and -11.24 m/y (EPR) at PLK Creek Resort, NSM estimated erosion is -22.46 m and -195.03m at Chouldari

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(Fig. SM 4). We observed the shoreline erosion area using the Landsat time-lapse satellite images between 2004-2005, and 2022 near Flat Bay, South Andaman, has revealed noteworthy environmental changes. The dark blue color observed in 2004 and 2005 indicates the presence of deep-water bodies, whereas the light blue color in the 2022 image suggests the water bodies have become shallow with significant fresh sediment load.

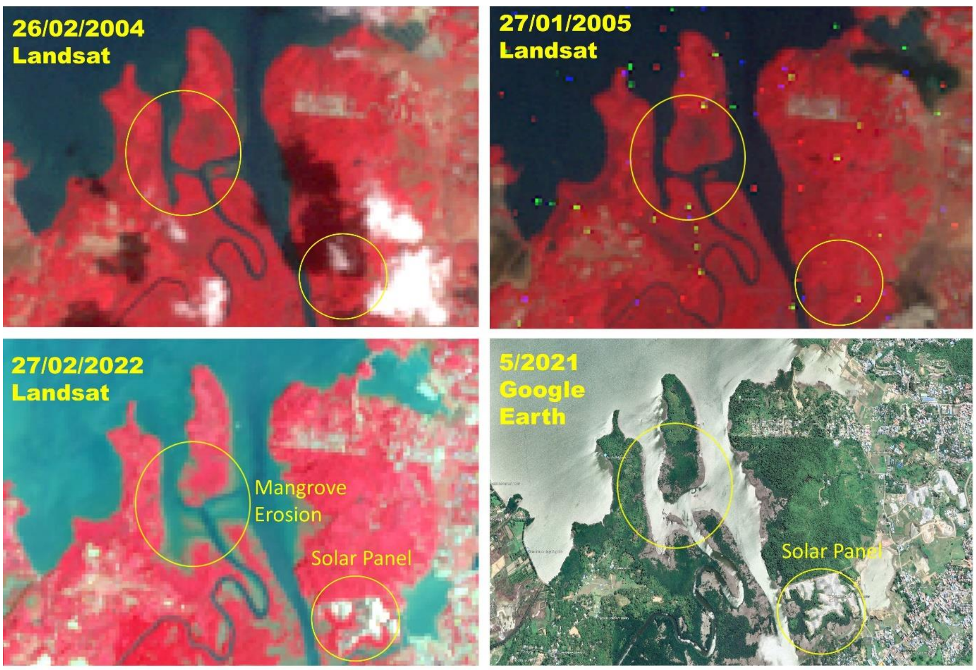

Figure 6 shows a time-lapse satellite imagery of Landsat 8 FCC near the Flat Bay area (marked in yellow circle) during the years 2004 and 2005 showing robust mangrove coverage is evident. However, when comparing the Landsat 8 image in 2022 and the corresponding Google Earth image (© Google Earth), it is apparent that the mangrove ecosystem in this area has experienced substantial erosion and the development of Solar panels.

ZONE 5: The maximum erosion rate of -21.47 m/y (2004-05) and -7.95 (EPR 2005-22) is recorded at Mithakhari. According to the NSM analysis, the shoreline retreated by -19.7 m and -132.39 meters at Mithakhari (Fig. SM 5). In this zone, Coastal development, infrastructure construction, and alteration of natural hydrological patterns can disrupt sediment transport and exacerbate erosion.

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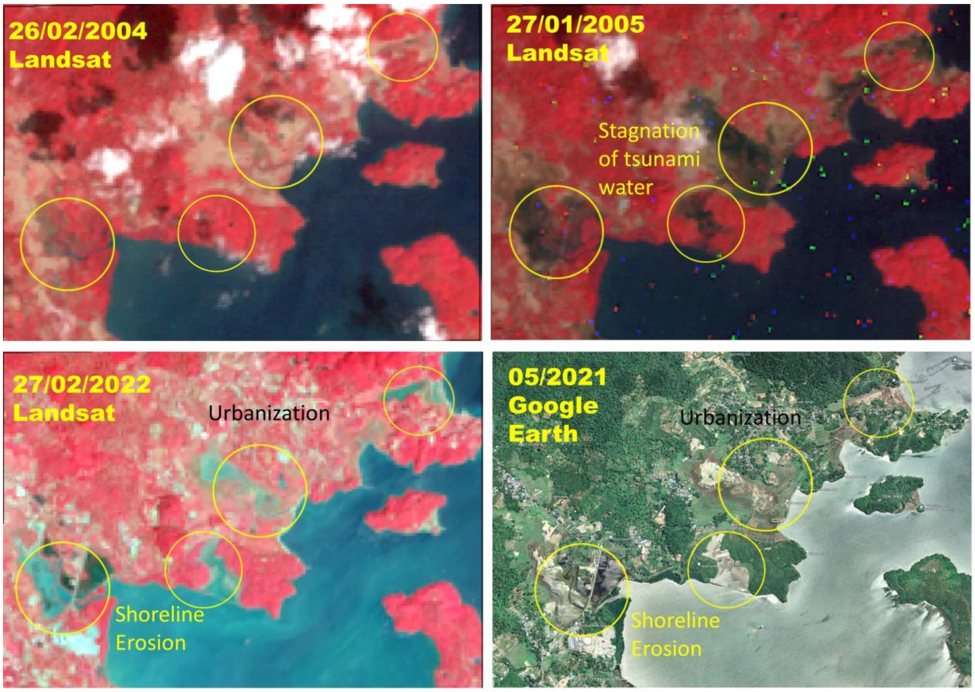

Figure 7 shows Landsat 8 time-lapse imagery and © Google Earth imagery near the Ograbraj and Mithakhari region depicting the erosion activity during and after the tsunami and the imagery shows significant growth in the built-up areas surrounding the tsunami-affected areas in 2004.

ZONE 6: This zone is predominantly affected by erosion, with no observed accretion. The maximum erosion rate is -21.18 m/y and -7.75 m/y (EPR) at Namunaghar, and the NSM estimated erosion is -19.44 m and -132.39m at Namunaghar (Fig. SM 6). In February 2004, immediately before the catastrophic tsunami event, there was no observable presence of stagnant water in the area (Fig. 8). However, by January 2005, following the tsunami, the images distinctly exhibited the stagnant water. In February 2022, the same location exhibited substantial shoreline erosion within the extensive mangrove and agricultural area, accompanied by increased urban development along the shoreline. The urban development progression is also validated using Google satellite imagery. The sediment carried by ocean currents deposited in low-lying areas revealed caused shallowing and significant changes in ocean water color.

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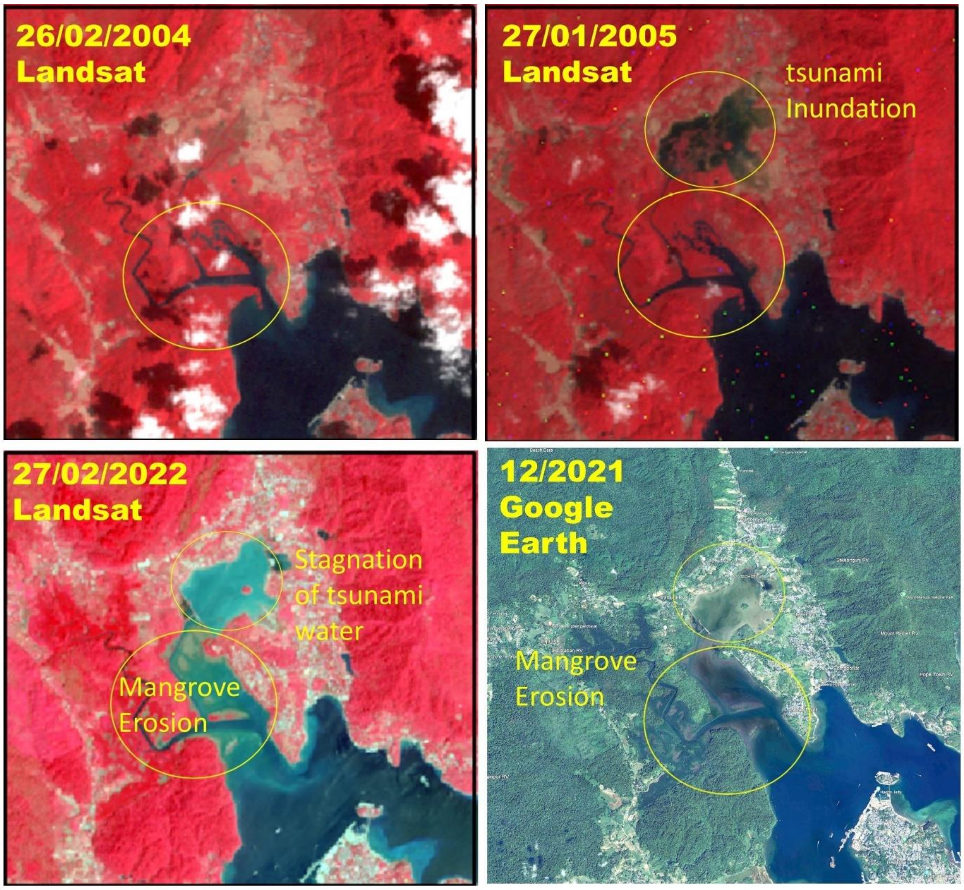

Figure 8 shows the Change detection of the shoreline using Landsat 8 time-lapse imagery and © Google Earth imagery for 2004 before, 2005 after the tsunami, and the 2022 present status of the shoreline.

ZONE 7: This zone experienced a combination of erosion and accretion between 2004-05 and 2005-21. The maximum erosion rate is -8.36 m/y and -11.7 m/y (EPR) at Shore Point, while the maximum accretion rate is 9.77 m/y (EPR). The NSM analysis indicated an erosion of -17.29 m at Shore Point and -199.96 meters at North Bay (Fig. SM 7). Notably, a tsunami with a height of 9.6 meters is observed at Shore Point.

The natural rate of shoreline movement in the South Andaman region has increased following the tsunami event, which is attributed to several factors, including the removal of vegetation cover, the softening of exposed bedrock, and the destabilization of unconsolidated materials caused by the tsunami, all of which have made the region more susceptible to erosion

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(Yunus et al., 2016). Comparing the erosion and accretion rates between the 2004-05 and 2005 -2022 periods, it is observed that the erosion rates were significantly less in the latter years.

4.3 Land Use and Land Cover (LULC) Analysis

The LULC is categorized into 5 distinct classes Built-up, Forest, Inundation, Cropland, and water Bodies (Fig. 9). The overall accuracy obtained is 80%, 83%, and 82% with a quantitative assessment of K_{hat} (Kappa) coefficient is 0.741, 0.762 and 0.759 for 2004,2005 and 2022 images, respectively. Our primary objective is to determine the extent of land use pattern changes from 2004 to 2022 in areas affected by the 2004 tsunami. Several researchers have already examined the vulnerability and impact of the 2004 tsunami on South Andaman including (Velmurugan et al. 2006; Debjani et al. 2012; Sachithanandam,2014).

The LULC classification for the South Andaman region in tsunami-impacted areas in the years 2004, 2005, and 2022 reveals significant changes (Fig. 9, Table 5): 1) The built-up area decreased from ~7.38% in 2004 to 6.23% in 2005, marking a 1.15% decrease. However, it subsequently increased by 11.11% by 2022. 2) Cropland coverage decreased from around 22.12% in 2004 to ~11.93% in 2005, indicating a substantial reduction of 10.19%. It then increased to 17.15% by 2022. 3) Inundation areas increased from about 3.29% in 2004 to 27.65% in 2005, showing a notable rise of 24.36%. However, by 2022, they decreased by ~18.57%. 4) Forested areas saw a significant decrease from ~66.46% in 2004 to about 51.10% in 2005, signifying a reduction of 15.36%. This decrease persisted in 2022, remaining at ~51.10%. 5) Water bodies covered around 0.62% of the area in 2004, which increased slightly to about 0.76% in 2005. By 2022, there is a more significant increase, reaching 2.05%.

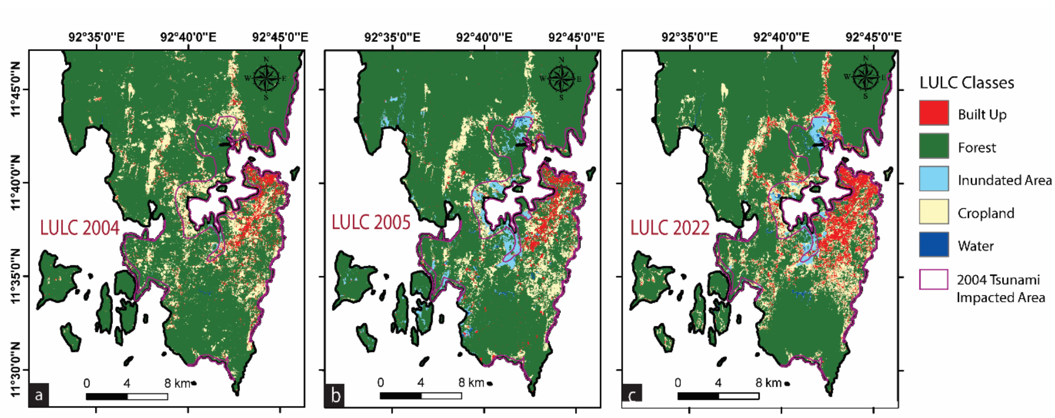

Figure 9 (a) LULC 2004 (b) LULC 2005, and (c) LULC 2022 in tsunami-impacted areas (pink color) and South Andaman.

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Table 5 LULC Analysis for 2004, 2005 to 2022 in tsunami impacted area

LULC	2004 Area in km^2	2004 % of Area	2005 Area in km^2	2005 % of Area	2022 Area in km^2	2022 % of Area
Built-Up	3.57	7.38	3.01	6.23	5.38	11.11
Forest	32.19	66.46	25.79	53.40	24.74	51.10
Inundation Area	1.64	3.39	13.36	27.65	8.99	18.57
Cropland	10.71	22.12	5.76	11.93	24.74	17.15
Water Bodies	0.30	0.62	0.36	0.76	0.99	2.05
Total Area (Sq. Km)	48	100	48	100	48	100

The LULC classification for the South Andaman region in the years 2004, 2005, and 2022 shows significant changes (Figure 9, Table 6)

1) Built-Up Area: In 2004, the built-up area covered 19.92 km², constituting ~3.84% of the total study area. By 2005, this area reduced to 17.66 km², accounting for 3.41% of the total area. by 2022, there was a significant expansion, with the built-up area occupying 45.07 km², representing 8.68% of the total region.

2) Forest: In 2004, forests dominated the landscape, covering 432.85 km², which was approximately 83.43% of the total study area. By 2005, this forested area slightly decreased to 420.79 km², comprising 81.27% of the total area. However, by 2022, the forest cover continued to decline, with an area of 408.66 km², accounting for 78.78% of the total region.

3) Inundation Area: In 2004, the inundation area was limited, covering 3.40 km² or 0.65% of the total area. In 2005, there was a substantial increase, expanding to 28.41 km², which represented 5.48% of the total area. By 2022, the inundation area decreased to 13.89 km², making up 2.66% of the total region.

4) Cropland: Cropland covered 61.77 km² in 2004, accounting for 11.90% of the total study area. By 2005, this area reduced to 49.34 km², representing 9.53% of the total area. In 2022, the cropland area further decreased to 48.65 km², making up 9.37% of the total region.

5) Water Bodies: In 2004, water bodies covered a small area of 0.83 km², which was approximately 0.16% of the total area. By 2005, this area slightly increased to 1.54 km², constituting 0.29% of the total region. In 2022, there was a more significant expansion, with water bodies occupying 2.45 km², accounting for 0.47% of the total area.

Table 6 LULC Analysis for 2004, 2005 to 2022 in the Study region

LULC	2004 Area in km^2	2004 % of Area	2005 Area in km^2	2005 % of Area	2022 Area in km^2	2022 % of Area
Built-Up	19.92	3.84	17.66	3.41	45.07	8.68
Forest	432.85	83.43	420.79	81.27	408.66	78.78
Inundation Area	3.40	0.65	28.41	5.48	13.89	2.66
Cropland	61.77	11.90	49.34	9.53	48.65	9.37
Water Bodies	0.83	0.16	1.54	0.29	2.45	0.47
Total Area (Sq. Km)	518	100	518	100	518	100

5. Discussion

The complex interaction between geomorphology, shoreline change, LULC changes, and economic factors in tsunami vulnerability and impact assessment in South Andaman is discussed below;

5.1 Shoreline changes VS LULC

The impact of tsunamis varies due to differences in landforms, relief, slope, elevation, and the presence (or absence) of natural barriers such as coral reefs and mangroves. It has been observed that for a given water depth on the shelf, if the continental slope is steeper, greater mangrove cover, greater relief, and higher elevation can result in a greater amount of energy being reflected back, leading to a smaller tsunami wave height on the shelf. On the other hand, with a flatter slope, low relief, and less vegetation cover area on the coastal side, the reduced reflection and effect of shoaling can increase tsunami wave height (Siva et al. 2016). Coastal erosion is a natural process in south Andaman that occurs when waves, currents, tsunamis, and tides erode the shoreline, removing sediment and land over time. Factors such as sea-level rise, wave energy, storm events, and human activities can contribute to increased rates of erosion.

Over time, the geomorphological landforms continue to shape and modify the landscape. However, human activities and developmental pressures are significant drivers of LULC change in South Andaman (Fig. 9 a, b, c). Common LULC changes observed in the area include deforestation for urban expansion, conversion of land for agriculture, infrastructure development, and alterations to the coastal zone (Yuvaraj et al., 2014; Thakur et al., 2017; Jaman et al., 2022). The interaction between geomorphology and LULC change is particularly evident in the coastal regions of South Andaman, where coastal erosion and accretion processes influence both LULC patterns and development decisions. The erosion occurring near the

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shoreline leads to the loss of valuable land, affecting agricultural areas, and forest regions (Fig.6-8). Conversely, accretion processes can contribute to the growth of coastal areas by building new landforms, and influencing land use decisions in those locations (Nagabhatla et al. 2006; Ali and Narayana, 2015; Mageswaran et al. 2021).

5.2 Inundation and run observation

Our computations have shown that the tsunami wave heights for around 5.5 m inundation 90 m are observed (Fig.3 d). similarly, the harbour area of Port Blair has seen structural failures in some building's foundations and our computations show wave heights of 3.6m in that area. Chidiya Tapu which is 25 km from Port Blair the estimated run-up is 3.9 m and the inundation is 585 m, Figure No 2 i shows a gradual slope in the region. Coming to the Southpoint Magar area (Port Blair), a high run-up of 8.5 m is computed and the inundation level is 550 m. Houses located near the open sea were completely washed away. At Wandoor Jetty in Port Blair, the calculated runup is 3.46, the inundation is 450m, and the saltwater intrusion was observed due to the tsunami.

5.3 LULC vs economic change:

The presence of people, infrastructure, or assets in a hazard-prone location is referred to as exposure and Vulnerability is the degree to which a person, community, or system is susceptible to the impacts of a hazard. Vulnerability is determined by a combination of physical, social, economic, and environmental factors. (United Nations Office for Disaster Risk Reduction). Several factors can contribute to changes in exposure such as population growth, Industrial development, and LULC change. It is anticipated that the population of the Andaman and Nicobar Islands will double by 2050 (Nanda and Haub, 2007), and the islands are experiencing an increasing influx of tourists. The increased population density in these regions intensifies the strain on already vulnerable lands. As a result, when a disaster, such as a natural calamity, occurs in these areas, it affects the tourists and has severe repercussions for the large local population heavily dependent on tourism-related activities (Annan et al., 2005; Wood et al., 2019; Sathiparan et al.2020, Hamuna et al. 2019). The increases in population from 1971 to 2020, and built-up area is shown before and after the 2004 tsunami, and GSDP from 2001 to 2020 in tsunami-prone areas of South Andaman are observed in Fig. 10.

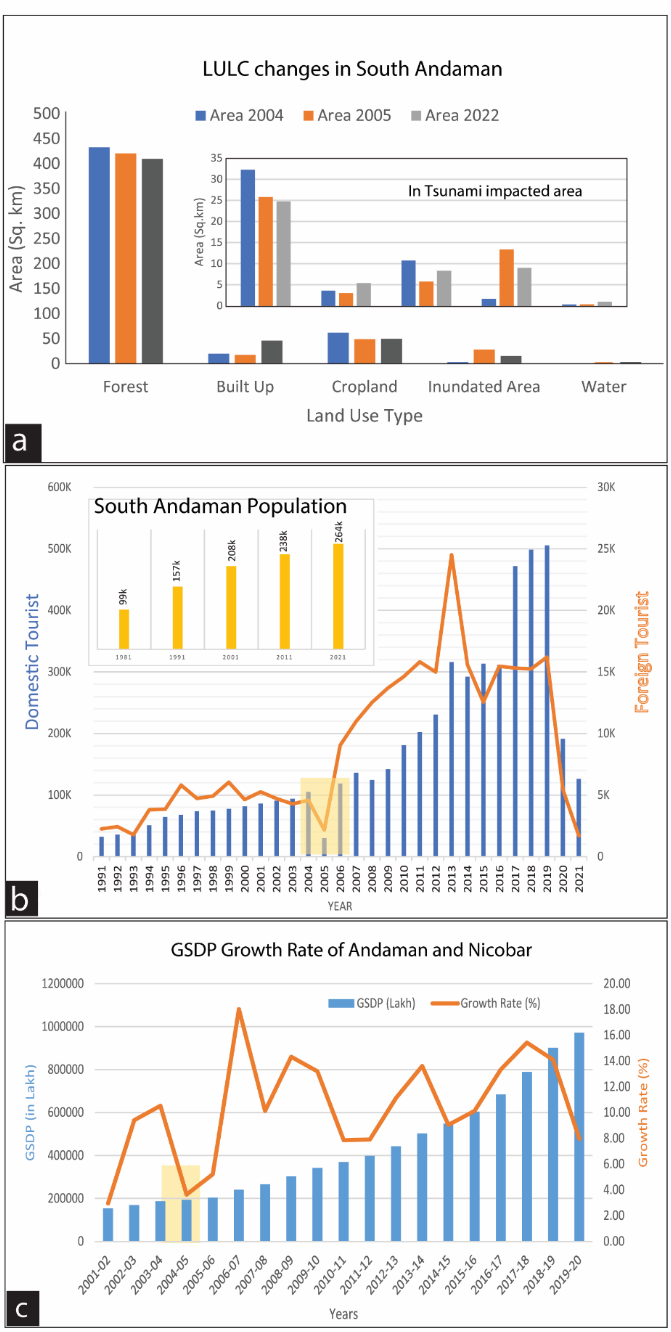

Figure 10 (a) LULC change in south Andaman and also in tsunami-affected areas of 2004. The LULC classification reveals that there has been a significant increase in built-up areas, inundated areas, and water bodies, while the agricultural land and vegetation have decreased. The increasing trends of tourists and local population in south Andaman can be seen in Fig. (b). and the GSDP growth rate shows the macroeconomic impact on GSDP in 2005 due to the tsunami impact (c).

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The increase in built-up areas could also positively impact the GSDP by boosting the construction and real estate sectors and providing more job opportunities in the tourism and hospitality industries. The 2004 Indian Ocean tsunami significantly impacted the GSDP of the Andaman and Nicobar Islands, particularly in the tourism and fisheries industries. According to a report by the National Institute of Disaster Management, the Andaman and Nicobar Islands suffered losses amounting to INR 7.5 billion due to the 2004 tsunami, with damages to the tourism industry being the most significant. It is important to carefully manage this growth and ensure sustainable development practices protecting both the natural environment and the well-being of the local population. This includes implementing effective disaster preparedness measures, promoting sustainable tourism practices, and balancing economic development with environmental conservation in the region.

5.4 Implication for changing scenario of vulnerability

India Inc. estimates that the total losses surpassed Rs 3,000 crore. Specifically, the losses in Andaman & and Nicobar Islands exceeded Rs 1,000 crore as per industry estimates (Economictimes.com). If a tsunami of similar magnitude were to occur again, the economic loss would be five times as high as those experienced in 2004. After the 2004 tsunami, the coastal area experienced significant development, with built-up areas expanding in already affected areas from ~7.38 % in 2004 to ~11.11 % in 2022. This increase in urbanization and infrastructure means that more properties, businesses, and critical facilities are now located in the coastal zone. The affected region's local population grew from 208k people in 2001 to 264k people in 2021 (Figure 10). With more people living in the coastal area, there is a higher risk of casualties and a greater demand for resources and aid during and after a tsunami. The number of tourists visiting the coastal area has increased significantly over the years. In 2001, there were 98,000 tourists, but by 2019, this number rose to 500,000 (Figure 10). Tourists are generally less familiar with local hazards and evacuation routes, making them more vulnerable during a tsunami. The presence of a large number of tourists can add complexity to evacuation and relief efforts, potentially leading to higher economic losses. The region has experienced a sharp decline in forest and cropland areas. Forests act as natural buffers, helping to reduce the impact of a tsunami by absorbing some of the wave energy. Additionally, the loss of cropland can disrupt the supply chain during and after a disaster, affecting food availability and leading to economic losses beyond property damage.

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6. Conclusions

The South Andaman region is vulnerable to tsunamis due to its location in the seismically active zone. In such an environment, tsunami preparedness and resilience are crucial. This includes implementing effective early warning systems, raising public awareness, and strengthening infrastructure resilience. Incorporating ecosystem-based approaches, such as the preservation and restoration of natural coastal land, can also contribute to reducing tsunami vulnerability. The South Andaman region is prone to shoreline changes due to natural processes and human activities. It is crucial to monitor and assess these changes regularly to understand their impacts on coastal ecosystems and communities. Implementing appropriate coastal management strategies, such as beach nourishment, dune restoration, and erosion control measures, can help mitigate the negative effects of shoreline changes. It is important to adopt sustainable land use practices that balance economic development with the conservation and responsible use of resources. This involves promoting eco-friendly tourism, protecting sensitive ecosystems like mangroves and coral reefs, and implementing land use planning that considers the carrying capacity and vulnerability of the region. Tsunami modeling along the coastal locations shall help decision-makers how to construct structures along the coast. Decision makers will also be able to quantify the tsunami impact on sloping beaches, Flat beaches, and areas having boulders/mangroves. Engaging local communities, stakeholders, and indigenous knowledge holders in decision-making processes and promoting capacity-building initiatives are critical for ensuring the sustainable development of the Andaman region.

Code availability

No

Data availability

All data included in this study are available upon request by contacting the corresponding author.

Authors' contributions

Vikas Ghadamode: Computations, Fieldwork, and Manuscript Writing.
K. Kumari Aruna: TUNAMI-N2 Computation and Fieldwork, Manuscript Writing
Anand Kumar Pandey: Manuscript Editing and Contribute Ideas and Suggestions
Kirti Srivastava: Paper Writing and TUNAMI-N2 Computations

Competing interests / Conflicts of interest/

The authors declare that they have no known conflicts of interest.

Declarations

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