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Mapping disappearance: spatial analysis of vulnerable coastal destinations

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Abstract

Many coastal regions around the world face increasing risks from both natural and anthropogenic drivers, including climate change, rising sea levels, and rapid, unauthorized urbanization. This study presents an integrated geo-spatial approach to evaluate the coastal vulnerability of Visakhapatnam and Uppada Village, both located in coastal Andhra Pradesh, India. These areas are exposed to multiple natural hazards and disasters but lack comprehensive multi-temporal analysis. This research uniquely integrates remote sensing and GIS with a multi-parameter coastal vulnerability assessment and extensive field validation, representing a comprehensive 35-year evaluation (1990–2024) of these critical coastal zones. To assess overall coastal vulnerability, five physical parameters were considered: Shoreline change, coastal slope, land use/land cover, relative sea level, and mean tidal range. The results were further validated through field visits. The findings indicate significant shoreline erosion at both locations, with Uppada Village identified as a highly vulnerable coastal zone experiencing ongoing and rapid erosion. In Visakhapatnam, erosion rates have reached a maximum of -13.1 m/year, alongside accretion rates of up to 21.1 m/year in certain areas, resulting in a net average coastline retreat of 64 m between 1990 and 2024. In contrast, Uppada Village has experienced consistent erosion along its coastline, with rates reaching -3.95 m/year and no notable accretion, resulting in an average loss of 90 m over the study period. Uppada Village lacks natural protective features and exhibits a uniformly high level of vulnerability due to wave action and sea-level rise. In Visakhapatnam, both anthropogenic and natural factors have contributed to coastal vulnerability. These findings underscore the urgent need for government and multi-stakeholder intervention to conserve these sensitive coastal areas. Potential measures include the implementation of both soft and hard coastal engineering solutions, as well as nature-based approaches such as mangrove restoration and seagrass development. If no action is taken, and current erosion rates of -3.95 m/year persist, significant portions of Uppada's coastline face a high risk of severe degradation within the next two to three decades. This study provides essential baseline data and actionable recommendations for policymakers, coastal managers, and stakeholders to support the development of evidence-based adaptation strategies for these increasingly vulnerable coastal regions.

Keywords Coastal vulnerability, Digital Shoreline Analysis System (DSAS), Sea level rise, Shoreline analysis, Vulnerability maps

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1 Introduction

Coastal vulnerability refers to the susceptibility of coastal regions to adverse impacts caused by both natural processes and human activities, including climate change, sea-level rise, and anthropogenic interventions (Bukvic et al., 2020). Coastal areas are critical to global socioeconomic systems, supplying vital resources, ecosystems, and services (Sankari et al., 2015). Despite their importance, these regions are highly dynamic and face increasing risks due to their location at the interface of land, sea, and atmosphere. Nearly two-thirds of the global population resides within 400 km of coastal regions, with over half depending on these areas for their livelihoods (Sahoo & Bhaskaran, 2018). Global evidence indicates that coastal degradation and land loss are interconnected processes, forming a broader pattern of climate-induced spatial transformation affecting vulnerable regions worldwide (Paul et al., 2024; Queiroz et al., 2022). Recent studies have documented accelerating rates of environmental degradation driven by human activities and rising sea levels across multiple continents (Bagheri et al., 2023; Chowdhury et al., 2025).

The integration of geospatial modeling with environmental indicators has become an essential tool for quantifying these changes and developing evidence-based adaptation strategies (Zhang et al., 2020). Coastal vulnerability assessments have evolved from basic index-based approaches to advanced multi-criteria frameworks that incorporate remote sensing, field validation, and socioeconomic analysis (Das et al., 2025; Durap & Balas, 2024; Tanim & Goharian, 2023). Recognizing these global patterns is crucial for understanding regional vulnerability and formulating effective mitigation strategies. This global trend is particularly evident in India, where 46% of the coastline of Tamil Nadu is categorized as highly vulnerable to flooding (Palpanabhan et al., 2024). In India, over 13% of the population lives in coastal regions, making them highly exposed to cyclonic hazards (Rout & Thussu, 2024). According to IPCC projections, a one-meter rise in sea level could displace approximately seven million people in India (IPCC, 2001). India's eastern coastline, particularly in Andhra Pradesh, is frequently affected by tropical cyclones that form in the Bay of Bengal (Ganesh et al., 2017). In May 2023, Cyclone Mocha formed in the southeastern Bay of Bengal, causing significant impacts (Rathaur et al., 2023). In 2024, two additional cyclones, Dana and Fengal, also caused considerable damage in southern India and Sri Lanka.

Different approaches have been designed to evaluate coastal vulnerability, from simple index-based methods to advanced dynamic computer models (Bagheri et al., 2023; Durap & Balas, 2024; Olivares-Aguilar et al., 2022; Tanim & Goharian, 2023). Specifically, four main

approaches can be identified: (i) index/indicator-based methods, (ii) methods based on dynamic computer models, (iii) GIS-based decision support tools, and (iv) visualization tools (Sekovski et al., 2020). Gornitz et al. (1991) introduced the Coastal Vulnerability Index (CVI), which is widely used for its capacity to incorporate various factors, including sea-level rise, tidal range, wave height, and geomorphology. GIS-based decision support tools are also increasingly utilized, enabling the integration and spatial analysis of multi-temporal data to produce detailed vulnerability maps (Durap, 2024; Ghorai & Paul, 2023; Theocharidis et al., 2024). This research focuses on the coastal regions of Visakhapatnam and Uppada Village in Andhra Pradesh, India, which are experiencing significant environmental transformations. Uppada Village has witnessed the loss of over 127 acres of land to oceanic encroachment over the past four decades, with the neighbouring region, Kakinada, potentially facing submersion within 80 years (Mahendra et al., 2021; Santhi & Latha, 2024; Tharapatla et al., 2024). Similarly, Visakhapatnam faces challenges from its unique headland-bay geomorphology and increasing urbanization, requiring vulnerability assessments (Mahendra et al., 2021). Such localized case studies are crucial for understanding overall coastal risk.

Numerous studies (Abuodha & Woodroffe, 2010; Bagheri et al., 2023; Chowdhury et al., 2025; Cogswell et al., 2018; Deb et al., 2024; Durap & Balas, 2024; Hamid et al., 2024; Nigam et al., 2024; Olivares-Aguilar et al., 2022; Tanim & Goharian, 2023) have evaluated coastal vulnerability using GIS-based techniques and index methods; however, significant methodological gaps persist in the literature. Many existing CVI studies rely on a limited number of parameters and single-epoch data, producing static snapshots rather than capturing long-term trends. Digital Shoreline Analysis System (DSAS)-based multi-temporal analyses have rarely been integrated with multi-parameter GIS vulnerability mapping within a single framework, and field validation through systematic ground-truthing is frequently absent, reducing confidence in remotely sensed assessments in data-scarce regions. Comparative analyses between urban and rural coastal settings within the same regional context also remain scarce, particularly along the understudied coastline of Andhra Pradesh, India. Addressing these gaps, this research presents a unique integrated geospatial approach for Visakhapatnam and Uppada Village, combining a high-frequency 35-year multi-temporal shoreline analysis using DSAS with five physical parameters, extensive field validation, and a dual-site comparative design. Unlike previous studies, this approach captures decadal variability, ensures ground-truth accuracy, and delivers a comprehensive vulnerability profile across

contrasting coastal settings, making it a valuable tool for coastal management and policymaking.

The primary objectives of this research are: (1) to conduct a comprehensive assessment of coastal vulnerability in Visakhapatnam and Uppada Village using integrated geospatial techniques; (2) to validate the geospatial findings through extensive field observations and ground-truthing; (3) to generate high-resolution coastal vulnerability maps and provide evidence-based recommendations for multi-stakeholder interventions. The maps will help identify vulnerability levels in different regions and help address the existing knowledge gap.

2 Materials and methods

2.1 Study area

The current study examines the coastal vulnerability of two areas, Visakhapatnam and Uppada Village, located along India's eastern coastline. These locations are situated along the Bay of Bengal coast in Andhra Pradesh, one of India's coastal states (Fig. 1). They were selected as case study sites due to their geographical positions and high levels of coastal vulnerability, particularly their significant exposure to various natural hazards that necessitate a comprehensive vulnerability assessment. During a recent field visit, some of the authors observed a notable

degree of erosion in these areas. These observations underscore the importance of addressing coastal vulnerability in both Visakhapatnam and Uppada Village.

Visakhapatnam, one of the most populous metropolitan cities, commonly known as Vizag, is located between the latitudes of 17°10'N and 18°30'N, and the longitudes of 81°50'E and 83°30'E along India's northeastern coastline. The coastal geomorphology exhibits a unique headland-bay formation, featuring rocky promontories that extend into the sea, along with elements such as sea cliffs, wave-cut terraces, and sea stacks (Babu et al., 2007). The beaches are composed predominantly of medium-to-coarse quartz sand with scattered shell fragments (Kumar et al., 2001). The region receives moderate rainfall, averaging between 1,000 and 1,200 mm annually during the southwest and northeast monsoons (Rao et al., 2013). Visakhapatnam is the seventh largest district in Andhra Pradesh, covering an area of 11,161 km² and having a coastline of 135 km (Kannan et al., 2015). The area comprises both coastal plains and hilly regions, with elevations reaching up to 253 m above mean sea level at the Madhurawada dome, which contributes to its diverse topography (Rao et al., 2013). The area's susceptibility to coastal hazards is highlighted by historical records, which indicate that 60 tropical cyclonic events affected the

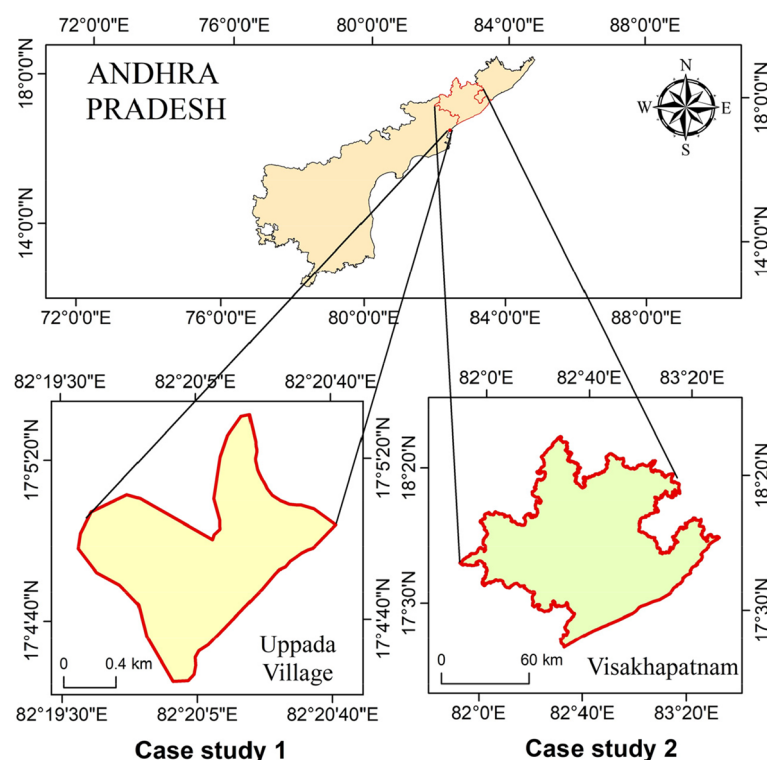


Fig. 1 Location map of the study area, showing Visakhapatnam and Uppada Village along the Bay of Bengal on the eastern coast of India. Source: Created by the second author using ArcGIS 10.5

Andhra Pradesh coast between 1971 and 2014. Notable storms include the severe cyclones Hudhud and Phailin, which occurred in 2014 and 2013, respectively (Ganesh et al., 2017).

Uppada Village is a coastal village located in the East Godavari district of Andhra Pradesh, situated along the Bay of Bengal at around 17.09°N latitude and 82.33°E longitude. The village spans 4.50 km² at an elevation of 15 m above sea level, with a 5 km-long coastline (Santhi & Latha, 2024). Unlike the rocky coastline of Visakhapatnam, Uppada Village's coast is entirely sandy and low-lying, composed of unconsolidated Holocene alluvial and deltaic sediments derived from the Godavari River system (Rao et al., 2005). The village once served as a key marine fish landing center in the Kakinada region, where prawns contributed significantly to the total fish landings (Lalitha Devi, 1985). Along with the neighboring villages of Subbampeta and Ameenabad, Uppada Village has been severely affected by coastal erosion (Raju, 2018). Historical records indicate that coastal Andhra Pradesh lost approximately 4.18 km² of land due to coastal erosion between 1990 and 2006, with Uppada Village being one of the most impacted locations in the state (Padam et al., 2012). According to the Population Census 2011, Uppada Village has a population of around 12,964 residents, who face significant environmental challenges, particularly severe coastal erosion that has persisted for multiple decades. The shoreline recession has adversely affected livelihoods, housing, and fishery resources (Prasad & Rao, 2014). The climatic conditions further compound these environmental challenges. Uppada Village's open, linear coastline is particularly vulnerable during the northeast monsoon (October–December), when high-intensity waves from the east-northeast create rougher sea conditions (Kavya et al., 2019). Moreover, the humidity in Uppada Village (81%) is considerably higher than that in nearby Yadavole (42%) (Peddakapu et al., 2024).

2.2 Data collection

The datasets used for this study are briefly described in Table 1. Satellite data from Landsat sensors, including the Thematic Mapper (TM), Enhanced Thematic Mapper

(ETM), and Operational Land Imager with Thermal Infrared Sensor (OLI/TIRS), covering the period from 1990 to 2024, along with 1 arc-second resolution Shuttle Radar Topography Mission (SRTM) data obtained from the United States Geological Survey (USGS). In addition, monthly sea-level records were obtained from the Global Sea Level Observing System (GLOSS). Land use/land cover data for the years 1990 and 2024 were derived from Landsat 5 and Landsat 9 imagery, respectively. Tidal data were obtained from Tides4Fishing.com.

2.3 Parameters and methods for vulnerability assessment

Modern methods integrate physical, environmental, and socio-economic factors to develop a more comprehensive vulnerability profile. Recent advancements in geospatial tools, including high-resolution remote sensing, LiDAR, and machine learning, have significantly enhanced mapping accuracy and detail (Hamid et al., 2024). New approaches now utilize Bayesian networks for hazard analysis, connecting climate projections with vulnerability indices and employing dynamic, scenario-based frameworks (Durap & Balas, 2024). These improvements help identify areas with significant vulnerability. However, their effectiveness relies on data quality, temporal consistency, and validation through fieldwork. Integrating multi-temporal satellite imagery with ground-truth data is essential for ensuring reliability, particularly in rapidly changing coastal regions (Olivares-Aguilar et al., 2022).

This study selected five parameters — shoreline change, coastal slope, land use/land cover, relative sea level, and mean tidal range (Table 2) — which align with established coastal vulnerability assessment frameworks (Gornitz et al., 1991; Sahoo & Bhaskaran, 2018; Thieler & Hammar-Klose, 2000; Thieler et al., 2009). Compared to prior studies that typically use static, single-date satellite imagery and standard CVI values, this study improves on existing methodologies in three ways: (1) DSAS is applied using five temporal epochs (1990, 2000, 2010, 2020, 2024), enabling robust decadal trend analysis through both Net Shoreline Movement (NSM) and the statistically more robust Weighted Linear Regression (WLR) method; (2) all five parameters are derived

Table 1 Data sets and data sources

Data type	Spatial resolution	Period	Source
Landsat	30 m	1990, 2000, 2010, 2020, 2024 (5 time points at 10-year intervals)	USGS (accessed on Oct 01, 2024)
SRTM	1 arc-second (~30 m)	Sep 23, 2024	USGS (accessed on Nov 15, 2024)
Sea level rise	Point data	1990–2022	GLOSS (accessed on Oct 15, 2024)
Land use/Land cover	30 m	1990 and 2024	USGS (accessed on Nov 27, 2024)
Tidal range	Point data	Aug 01 to Oct 31, 2024	Tides4Fishing.com (accessed on Nov 10, 2024)

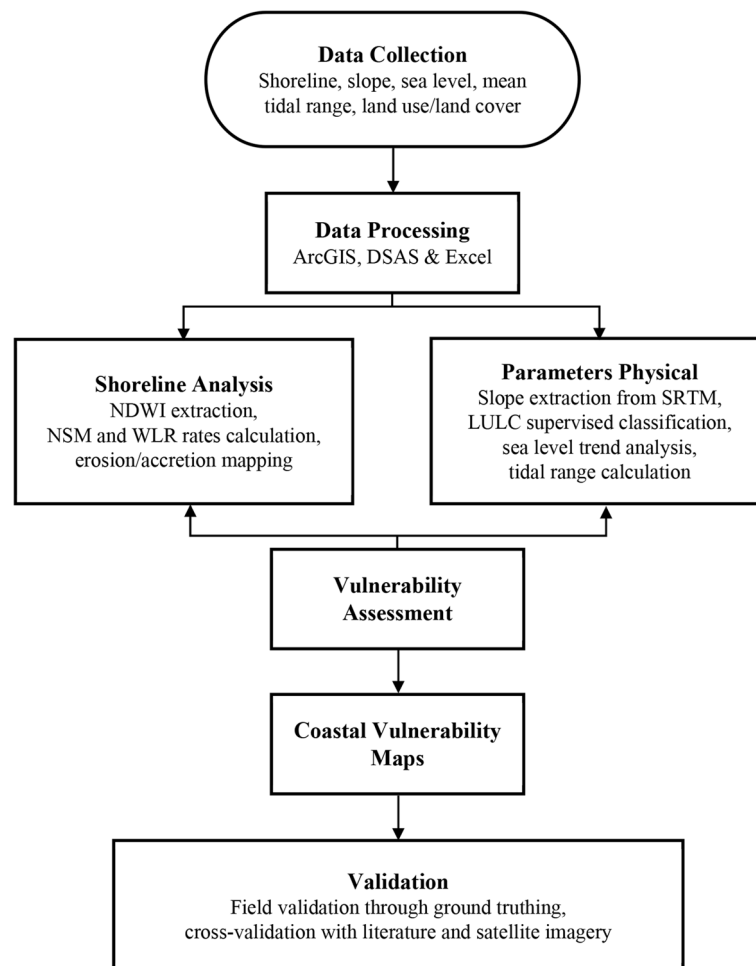
Table 2 Threshold for coastal vulnerability assessment

Parameter	Very low	Low	Moderate	High	Very high	References
Shoreline change (m/year)	Accretion > 6	3–6	(–3)–(3)	(–6)–(–3)	Erosion < –6	Mahapatra et al. (2015)
Coastal slope (%)	> 12	8–12	4–8	2–4	< 2	López Royo et al. (2016)
Relative sea level (mm/year)	< 1	1–2	2–3	3–4	> 4	Sahoo and Bhaskaran (2018)
Mean tidal range (m)	< 1.0	1.0–2.0	2.0–4.0	4.0–6.0	> 6.0	Kwasi (2014)
Land use	-	Barren land	Water, grassland	Forest, crops	Built-up area	Dang et al. (2011); Yin et al. (2012)

from locally acquired or field-validated data, rather than global default datasets; and (3) geospatial outputs are cross-validated through systematic field observations and geo-referenced photography.

The research methodology is illustrated in the flow chart shown in Fig. 2. Shoreline change rates were estimated from Landsat data using ArcGIS software. Sea-level trends were accessed using GLOSS, while relative sea-level data were obtained from Sahoo and Bhaskaran

(2018). Tidal data were sourced from Tides4Fishing.com to determine mean tidal range. Landsat images were utilized for land use classification. Additionally, SRTM Digital Elevation Model data were used to estimate the coastal slope. The overall coastal vulnerability assessment was derived by integrating these individual parameter maps using GIS techniques, thereby enabling the identification of areas where multiple vulnerability factors converge.

**Fig. 2** Methodological flow chart illustrating the integrated geospatial approach employed in this study

2.3.1 Coastal erosion and shoreline changes

Shoreline changes result from dynamic coastal processes influenced by wave behaviour, nearshore currents, sediment properties, beach morphology, and other contributing factors (Ganesh et al., 2017). The DSAS is one of the most commonly used ArcGIS 10.5 extensions for estimating shoreline change through statistical methods (Abd-Elhamid et al., 2023; Thieler et al., 2009). Several studies (Baig et al., 2021; Mutaqin, 2017; Thieler et al., 2009) have employed this method to evaluate both temporal and spatial shoreline movements. In this study, the DSAS v4.0 statistical methods of NSM and WLR were applied to analyze shoreline changes in the Visakhapatnam and Uppada areas. NSM was used to measure the total shoreline displacement over a specific period, providing a straightforward assessment of long-term shoreline shifts. WLR was used to determine the rate of shoreline change while accounting for data variability, offering a more statistically robust trend analysis. For this study, a multi-temporal dataset at approximately decadal intervals was used to effectively capture shoreline change, focusing on the years 1990, 2000, 2010, 2020, and 2024. Landsat data were obtained from the USGS to estimate shoreline changes, and ArcGIS was used to digitize the shorelines along the coast. Landsat Collection 2 Level 2 Surface Reflectance products were utilized, which are atmospherically and terrain corrected by the USGS. Images were carefully selected with less than 10% cloud cover over the study areas to ensure data quality and minimize the need for additional cloud masking.

The land–water boundary was delineated using the Normalized Difference Water Index (NDWI) derived from Landsat imagery. The data were then reprojected to the Universal Transverse Mercator (UTM) coordinate system using the WGS-84 datum. Finally, the DSAS tool was employed to analyze the rate of shoreline change using the vectorized shoreline data. Coastal areas experiencing accretion are considered less vulnerable, whereas erosion indicates increased risk due to the loss of public and private property (Ganesh et al., 2017). The coastal vulnerability assessment due to shoreline changes was conducted using the classification method described by Mahapatra et al. (2015).

2.3.2 Coastal slope

The coastal slope is a key indicator of relative vulnerability to inundation and the potential speed of shoreline retreat. This parameter is used to assess the risk of flooding, and to estimate the rate at which the coastline may retreat (Rao et al., 2008; Szlafsztein & Sterr, 2007). The SRTM global elevation data with a resolution of 1 arc-second were utilised to generate the coastal slope, which was downloaded from the USGS. The slope was calculated using the Slope

tool in ArcGIS 10.5. The slope ranges were classified according to a method proposed by Pantusa et al. (2022), originally developed by López Royo et al. (2016). When assessing vulnerability to inundation, storm surges, and associated land loss, coastlines with gentle slopes are more vulnerable than those with steeper slopes.

2.3.3 Relative sea level

To analyze sea level patterns, tide gauge measurements from the GLOSS database were used. Monthly average readings from Visakhapatnam tide gauge over a 33-year period (1990–2022) were plotted to determine the sea level trend. However, the GLOSS tide gauge data primarily provide long-term sea level trends rather than the specific relative sea level values required for vulnerability classification, due to the non-linearity of sea level variations over time. Therefore, an alternative approach was adopted.

For vulnerability assessment, a reference relative sea level value was obtained from Sahoo and Bhaskaran (2018), which identified a relative sea level for the Bay of Bengal. Since this value closely represents the conditions near the study area, it was used for classification to ensure methodological consistency and reliability in the analysis. The vulnerability classification was subsequently conducted following the same method as Sahoo and Bhaskaran (2018).

2.3.4 Land use/Land cover

In this study, a comparative analysis of land use patterns was conducted using data from two different periods: 1990 and 2024. The historical land use data for 1990 and 2024 were obtained from Landsat images using supervised classification. The analysis identified and classified various land use features, including barren land, built-up areas, crops, forest, grassland, and water bodies. Land use classes were categorized based on an effective land use classification system developed by the USGS. This temporal comparison of land use patterns helps assess how land use changes have either enhanced or reduced the vulnerability of the coastal area over 34 years. To assess coastal vulnerability related to land use and land cover, the classification method used by Dang et al. (2011) and Yin et al. (2012) was employed.

2.3.5 Tidal range

The vulnerability classification related to the tidal range was conducted according to Kwasi (2014).

3 Results

3.1 Coastal vulnerability of Visakhapatnam

3.1.1 Coastal erosion and shoreline changes

The map (Fig. 3) illustrates shoreline change patterns along the Visakhapatnam coast, categorized into high erosion, low erosion, stable shoreline, low accretion, and

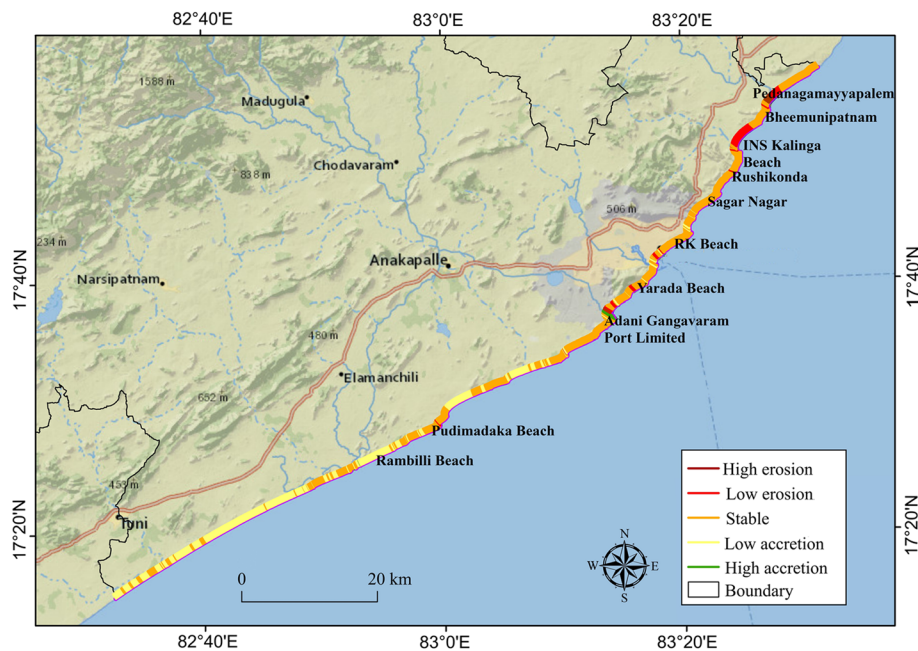


Fig. 3 Shoreline erosion and accretion trends for Visakhapatnam (1990–2024). Source: Created by the second author using ArcGIS 10.5

high accretion zones. The analysis was conducted using shoreline data from 1990 to 2024 to determine long-term coastal changes. Notable locations experiencing high erosion impacts, such as Rushikonda Beach, RK Beach, and Yarada Beach, are highlighted.

Three zones have been identified along the Visakhapatnam coastline based on visible areas of maximum erosion and accretion (Fig. 4a). The shoreline shows different change rates across the three zones. Zone II shows the most dramatic fluctuations, with the maximum erosion rate of -13.1 m/year and the maximum accretion rate of 21.1 m/year. Zone I shows moderate changes, with maximum erosion rate of -5.18 m/year and maximum accretion rate of 6.65 m/year, while Zone III only shows accretion, with the maximum accretion rate of 4.25 m/year.

A temporal analysis of shoreline positions indicated significant patterns of erosion and accretion across the study areas. Throughout the study period, the NSM values in Visakhapatnam fluctuated markedly, with maximum erosion reaching -383.2 m and maximum accretion extending to 604.7 m (Fig. 5a). The WLR analysis revealed the maximum erosion rate of -13.1 m/year and the maximum accretion rate of 21.1 m/year (Fig. 4a). Between 1990 and 2024, DSAS results showed evident patterns of erosion and accretion across the study area. Zone II experienced the highest level of accretion, with a maximum NSM of 604.7 m, as well as the most significant erosion, with a minimum NSM of -383.2 m. In Zone I, the maximum accretion of 40.56 m and the minimum NSM

of -185 m indicate moderate erosion. Zone III displayed a maximum accretion of 137.59 m, with no notable erosion recorded. The DSAS findings indicate that, on average, the coastline of Visakhapatnam has experienced a net erosion of 64 m from 1990 to 2024. Considering the coastal vulnerability of Visakhapatnam (Sect. 3.1.5), it is evident that most areas in Zone I are classified as having high coastal vulnerability. Zone II exhibits a mix of very high and very low vulnerability in specific areas, while Zone III is characterized by moderate vulnerability. Overall, when assessing the entire region, nearly all areas are found to exhibit moderate vulnerability.

3.1.2 Relative sea level and tidal range

Tide gauge data from Visakhapatnam were analyzed to assess sea level trends between 1990 and 2022. The findings indicate a notable rise in sea level between 1990 and 2022 despite intermittent data gaps common to long-term tide gauge records (Fig. 6). The relative sea level has been identified as 3.8 mm/year in the Bay of Bengal according to the study by Sahoo and Bhaskaran (2018). Based on the coastal vulnerability classification (Sect. 3.1.5), Visakhapatnam is classified as having high vulnerability to sea level rise.

Tidal observations conducted from August to October 2024 revealed consistent patterns in Visakhapatnam (Fig. 7). The tidal range fluctuated regularly between 0.4 m and 1.8 m, displaying a cyclical pattern throughout the observation period. The highest tidal values,

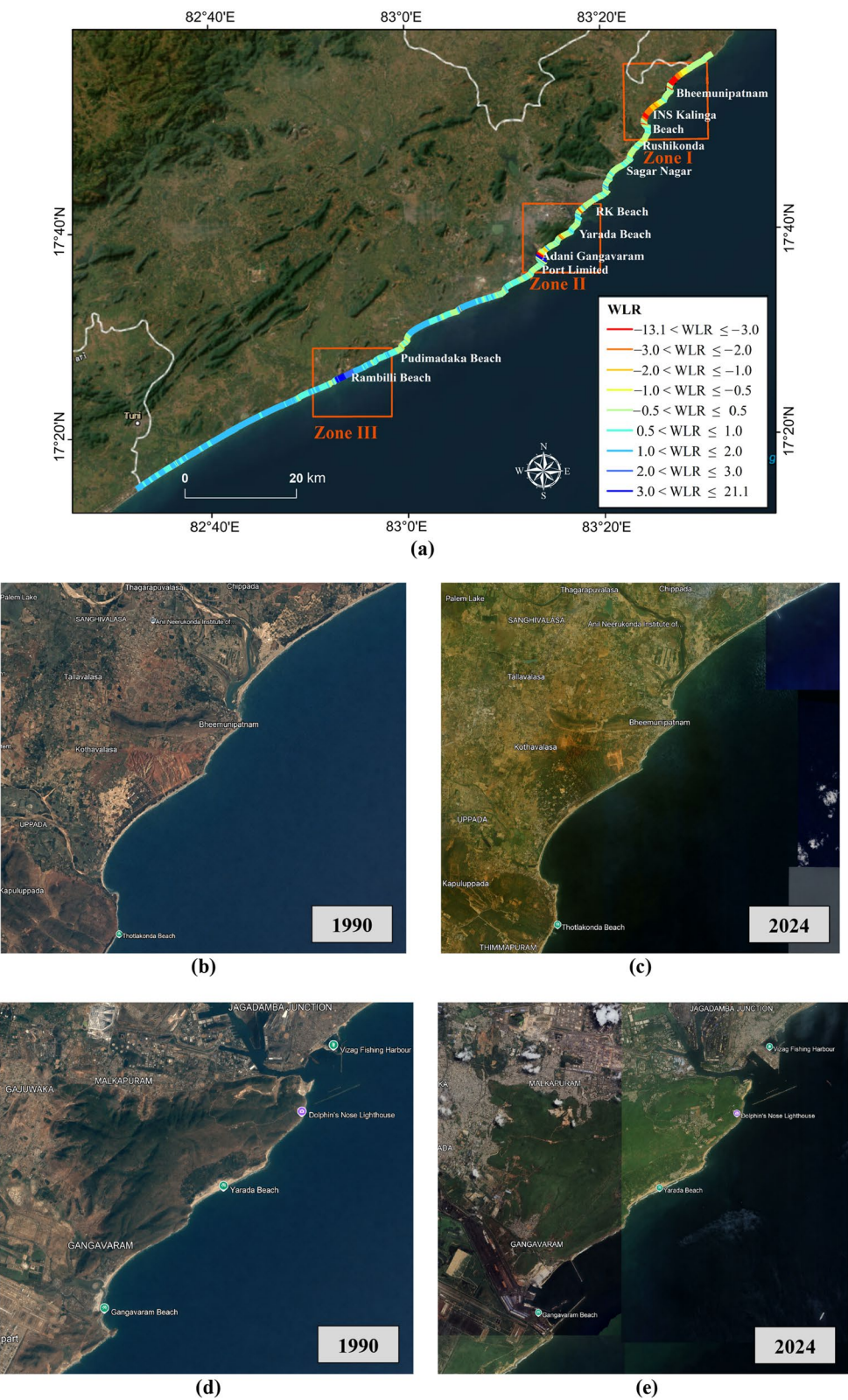


Fig. 4 Identified zones with WLR values in Visakhapatnam from 1990 to 2024. **a** Three zones; **b** 1990 satellite image, Zone I; **c** 2024 satellite image, Zone I; **d** 1990 satellite image, Zone II; **e** 2024 satellite image, Zone II. Source: Created by the second author using ArcGIS 10.5 and Google Earth Pro 7.3.6

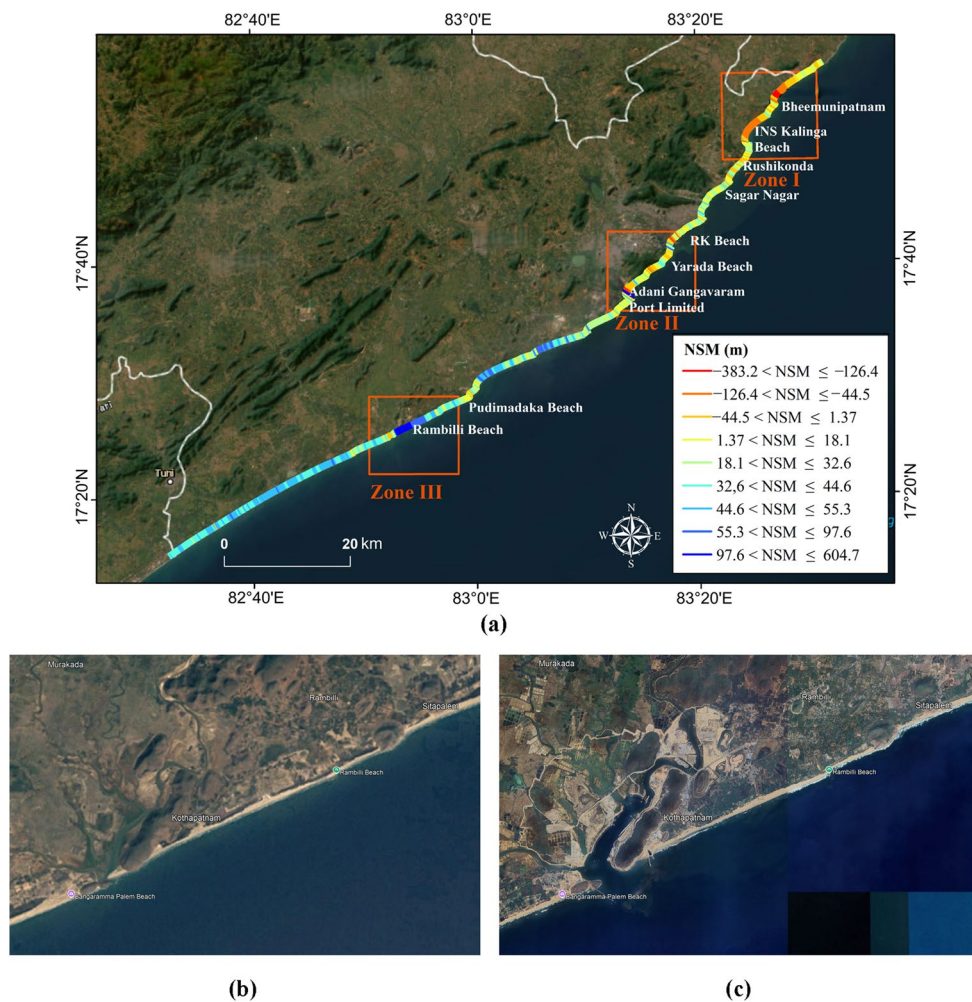


Fig. 5 Identified zones with NSM values in Visakhapatnam from 1990 to 2024. **a** Three zones; **b** 1990 satellite image, Zone III; **c** 2024 satellite image, Zone III. Source: Created by the second author using ArcGIS 10.5 and Google Earth Pro 7.3.6

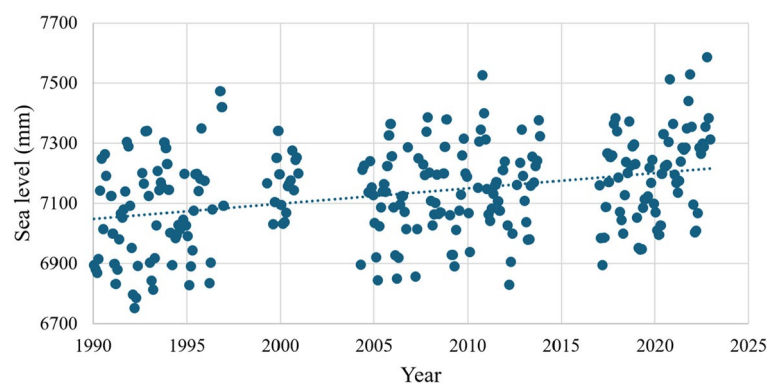


Fig. 6 Sea level data from the Visakhapatnam tide gauge, showing trends from 1990 to 2022

approximately 1.8 m, occurred in mid-August, mid-September, and mid-October, while the lowest values dropped to between 0.4 m and 0.5 m during early to late

September. According to the coastal vulnerability classification (Sect. 3.1.5), Visakhapatnam is categorized as having low vulnerability to the mean tidal range.

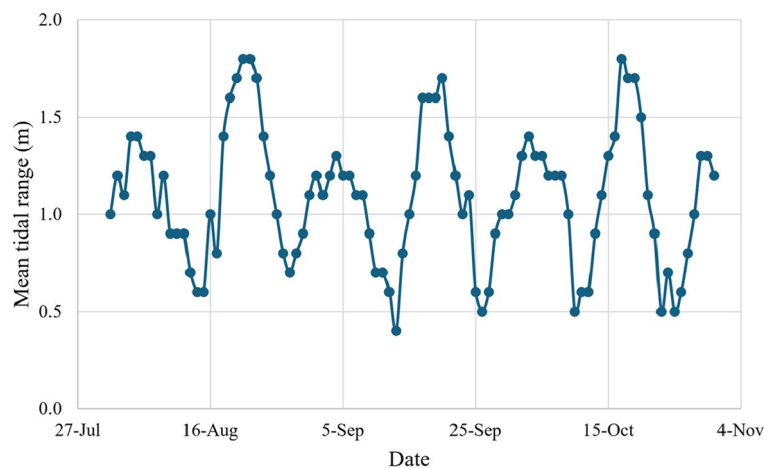


Fig. 7 The mean tidal range at Visakhapatnam from August to October 2024

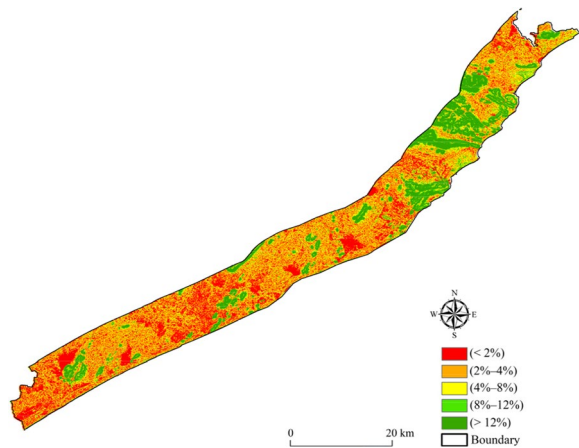


Fig. 8 Slope map for Visakhapatnam derived from SRTM Digital Elevation Model with 1arc-second (~30 m) resolution. Source: Created by the second author using ArcGIS 10.5

3.1.3 Slope

The morphological assessment, as shown in Fig. 8, indicates that Visakhapatnam has predominantly moderate coastal gradients. There is some variation, particularly on the eastern side of Visakhapatnam boundary, where slopes range from 8% to 12%. In contrast, the slopes in most areas are less than 4%. The coastal vulnerability map (Sect. 3.1.5), reveals that nearly all regions in Visakhapatnam fall into the very high vulnerability category. However, some locations on the eastern side of the city exhibit very low levels of vulnerability.

3.1.4 Land use

An analysis of land use and land cover in Visakhapatnam from 1990 to 2024 (Fig. 9) reveals significant changes. The built-up area has increased dramatically from 10.64% to 38.75%, reflecting rapid urbanization.

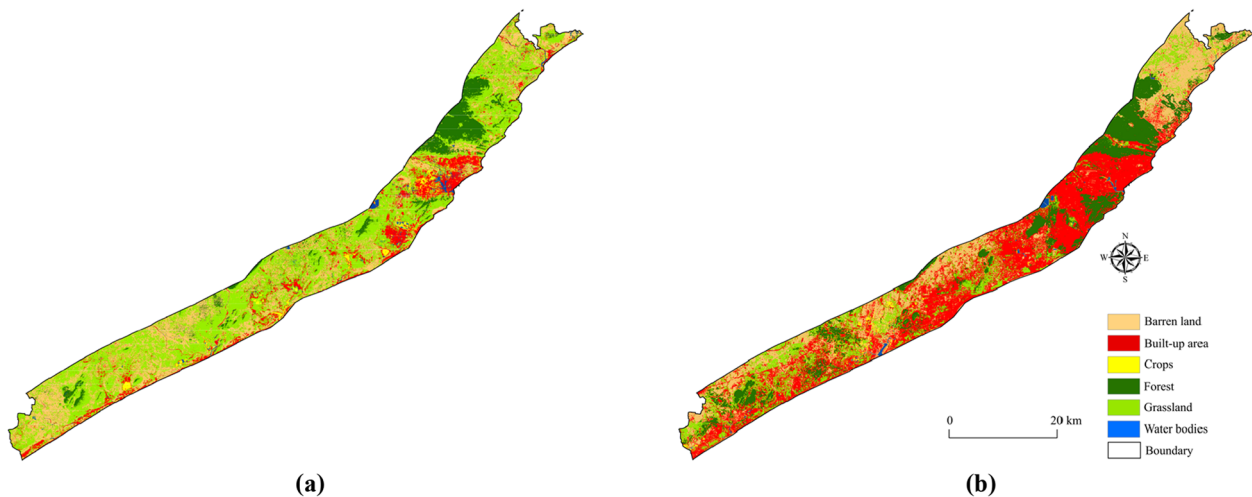


Fig. 9 Temporal variation of land use. **a** Visakhapatnam in 1990; **b** Visakhapatnam in 2024. Source: Created by the second author using ArcGIS 10.5

Forest cover has also expanded, rising from 8.76% to 18.31%. In contrast, grassland has decreased substantially, dropping from 50.48% to 17.48%. Croplands have shrunk from 2.77% to 1.28%, while barren land has experienced a slight decline from 25.37% to 23.47%. Water bodies have diminished significantly, falling from 1.97% to 0.17%. These changes underscore the rapid urban expansion occurring in the coastal zone of Visakhapatnam. Satellite images from 1990 and 2024 (refer to Figs. 4b–e, 5b–c) further confirm this trend of urbanization. Additionally, the coastal vulnerability classification (Sect. 3.1.5), based on land use, indicates that Visakhapatnam has very high levels of vulnerability in most areas, with some regions along the eastern edge of the boundary exhibiting low vulnerability.

3.1.5 Overall coastal vulnerability of Visakhapatnam

The analysis of coastal vulnerability along the eastern Indian coastline showed significant variations in shoreline, morphological characteristics, and land use patterns. This study examined these changes through various physical parameters to understand the coastal vulnerability of Visakhapatnam. Accordingly, GIS vulnerability maps were generated to reach both technical and non-technical audiences (Fig. 10). The areas of highest vulnerability include Yarada Beach, Bheemuni-patnam, Pedanagamayyapalem, RK Beach, Rushikonda Beach, Pudimadaka Beach, Sagar Nagar, INS Kalinga Beach, and Relli Beach.

3.2 Coastal vulnerability of Uppada Village

3.2.1 Coastal erosion and shoreline changes

The Uppada Village shoreline analysis shows contrasting patterns compared to Visakhapatnam, demonstrating consistent erosion along the coastline without significant accretion (Fig. 11). The WLR analysis (Fig. 12a) indicated erosion rates between -4 m/year and 0 m/year, with a maximum rate of -3.95 m/year, while the NSM (Fig. 12b) showed a maximum erosion of -156 m, with an average coastline erosion of 90 m from 1990 to 2024, indicating that the most severe erosion occurred in the mid-area and along the left boundary of Uppada Village. Given the coastal vulnerability of Uppada Village (Sect. 3.2.5), nearly the entire area is classified as having high coastal vulnerability, with the western Uppada Village exhibiting moderate vulnerability.

3.2.2 Relative sea level and tidal range

In Uppada Village, the relative sea level has been identified as 3.8 mm/year based on the literature (Sahoo & Bhaskaran, 2018). However, the mean tidal range exhibits a cyclical pattern similar to that observed in Visakhapatnam, with peak heights of approximately 1.8 m occurring in mid-August, mid-September, and mid-October (Fig. 13). Conversely, the minimum tidal range, measuring between 0.2 m and 0.4 m, is recorded during early to late September. Based on the coastal vulnerability classification (Sect. 3.2.5), Uppada Village is categorized as having low vulnerability to the mean tidal range but high vulnerability to the relative sea level.

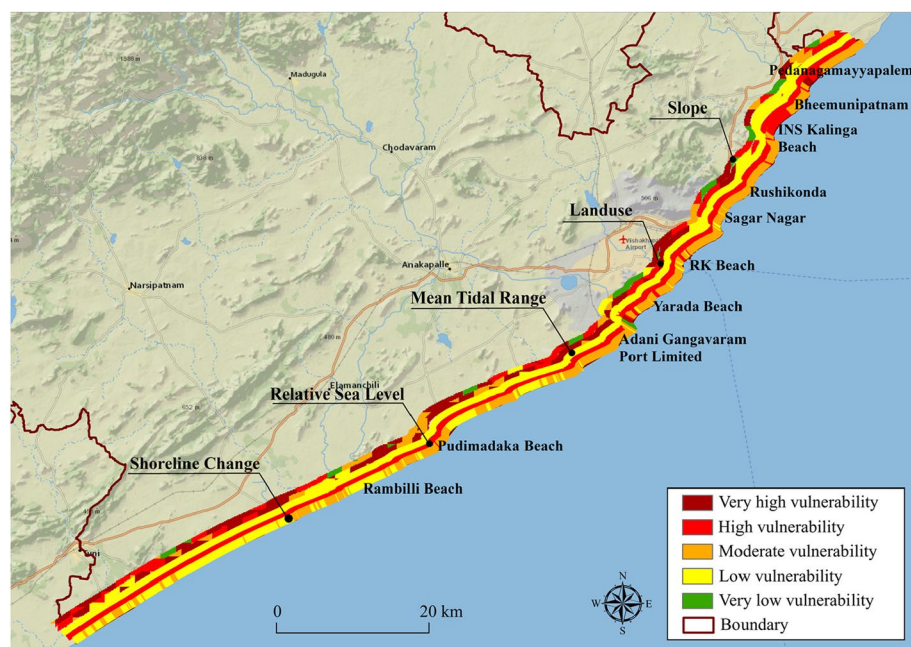


Fig. 10 Coastal vulnerability map for Visakhapatnam. Source: Created by the second author using ArcGIS 10.5



Fig. 11 Shoreline erosion and accretion trends for Uppada Village (1990–2024). Source: Created by the second author using ArcGIS 10.5

3.2.3 Slope

The slope map of Uppada Village indicates predominantly low-gradient coastal terrain, with most of the region having a slope of below 4% (Fig. 14), while the boundary edges exhibit slopes ranging from 8%–12%. In terms of coastal vulnerability classification (Sect. 3.2.5), the area is categorized as being of very high vulnerability.

3.2.4 Land use

Compared to Visakhapatnam, Uppada Village showed smaller but still significant changes (Fig. 15). The built-up area increased from 4.6% to 82.8%. Forest cover increased slightly from 0.2% to 0.6%, while croplands expanded from 0.8% to 4.5%. However, grassland declined sharply, dropping from 36.3% to 1.5%. Barren land decreased from 57.0% to 9.7%, and water bodies remained relatively stable, decreasing from 1.0% to 0.8%. These changes indicate that Uppada Village is also experiencing rapid urban expansion in the coastal zone. The Google Earth images from 2011 and 2024 in Sect. 4.1 validate this rapid urbanization. The coastal vulnerability classification (Sect. 3.2.5) based on land use suggests that the Uppada coastal area falls under the very high vulnerability category.

3.2.5 Overall coastal vulnerability of Uppada Village

Figure 16 clearly illustrates that nearly the entire area of Uppada Village, encompassing both residential and commercial zones, is classified as having high coastal

vulnerability. This vulnerability is primarily due to its proximity to the coastline, which exposes it to threats such as rising sea levels, increased storm intensity, and erosion.

4 Discussion

4.1 Comparing vulnerability between Visakhapatnam and Uppada Village

The assessment of coastal vulnerability in Visakhapatnam and Uppada Village provides a comprehensive overview of the natural and anthropogenic factors that impact shoreline changes. Visakhapatnam's vulnerability is influenced by its diverse geomorphological features, human activities, and disruptions in sediment transport. In contrast, Uppada Village faces challenges primarily due to natural erosion processes, which are further exacerbated by climate change and a lack of protective features.

The shoreline changes in Visakhapatnam exhibit distinct patterns across three zones (Fig. 4). Zone I, located near the Gosthani River mouth, experiences significant erosion, which is largely influenced by fluctuations in sediment supply. This aligns with Duy et al. (2023), who reported similar dynamics in river-mouth regions globally, emphasizing the critical role of sediment deposition in shaping coastal morphology. Additionally, Zone II, which includes the Adani Gangavaram Port, is characterized by both high erosion and accretion rates. This area records the highest individual erosion (−13.1 m/year) and accretion (21.1 m/year) rates, with accretion exceeding erosion overall. The construction and operation of

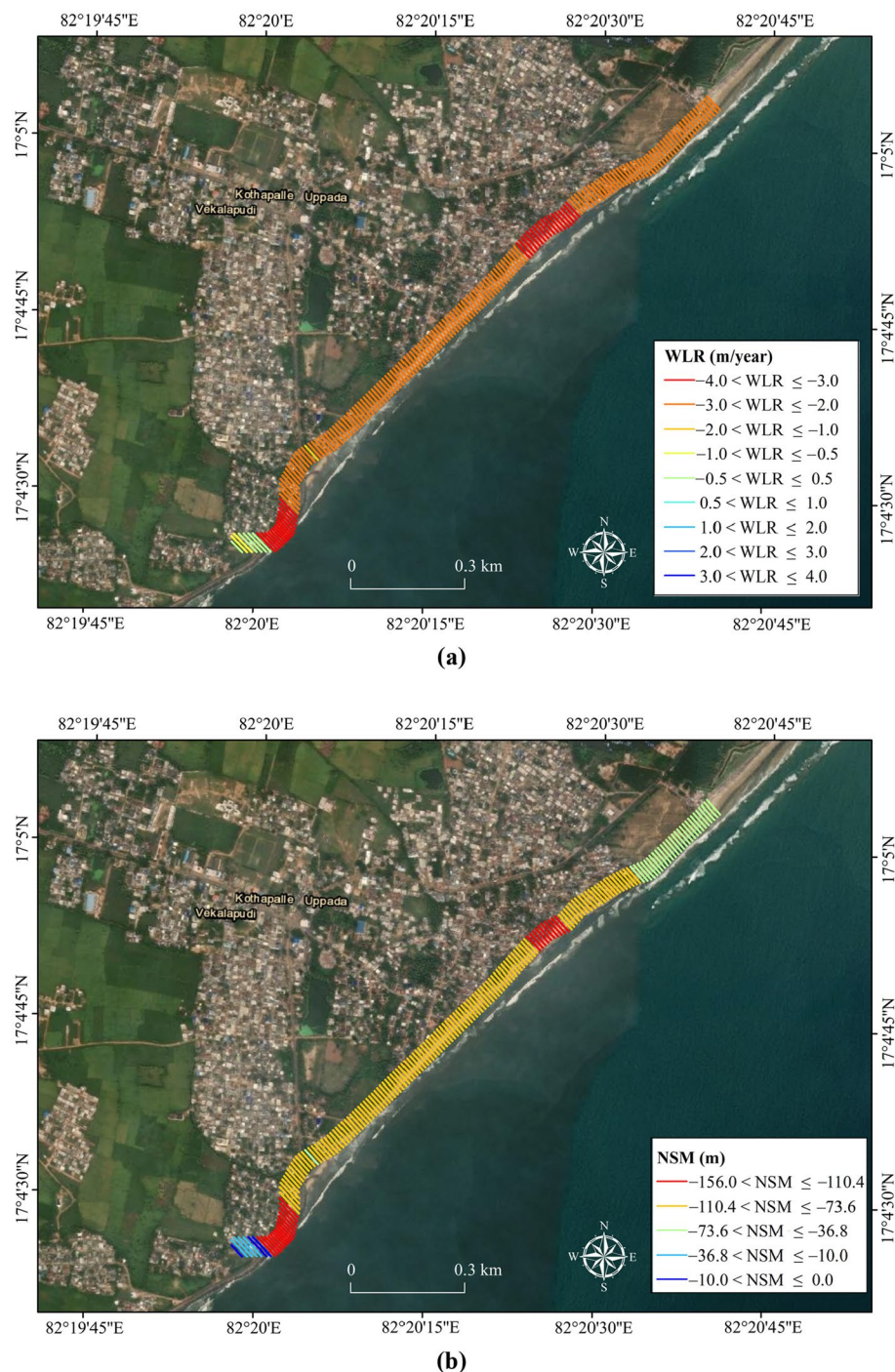


Fig. 12 Shoreline change in Uppada Village with WLR values (a) and NSM values (b) from 1990 to 2024. Source: Created by the second author using ArcGIS 10.5

the port have significantly altered sediment transport processes, reflecting findings by Hein et al. (2019), who observed that similar infrastructural developments often disrupt natural sediment pathways, leading to localized cycles of erosion and deposition. For example, at the

Merrimack River Inlet in Massachusetts, the construction of jetties has resulted in alternating patterns of erosion and accretion on adjacent beaches, driven by the dynamics of storm wave refraction and sediment transport (Hein et al., 2019). Zone III, near the Varaha River

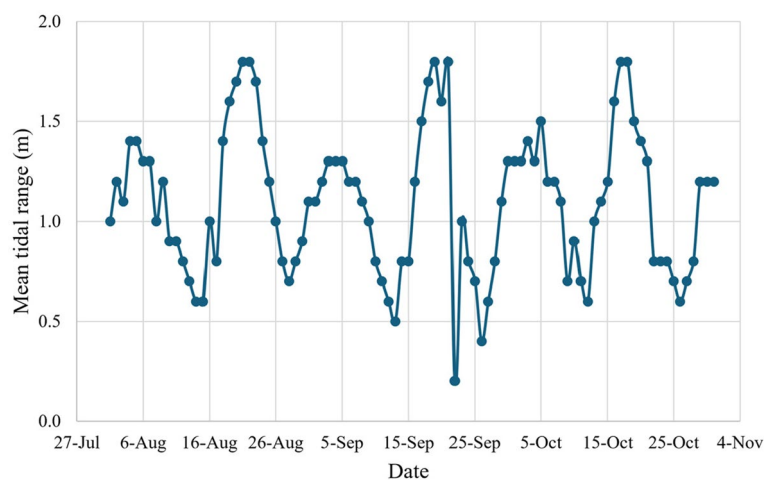


Fig. 13 The mean tidal range at Uppada Village from August to October 2024

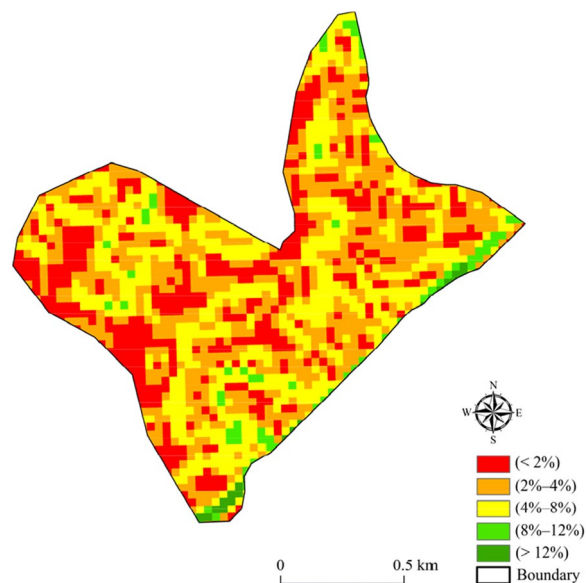


Fig. 14 Slope map for Uppada Village derived from SRTM Digital Elevation Model. Source: Created by the second author using ArcGIS 10.5

mouth, demonstrates substantial accretion, which is likely influenced by breakwater structures and sediment deposition. Similar patterns are observed at the Ba Lat mouth of Vietnam, a region characterized by significant sediment transport and deposition (Hung & Larson, 2014).

Furthermore, Visakhapatnam's land use changes indicate significant urbanization between 1990 and 2024, with built-up areas increasing from 10.64% to 38.75%. This rapid expansion has contributed to sediment disturbance and increased vulnerability to coastal hazards due to the loss of natural buffers like vegetation and wetlands.

According to research conducted by ISRO (2012), approximately 25% of Visakhapatnam's coastal regions exhibit moderate to severe vulnerability to coastal hazards.

The study indicates that over 50% of the area demonstrates minimal risk levels. It suggests that this is primarily due to the limited presence of natural protective features along the district's coastal zones, specifically the distribution of mangrove ecosystems, estuarine environments, and mudflat formations. Despite having moderate tidal ranges (0.4–1.8 m) and gentle slopes (<4%), the city's vulnerability is increased by anthropogenic activities and its unique headland-bay geomorphology (Fig. 17). Visakhapatnam's shoreline behaviour has changed noticeably since 2014 (Gorle et al., 2024). For instance, coastal curvature at RK Beach has shown significant changes, with accretion observed in 2017 compared to 2016 (Gireesh et al., 2023). According to Rao et al. (2014), RK Beach has experienced erosion in recent years, possibly due to ineffective beach nourishment caused by sediment cutoff at Gangavaram Port. Yarada Beach, located near Visakhapatnam, has shown a predominantly southward net sediment transport, resulting in erosion in the northern sector and accretion in the southern sector during periods of increased wave action (Ramakrishnan et al., 2018). These fluctuations highlight the complex and dynamic nature of Visakhapatnam's vulnerability to coastal hazards. Field photographs taken near Yarada Beach (Fig. 18) illustrate this erosion, along with the coastal revetments installed as a mitigation measure to control further shoreline loss.

Figure 19 presents selected field visit locations in Visakhapatnam overlaid on the shoreline change analysis derived from DSAS results. The field photographs

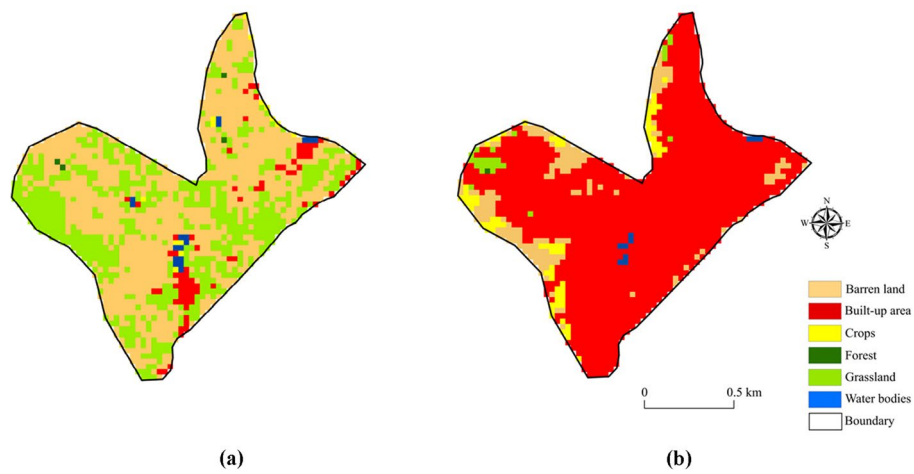


Fig. 15 Temporal variation of land use. **a** Uppada Village in 1990; **b** Uppada Village in 2024. Source: Created by the second author using ArcGIS 10.5

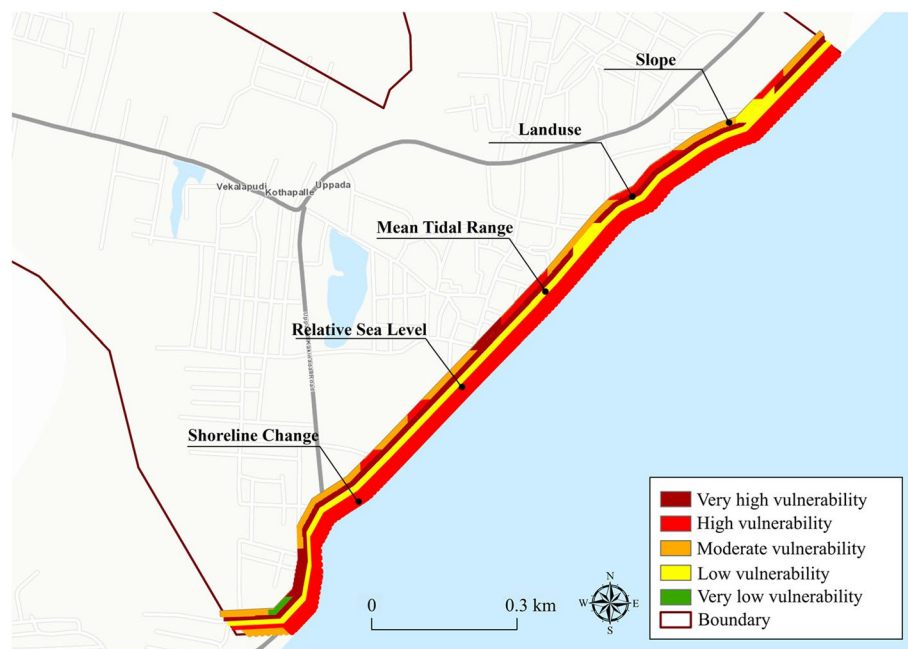


Fig. 16 Coastal vulnerability map for Uppada Village. Source: Created by the second author using ArcGIS 10.5



Fig. 17 Headlands in Visakhapatnam captured during the field visit. **a** Rushikonda Hill; **b** Yarada Hill. Source: Photographs were taken by the fourth and fifth authors in Feb 2025 during the data collection



Fig. 18 Photographs captured near Yarada Beach, Visakhapatnam. **a** The severely eroded coastal area; **b** Coastal revetments implemented as a mitigation strategy to control erosion. Source: Photographs were taken by the first and fourth authors in Feb 2025 during the data collection

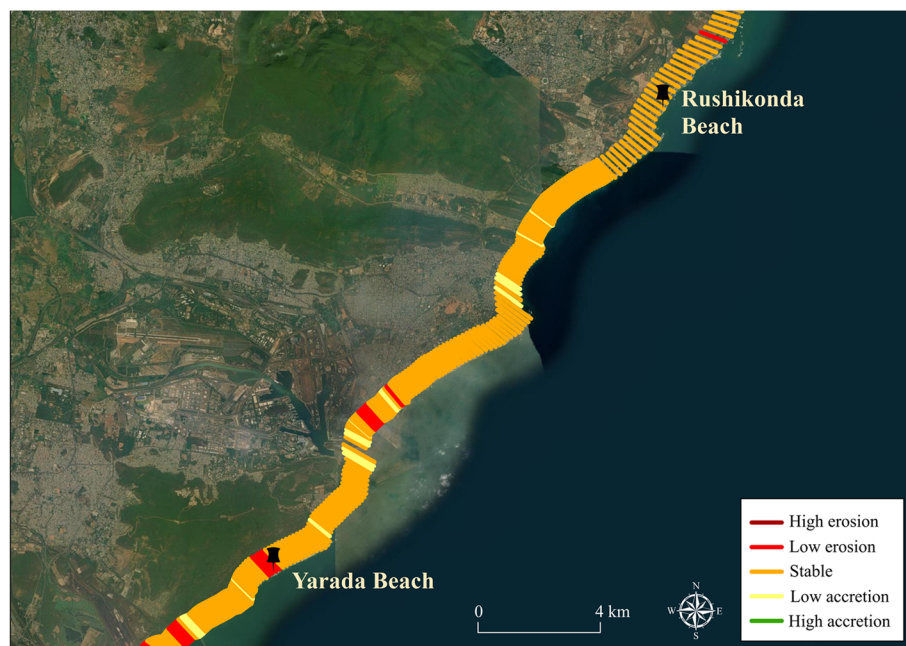


Fig. 19 Field validation of shoreline change analysis of Yarada and Rushikonda Beaches. Source: Created by the second author using ArcGIS 10.5

validate the DSAS findings, confirming that Yarada Beach is a highly vulnerable area.

In contrast, Uppada Village's coastal vulnerability is primarily influenced by severe shoreline erosion due to a lack of natural defences and frequent exposure to extreme weather events. The interactions at the river mouth in this region might contribute to the observed erosional trends through the influence of longshore sediment transport and seasonal variations in sediment discharge. According to Kavya et al. (2019), in the Uppada region near the Nilarevu River mouth, severe beach erosion occurred between 2002 and 2017. According to first-generation fishers in Uppada Village, significant shoreline erosion of at least 0.5 km has been observed (Raju, 2018).

This qualitative evidence supports the shoreline change rates obtained through DSAS analysis, further confirming the long-term vulnerability of Uppada Village's coastline. The region's erosion rates, reaching up to -3.95 m/year, align with the research conducted by Williams et al. (2018) and Parthasarathy and Natesan (2015). Their studies emphasize the vital importance of mangroves and mudflats in reducing coastal erosion. The lack of these protective features has made the area particularly susceptible to wave action and the impacts of rising sea levels. In Uppada village, the western boundary has moderate vulnerability, while the rest of the area experiences high vulnerability. This may be attributed to the presence of revetments along the western edge.

Historical records illustrate the significant impact of natural disasters on Uppada Village. Cyclones such as Laila and Nilam have caused massive damage, increasing the risks of erosion and flooding (Prasad & Rao, 2014). Additionally, local fishermen have reported a noticeable increase in the frequency and intensity of cyclones and heat waves, directly impacting coastal stability and marine resources (Raju, 2018). The cumulative loss of land, estimated at over 127 acres in recent decades, highlights the urgent need for action (Santhi & Latha, 2024). Similar trends can be seen in the Cauvery and Godavari deltas, where rising sea levels and saltwater intrusion have severely affected livelihoods and ecosystems (Udayakumar, 2014). Field observations (Figs. 20, 21 and 22), particularly in Uppada Village, provide strong evidence of ongoing coastal erosion and its impact on infrastructure and local communities. Climate-induced changes in wind patterns, sea currents, and rising sea surface

temperatures have had severe economic consequences for coastal fishing communities in Andhra Pradesh. Fishermen report that they must travel farther offshore due to declining nearshore fish stocks. Observations from multiple generations of fishermen in Uppada Village indicate that wind patterns have changed significantly over the past 30 years (Raju, 2018). The loss of structures and land area, as shown in the aerial images of 2011 and 2024 (Fig. 20), demonstrates the tangible impact of coastal vulnerability on local communities.

Uppada Village's tidal characteristics and slopes further contribute to its vulnerability to erosion. While certain areas exhibit steeper slopes that offer localized resistance, the overall area has a gentle slope, which makes it vulnerable to erosion. Moreover, the loss of grasslands and barren lands, combined with minimal changes in other land use categories, highlights the decreasing ability of natural systems to protect against coastal hazards. However,



Fig. 20 Comparison of coastal erosion at identified locations (A, B, C, and D) during the field visit, using Google Earth images from 2011 to 2024. The marked locations, which were inland in 2011 (a), had shifted to the shoreline by 2024 (b), highlighting significant erosion over time. Source: Created by the second author using Google Earth Pro 7.3.6



Fig. 21 Significantly eroded locations captured during field visits in location A (a) and location D (b) of Uppada Village. Source: Photographs were taken by the fifth author in Nov 2024 during the data collection

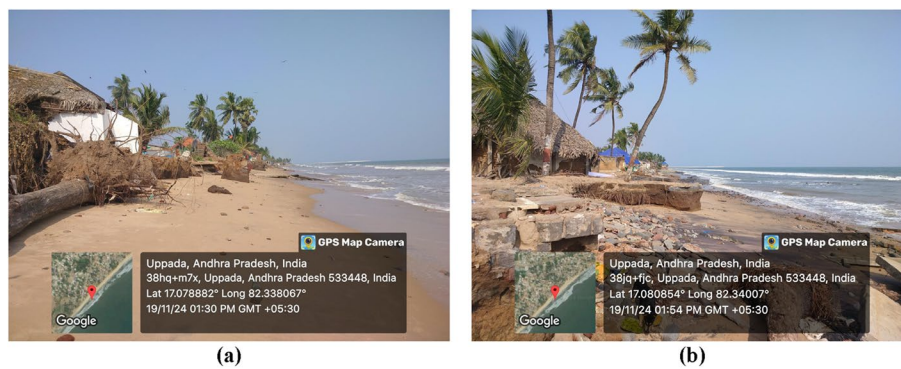


Fig. 22 Significantly eroded locations captured during field visits in location B (a) and location C (b) of Uppada Village. Source: Photographs were taken by the fifth author in Nov 2024 during the data collection

Uppada Village is classified as having low vulnerability to tides, and the presence of a river mouth near Uppada Village may contribute to coastal erosion, according to findings by Anwar and Rahman (2021). Their study indicates that regions close to river mouths, such as Bhola Island, have experienced significant erosion rates, with some areas losing up to 249 m/year due to high tidal pressures and sediment dynamics. Similarly, in the Sundarbans, the force of tidal currents severely impacts coastal erosion, causing significant land loss in these regions (Bhui et al., 2023). The findings from Visakhapatnam and Uppada Village highlight global trends regarding the increasing vulnerability of coastal areas as a result of climate change. Global sea level is projected to rise throughout the 21st century, emphasizing the importance of evaluating coastal areas for their vulnerability to such changes (Manik Mahapatra & Rajawat, 2013). Urgent action is required, as predicted sea level increases ranging from 1 m to 6 m can severely impact coastal ecosystems through saltwater intrusion (Islam et al., 2013).

The interplay of both natural and human-related factors highlights the importance of a comprehensive

approach to managing coastal zones. The complex interaction between natural processes (e.g., erosion and storm surges), and human-induced factors (e.g., urban development and deforestation) underscores the necessity for a comprehensive and integrated approach to coastal zone management.

The comparative analysis of Visakhapatnam and Uppada Village (Table 3) highlights the interaction between geomorphological features and human activities in contributing to coastal vulnerability. Visakhapatnam's unique headland-bay formation, combined with rapid urban growth, disrupts sediment transport processes and increases localized erosion. Similar trends have been observed in other coastal cities worldwide (Table 4), illustrating a global pattern of human-induced shoreline instability. In contrast, Uppada Village illustrates the challenges of lacking natural protection and ongoing exposure to high wave energy. Research conducted in Bangladesh and the Philippines indicates that community-based mangrove rehabilitation and hybrid coastal engineering approaches can significantly enhance resilience (Hasan et al., 2024; Williams et al., 2018).

Table 3 Comparative analysis of coastal vulnerability between Visakhapatnam and Uppada Village

Parameter	Visakhapatnam	Uppada Village
Erosion rate	– 13.1 m/year in Zone II (highest impact area)	– 3.95 m/year (consistent erosion across coastline)
Accretion rate	Up to 21.1 m/year in certain areas	No significant accretion
Total shoreline loss (1990–2024)	64 m average coastline erosion	90 m average coastline erosion
Coastal vulnerability	Dynamic vulnerability with localized high-risk zones	High vulnerability due to continuous erosion
Natural protective features	Some headland-bay geomorphology and rocky formations	Lacks natural defences like mangroves or dunes
Human impact	Urban expansion (built-up area increased from 10.64% to 38.75%)	Urban expansion (built-up area increased from 4.6% to 82.8%)
Sea level rise impact	High, due to increasing relative sea levels	High, due to increasing relative sea levels
Tidal range impact	Low vulnerability (tidal range of 0.4–1.8 m)	Low vulnerability (tidal range of 0.2–1.8 m)
Slope influence	Gentle slopes (< 4%) in most areas, moderate impact	Mostly gentle slopes, highly vulnerable to flooding
Current mitigation measures	Some revetments and shoreline protection in place	Very limited mitigation structures present

Table 4 Comparative analysis of coastal erosion rates and environmental disappearance in vulnerable regions

Region	Country	Erosion rate (m/year)	Key drivers	Time period	References
Sagar Island	India	Mean = − 10.66	Tidal action, cyclones, overwash	2000–2020	Paul et al. (2024)
Bhola Island	Bangladesh	Max = − 249	Tidal pressures, river dynamics	1989–2018	Anwar and Rahman (2021)
Nile Delta	Egypt	Max = − 50	Dam construction, sediment loss	1974–2022	Abd-Elhamid et al. (2023)

Incorporating such strategies into Andhra Pradesh’s coastal management framework could help mitigate future land loss. Such strategies require collaboration among governments, local communities, and environmental organizations to formulate and implement effective policies that enhance resilience and protect coastal ecosystems for future generations.

4.2 Comparison with global cases

When comparing the three global cases presented in Table 4, several clear differences can be identified. Sagar Island in India experiences an erosion rate of approximately −10.66 m/year, which is comparable to the peak erosion observed in Zone II of Visakhapatnam. However, the primary drivers of erosion on Sagar Island are tidal action and cyclone overwash, rather than human-made port infrastructure. In contrast, Bhola Island in Bangladesh exhibits an extremely high erosion rate of up to −249 m/year, driven by the powerful tidal forces of the Meghna Estuary. While Uppada Village experiences lower erosion rates, it faces a unique challenge due to a persistent erosion pattern along its coastline, with no accretion to offset the loss. This makes it a particularly high-risk case. The Nile Delta, with a maximum erosion rate of −50 m/year, shares a common issue with both study sites: Sediment starvation. This phenomenon results from factors such as dam construction in Egypt, human-made port infrastructure in Visakhapatnam, and river dynamics near Uppada Village. In summary, across all these cases, the combination of human-induced modifications and climate-driven sea level rise emerges as the primary factor exacerbating coastal vulnerability.

4.3 Limitations

Data limitations pose significant challenges in achieving accurate results for this study. The use of Landsat images, with a resolution of only 30 m, raises concerns about potential errors stemming from this coarse spatial resolution. This spatial resolution constraint results in a shoreline position uncertainty of approximately ±15 m (half-pixel error), and it may not accurately capture small-scale coastal features smaller than 30 m. The reliability of these images is often questioned, particularly for shoreline detection, as critical factors such as cloud cover and image quality can greatly diminish their

effectiveness. When selecting satellite images for shoreline change analysis, it is ideal to use images captured under similar tidal conditions to minimize the effects of tidal variation. However, due to limitations in image availability and issues with cloud cover, it was not possible to obtain cloud-free satellite images corresponding to the same tidal phase across all time periods considered in this study.

Sun-synchronous satellites capture imagery at nearly the same local time with each pass, but the actual tidal height at that time varies daily due to natural tidal cycles. Furthermore, satellite repositories, such as those from the USGS used in this study, do not provide a direct filter or metadata field for tidal levels at the time of image acquisition, making it challenging to automatically select images with consistent tidal conditions. Analysis at 10-year intervals (1990, 2000, 2010, 2020, 2024) may overlook episodic events, such as cyclones and storm surges, which can occur between the acquisition dates. This limitation may lead to the omission of short-term extreme erosion or accretion events that are important for understanding event-driven coastal changes.

The DSAS transect-based analysis introduces uncertainties, as shoreline change statistics are influenced by transect spacing and baseline positioning. The extreme localized values observed in this study, such as −13.1 m/year of erosion and 21.1 m/year of accretion, may be attributed more to anthropogenic structures than to natural processes. In many developing countries, the assessment of shoreline changes in specific regions is often challenged by insufficient ground measurement data. This is a widespread problem due to the absence of systematic monitoring systems that can effectively track shoreline variations over time (Zoysa et al., 2023). N. Apostolopoulos and G. Nikolakopoulos (2020) highlight that the limited spatial resolution of Landsat images is a considerable drawback for achieving the precision required in remote sensing data for shoreline monitoring. Furthermore, the relative sea-level rise of 3.8 mm/year is based on historical trends and may not accurately predict future acceleration. This study does not take into account future climate projections from the IPCC or regional climate models, nor does it explicitly model changes in cyclone frequency or intensity.

Additionally, human error and methodological uncertainties can further compromise the integrity of the results. Compounding these issues, this study also lacks the inclusion of social vulnerability parameters, which are crucial for a comprehensive assessment of coastal vulnerability. Addressing these limitations is essential to enhance the effectiveness and accuracy of shoreline analysis.

4.4 Recommendations

To reduce the impact of coastal vulnerability in both study areas, the following recommendations are proposed.

- (1) Building natural and artificial barriers, such as mangrove plantations, breakwaters, beach nourishment, and seawalls, including both hard and soft engineering structures as a hybrid model, can help mitigate erosion and offer environmental benefits in both Visakhapatnam and Uppada Village. This is particularly relevant for areas near the mouths of the Gosthani River (Zone I, Visakhapatnam), Varaha River (Zone III, Visakhapatnam), and the Nilarevu River (Uppada Village), depending on whether suitable mudflats are available. In areas without suitable mudflats, creating artificial mudflats through controlled sediment deposition may be considered as a preliminary step for establishing mangroves. Additionally, sustainable urban planning is essential for managing regulated urban expansion in the Visakhapatnam coastal zone, reducing sediment disruption and protecting natural buffers.
- (2) A two-layer coastal protection system is proposed for Uppada Village for immediate protection, with rock armour as the primary layer and a reinforced concrete seawall as the secondary layer. This approach effectively mitigates high-energy waves and coastal hazards. It is also recommended to prohibit residential and infrastructural development within a 0.2 km landward buffer zone from the coastal wall to minimize coastal risk exposure.
- (3) Enhancing public awareness and fostering community involvement are also fundamental in promoting sustainable coastal practices. Engaging local populations through educational programs and participatory initiatives can empower communities to take ownership of their coastal resources and advocate for protective measures.
- (4) Moreover, future research should incorporate social vulnerability parameters, including economic dependence on coastal resources and demographic factors, to paint a clearer picture of the potential impacts on local communities.
- (5) Enhancing accuracy and temporal coverage of vulnerability assessments requires advanced scenario-

based predictive modelling that incorporates IPCC climate projections along with high-resolution satellite data, such as Sentinel-2 and UAV/drone surveys. Comparative regional studies that examine tourism sustainability across various coastal destinations in Andhra Pradesh can offer valuable insights into balancing economic development with coastal protection.

- (6) Integrating hydrodynamic and sediment transport modelling will further enhance understanding of coastal processes. Additionally, establishing community-based participatory monitoring programs that combine local knowledge with scientific assessment will improve the accuracy of ongoing vulnerability tracking and strengthen community engagement in coastal management.

By implementing these comprehensive and evidence-based strategies, coastal vulnerability can be significantly reduced in Visakhapatnam and Uppada Village. This will not only ensure the protection of their unique ecosystems but also support the socio-economic stability and resilience of the communities that depend on these coastal areas for their livelihoods.

5 Conclusions

This study shows that both Visakhapatnam and Uppada Village are facing significant and increasing coastal vulnerability, though driven by fundamentally different factors. In Visakhapatnam, the main causes of vulnerability are human activities: Port infrastructure disrupts sediment transport, rapid urban expansion reduces natural buffers, and complex headland-bay dynamics create uneven erosion and accretion cycles. Conversely, in Uppada Village, the vulnerability stems mainly from natural conditions, including a low-lying, unprotected sandy coastline exposed to constant wave action, sea-level rise, and cyclone impacts, with no notable accretion to counteract the average 90 m of shoreline loss recorded since 1990. Shoreline change, assessed using the DSAS, was identified as the most critical factor differentiating vulnerability levels between the two sites. While tidal range contributes to low vulnerability in both cases, slope and land use increase risk, particularly in Uppada Village. This study makes three primary contributions to the literature on coastal vulnerability. First, it provides a 35-year multi-temporal assessment across five time periods, integrating DSAS shoreline analysis with five physical parameters, thereby offering a more comprehensive temporal and methodological framework. Second, it introduces a validated dual-site comparative framework that distinguishes between anthropogenic urban vulnerability (Visakhapatnam) and naturally driven rural

vulnerability (Uppada Village), providing a model applicable to other coastal regions with mixed land use characteristics. Third, the geospatial analysis is cross validated through systematic field observations and georeferenced photography, significantly enhancing the reliability of the vulnerability assessment and offering empirical evidence of ongoing land loss. The main limitations of the study include the 30-m spatial resolution of Landsat imagery, which introduces an estimated ± 15 m uncertainty in shoreline position. Future research should utilize higher-resolution data sources such as Sentinel-2 or UAV/drone surveys, implement continuous or annual shoreline monitoring, consider IPCC scenario-based sea-level projections, and include hydrodynamic and sediment transport modeling, along with social vulnerability indicators, to achieve a more comprehensive coastal risk assessment for these endangered destinations. Without immediate, evidence-based, and community-engaged intervention, Uppada Village and similar locations risk transitioning from threatened coastal systems to ones that are effectively disappearing. This shift will displace vulnerable populations and lead to the loss of unique coastal ecosystems. The choice between proactive adaptation and reactive crisis management rests with policymakers, coastal managers, and communities, but the window for effective action is rapidly narrowing.

Acknowledgements

Not applicable.

Authors' contributions

Conceptualization: Komali Kantamaneni, Ruchiru Dilshan Herath, Upaka Rathnayake; Methodology: Komali Kantamaneni, Ruchiru Dilshan Herath, Upaka Rathnayake; Formal analysis and investigation: Ruchiru Dilshan Herath, Upaka Rathnayake; Writing—original draft preparation: Komali Kantamaneni, Ruchiru Dilshan Herath; Writing—review and editing: Robert Walsh, Swarnalatha Purushotham, Sreenivasulu Vemu, Luiza C. Campos; Supervision: Komali Kantamaneni, Upaka Rathnayake. All authors read and approved the final manuscript.

Funding

This research received no external funding.

Data availability

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request. Source data are provided with this paper.

Declarations

Ethics approval and consent to participate

Not applicable. This article does not contain any studies with human participants.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Komali Kantamaneni is an Editorial Board Member for this journal and was not involved in the editorial review or the decision to publish this article.

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Received: 19 February 2026 Revised: 27 August 2026 Accepted: 8 September 2026

Published online: 28 September 2026

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