



RESEARCH ARTICLE

# Coastal Vulnerability Mapping by Integrating Geospatial Techniques and Analytical Hierarchy Process (AHP) along the Vishakhapatnam Coastal Tract, Andhra Pradesh, India

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## Abstract

The coastal area supports millions of population in terms of livelihood, settlement and social activities across the world and India. The increasing rate of socioeconomic activities made the coasts susceptible to various hazards. Therefore, this study is aimed to examine the coastal vulnerability of Vishakhapatnam Coastal district using remote sensing and geographic information system. To fulfill this objective, six physical indicators, i.e., geomorphology, land use/land cover, coastal slope, shoreline change rate, etc., were prepared using the multi-temporal datasets of 1991, 2001, 2011 and 2018 and mean tidal height has been considered to calculate the coastal vulnerability index (CVI). The indicators selected for the analysis of coastal vulnerability have been integrated using the rank and weighted methods. The shoreline change has been detected using the digital shoreline analysis system (DSAS). Analytical hierarchy process (AHP) has been used for calculating weights of various indices. The CVI values obtained using different indicators are 2.6 (min) and 14.39 (max). Based on the CVI values, the coast is classified as five classes of vulnerability, i.e., very low (0–4.9) covering 42.5 km, low (4.9–7.3) which covers 29.49 km, moderate (7.3–9.6) covering 23.46 km, high (9.6–12.0) which covers 34.61 km, and very high (12.0–14.39) covering 7.5 km. This integrated study is found useful for exploring the accretion and erosion processes and also for vulnerability mapping in the coastal tract of Vishakhapatnam district.

**Keywords** Shoreline change rate · Vulnerability index · Coastal slope · Digital shoreline analysis system (DSAS) · Geoinformatics

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## Introduction

Coastal areas provide important elements for the socio-economic development of the nations despite substantial and insubstantial benefits (Sankari et al. 2015). At the same time, many coastal areas are being affected by the dynamic elements of environmental, topographic and sociocultural systems due to growing human and environmental pressures which need urgent attention (Dhiman et al. 2019; Neumann et al. 2017). Coastal areas are under pressure because of the hydro-geomorphic phenomena which alter its shape over time and also because of the continuous human activities (Madricardo et al. 2019; Kamphuis 2010). Thus, the sustainable development of the coastal area is necessary because these are characterized by various ecological and natural values in terms of resources which plays crucial role in sustaining the coastal society (Vinuesa et al.

2020; Neumann et al. 2017). These coastal areas are the hot spots of stern impacts connected to the frequent inundation and flooding in low lying regions and also with the extreme events like a tsunami, storm surges, soil erosion at the beaches that increase salinity, damages to the agricultural lands and devastation due to cyclonic storms, etc. (Murali et al. 2013).

The increasing number of coastal hazards and disaster events has limited the decision-makers and coastal managers with a handful of resources and investment techniques (McCarthy et al. 2001). Therefore, the analysis of coastal vulnerability is necessary to make the appropriate and effective decisions (IPCC 2014). The vulnerability to the coastal hazards is not same at all places, and the risk of specific coastal hazards varies widely from the region to region based on the climatic as well as the physiographic setting of the regions (Bukvic et al. 2020; Pollard et al. 2019). Even a minor change in the climatic pattern of a region results in floods, storms and other hazards that could impact coastal areas (Bukvic et al. 2020; Balica et al. 2012). Following this, studies have been done to analyze the variation in the coastal vulnerability in different climatic zones or conditions (O'Brien et al. 2004; Krishnamurthy et al. 2014; Satta et al. 2017). Kumar and Tholkappian (2006) studied the relative vulnerability of the coastal districts of India to the cyclones and storm surge and found that the districts on the east coast of India are more vulnerable to the coastal hazards than the districts of the west coast. Similarly, O'Brien et al. (2004) investigated the regional coastal vulnerability of the Indian coastal plains based on the regional climatic zones.

According to the United Nations Environmental Programme (UNEP), vulnerability refers to the extent to which an ecosystem or a social group is likely to get affected by a hazard (UNEP 2005). The vulnerability is a composition of the processes and conditions that are the consequences of the physical, environmental and social factors, e.g., sea level rise, storm surge, shoreline change, coastal deforestation, population density, household density, road network, etc., which increases the vulnerability of a region or a population to the hazards (Prakash et al. 2016; Ciurean et al. 2013). There are various analytical methods which are based on the GIS and spatial data which include index-based techniques and decision support systems (DSS) like Community Vulnerability Assessment Tool (CVAT), DINAS-COAST, Dynamic Interactive Vulnerability Assessment (DIVA), Digital Shoreline Analysis Systems (DSAS), etc. (Ghoussein et al. 2018; Kantamaneni et al. 2019a). One of the most common techniques of the assessment of coastal vulnerability in terms of rising sea level and soil erosion is the development of coastal vulnerability index (CVI) which has been widely used in different parts of the globe (Pantusa et al. 2018; Koroglu,

et al. 2019). The CVI is an important tool for the overall assessment of vulnerability toward inundation and erosion processes (Serio et al. 2018). Further, the vulnerability levels estimates can be useful in land use planning and other developmental activities (Leo et al. 2019).

The increasing rate of occurrence of coastal disasters and the emerging concerns due to it have drawn the attention of researchers for dealing with the coastal areas in vulnerability reduction measures (Kantamaneni et al. 2019b). Coastal areas experience multifaceted geological conditions at different scales adding to diverse social and monetary exercises (Kantamaneni et al. 2019a). The population in the coastal areas are vulnerable to the various geo-climatic hazards and disasters due to the sea level rise and changes in the sea surface temperature (Bukvic et al. 2020). Nearly half of the Vishakhapatnam District is urbanized, and the pace of urbanization is rapid during the past few decades in the district. The proportion of urban population was only 20.30% in the Vishakhapatnam District in 1971 which increased to 47.45% in 2011 (Census of India, 2011) which makes the half of population of the district vulnerable to the coastal hazards and disasters. The most vulnerable areas to these hazards and disasters are the areas along coastal wetlands, coastal estuaries, the low lying settlement areas, etc. (Parthasarathy and Deka 2019). To examine the vulnerability of the coastal areas, a diversity of indicators and indices can be used such as Community Vulnerability Assessment (CoVI), Physical Vulnerability Assessment (PVI), Social Vulnerability Assessment (SVI), Digital Shoreline Analysis System (DSAS), etc. (Cutter et al. 2003; Mclaughlin and Cooper 2010; Antwi et al. 2015; Bukvic et al. 2020). All these indices involve changing intensity of sweeping statements and gathering of the sequence. Furthermore, to examine the applications of spatial pattern of coastal hazard risk assessment at national, regional and site levels, the multi-scale coastal vulnerability indices are used (Mclaughlin et al. 2010; Koroglu et al. 2019).

Vulnerability assessments of the coastal areas are based on the weighted parameters in diverse climatic scenarios (Martins et al. 2017; Goharnejad et al. 2013; Rocha 2020). Dynamic processes, geo-indicators and morphological and social indicators incorporated with modeled scenarios of rising sea level and future wave height changes were integrated to generate the coastal vulnerability index (Barnard et al. 2019; Martins et al. 2017). The analytical hierarchy process (AHP) was proposed by Saaty (1977) which gives a better understanding of parameters into a hierarchical way. By ranking the variables according to comparative importance, it gives a scale of preference among the parameters with pairwise comparison procedure between them (Ju et al. 2012). Better estimations could be provided by AHP as proved in several studies, and it is

suggested that AHP is an advancement of the conventional coastal vulnerability index (CVI) (Serio et al. 2018). The method is more applicable in regional studies where one variable may be more prominent than others. The opinion of various experts is required for the integration and conversion of quality information into quantitative weights (Saaty 2008). Logically derived weights are used in this method instead of arbitrary. For checking the effectiveness of measurements and judgments, test of consistency is used which offers a certain degree of reliability (Murali et al. 2013).

Despite the popularity of usage vulnerability index tools and other scientific methods, the coastal vulnerability index is one of the vital tools in highlighting potential coastal hot spots of climatic hazards (Koroglu et al. 2019). The narrow and low lying beaches in coastal plains are highly vulnerable to the coastal hazards and disasters as compared to dunes and vegetation-covered coastal plains (Pantusa et al. 2018). Therefore, to delineate the vulnerable coastal areas from the coastal hazards and disasters, a coastal vulnerability atlas has been prepared by Indian National Centre for Ocean Information Services (INCOIS) on 1:1,100,000 scales (INCOIS 2012). In this atlas, all the coastal states of India have been studied and area-wise statistics and related information have been provided (NDSAP 2012). This atlas has been prepared using seven risk indicators for the assessment of future risks of the coastal areas to the future sea level rise, i.e., coastal elevation, coastal slope, shoreline change, height of the wave, tidal range, historical sea-level change and geomorphology (Rani et al. 2015).

The significance of the study lies in the sense that coastal areas of India are becoming more and more urbanized day by day (Sterzel et al. 2020). This leads to the increased risk of such a large urban population in terms of vulnerability to the cyclone, coastal floods and other coastal hazards (Rani et al. 2015; Kantamaneni et al. 2019a; Rehman et al. 2020). Studies on coastal vulnerability assessment have been done for the coastal Andhra Pradesh (including Vishakhapatnam coastal tracts) and other coastal areas of India (Rao et al. 2008; Murali et al. 2013, 2019). However, these studies have been done using traditional methods and techniques. Therefore, in this study, the coastal vulnerability index (CVI) has been calculated for the Vishakhapatnam Coastal district using six risk indicators with the help of geospatial techniques. Therefore, the main objective of the present study is to analyze the coastal vulnerability of Vishakhapatnam coastal tract which is one of the most vulnerable coastal regions of India.

## Data Sources and Methods

### Study Area

Vishakhapatnam is a coastal district located in the north-western part of Andhra Pradesh State of India. The Vishakhapatnam District has been selected for this study because it has about 90-km-long coastal stretch and is highly vulnerable to the coastal hazards like a cyclone, storm surge, tsunami, etc. (Vivek et al. 2016). The district lies between the 17°15' N to 18°32' N and 81°54' E and 83°30' E. It is surrounded by Vizianagaram District in the north, East Godavari District from the south, Orissa State from the west and the Bay of Bengal in the east (Fig. 1). The climate of the district is wet and moist with annual temperature varying between 24.6 °C and 30.7 °C. The late spring temperature reaches up to 40 °C, while the winter temperature is about 15 °C due to its maritime location. Southwest and northeast rainstorms contribute roughly 1201 mm yearly precipitation in the area (Praveen et al. 2020). Inland *mandals* (subdivision of a district) get more precipitation from the southwest monsoon, while some of the *mandals* get more precipitation from the northeast monsoon. Loamy soils mainly prevail in the study area with some sandy soils as the topsoil in some *mandals*.

### Data Sources

Landsat TM, ETM, OLI/satellite data TIRS (for 1991, 2001, 2011 and 2018) have been used in this study to analyze the coastal vulnerability and to develop the CVI. Six risk indicators, i.e., geology, geomorphology, slope, shoreline change, sea-level change and tidal range data, were acquired from Wxtide32 software and downloaded in portable document format for further analysis. The Shuttle Radar Topography Mission (SRTM) data have been used for generating slope of the area, and general bathymetric charts of oceans (GEBCO) data have been used for general bathymetry; the particulars of the data used in the present research are given in Table 1.

### Methods

The methodology utilized for the present study is based on Thieler and Hammar-Klose (2000). Therefore, the indicators like land use/land cover, geomorphology, seaside incline, shoreline change, seaward bathymetry and mean tidal range have been generated. Each indicator has assigned an individual position and weightage, and then by incorporating the above indicators utilizing GIS, the beachfront weakness file is determined (Fig. 2). A general flowchart of methodology is shown in Fig. 2, and the

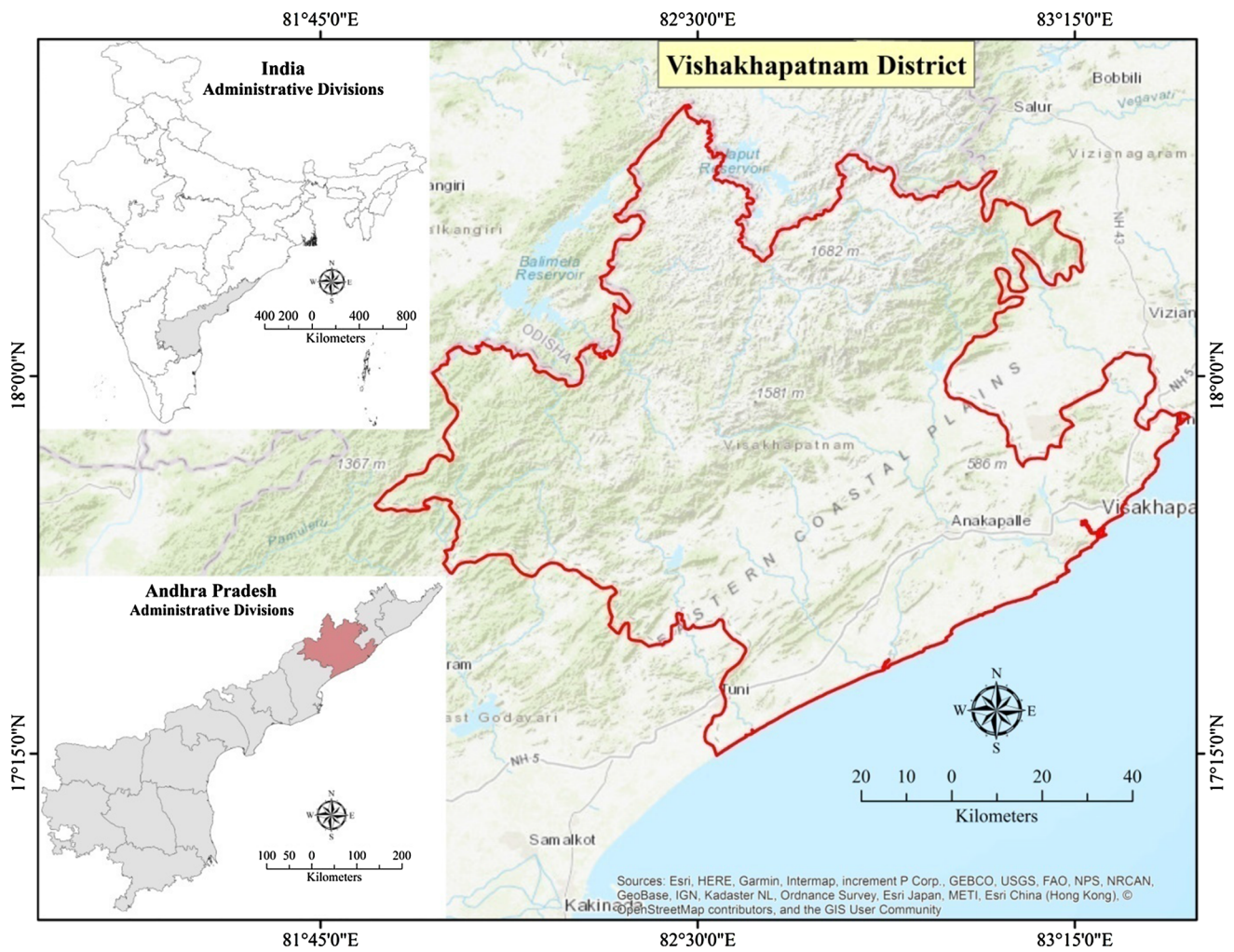
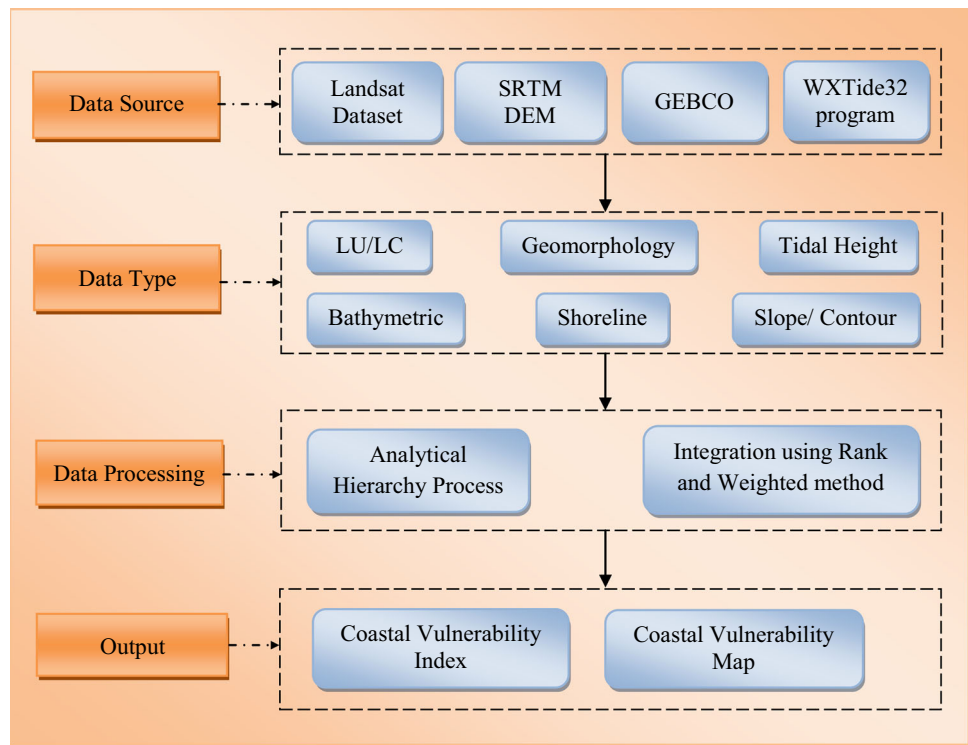


Fig. 1 Location of the study area

Table 1 Sources and extracted information

S. no	Data	Spatial resolution	Spectral bands	Path/row	Parameter
1	Landsat TM, ETM, OLI/TIRS (1991, 2001, 2011 and 2018)	30 m	7, 8, 8, 9	141/47 141/48 142/48 141/47	Shoreline change
2	Landsat 8 OLI/TIRS (2018)	30 m	9	141/48 142/48 141/47	Geomorphology
3	Landsat 8 OLI/TIRS (2018)	30 m	9	141/48 142/48 141/47	Land use/land cover
4	SRTM (2014)	90 m	1	141/48 142/48	Slope topographical information
5	GEBCO Bathymetry Data Chart	–	–	–	Bathymetry
6	Naval Hydrographic Chart	–	–	–	Tidal and wave height

**Fig. 2** Brief flowchart of the methodology

details of the methodology used for generation of various thematic layers and coastal vulnerability index have been given in the following section.

### Preparation of Coastal Vulnerability Index (CVI)

The CVI is calculated for the mapping of the relative coastal vulnerability of the coastal areas and to distinguish the susceptibility of the coast due to the human activities and the coastal processes (Koroglu et al. 2019). As compared with traditional methods of mapping, data analysis and final output mapping is simple and less time-consuming in geospatial techniques like CVI (Bukvic et al. 2020). So, in this study, the CVI was calculated by unifying the risk indicators to get a particular indicator. To do this, all the sections of coastline were allotted a threat value for each variable and the CVI was then prepared by using the square root of the product of the ranked indicators by dividing with the total number of indicators by following Pendleton et al. (2004) using Eq. 1:

$$CVI = \sqrt{\frac{a * b * c * d * e * f}{6}} \quad (1)$$

where a, b, c, d, e and f are the risk rating given to the geomorphology, land use/land cover, bathymetry, slope, shoreline change and mean tidal range, respectively.

### Geomorphology

Geomorphology is characterized as the investigation of topographic scenes, including the portrayal, grouping, beginning, improvement and account of planetary surfaces. The geomorphology distinguishes the constancy among landforms as well as processes which lead to the formation of these landforms. In the present investigation, Landsat data of 2018 have been used to prepare the coastal geomorphology maps (Fig. 3). The different waterfront geomorphic highlights distinguished in the study area are seashore edge, rivulet, deltaic plain, plateau or uplands, flood plain, estuarine, mudflat, waterway, coastal plain undissected uplands, lagoons, valley, etc.

### Land Use/Land Cover (LU/LC)

The LU/LC maps are fundamental to comprehend the adjustments in the LU/LC spread classes in a specific locale and the way it helps in expanding or lessening the powerlessness of a territory (Rahman et al. 2011). The LU/LC spread map has been prepared by utilizing the Landsat data of 2018. The LU/LC highlights and distinguishes the features like the vegetation, rangeland, agricultural land, wetlands, built-up, bare soil, water bodies, etc. (Fig. 4).

Fig. 3 Geomorphology map of the Vishakhapatnam district

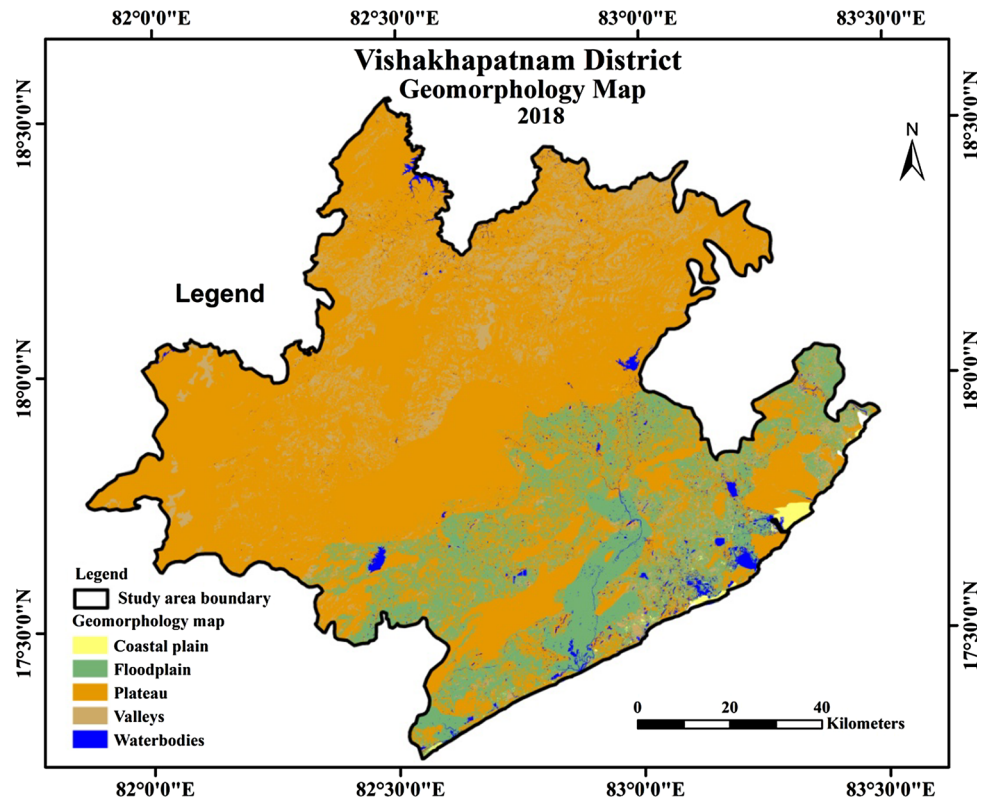
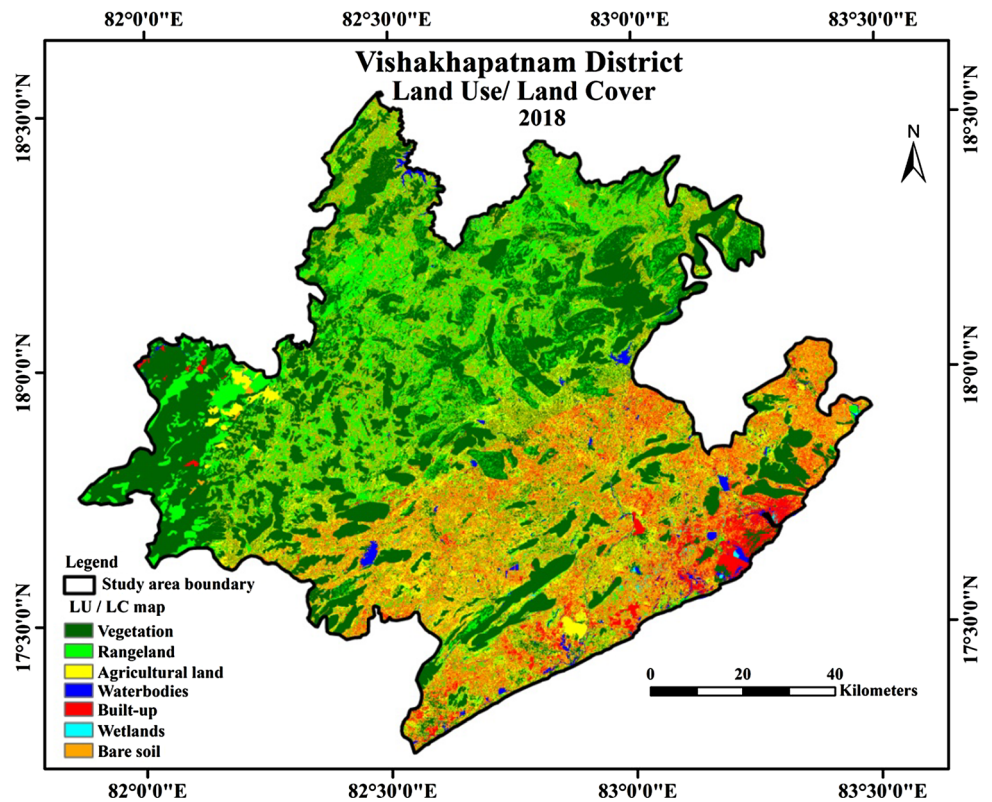


Fig. 4 Land use/land cover map of the Vishakhapatnam district



### Bathymetry

The bathymetry depicts the deepness from mean sea level (MSL) from the coast toward the sea. In this study, the GEBCO bathymetry data were utilized to prepare the bathymetry map of the Vishakhapatnam District (Fig. 5). The depth form was created utilizing GIS after geo-referencing with the UTM projection framework with WGS-44 datum (Eq. 2):

$$\text{Bathymetry} = \frac{\text{Distance between Shoreline and Contour}}{\text{Contour Interval}} * 100. \tag{2}$$

### Coastal Slope and Contours

The slope describes the extent of the incline, steepness and gradient of a line. In this study, the slope map was generated using SRTM data of 90 m resolution by using Eq. 3 (Fig. 6):

$$\text{Slope} = \frac{\text{Distance between Shoreline and Contour}}{\text{Contour Interval}} * 100 \tag{3}$$

### Shoreline Change

The shoreline represents the place where the land and water interface to each other (Dolan 1980). The close infrared band which is generally reasonable for the outline of the land and water limit was utilized to extort the shorelines of the Vishakhapatnam District. The extracted shoreline of the district for years 1991, 2001, 2011 and 2018 in vector format was applied to figure the pace of shoreline change by using digital shoreline analysis system (DSAS). The pace of the shoreline change was determined for the whole investigation territory, and hazard evaluations are carried out (Fig. 7).

### Mean tidal range

The tidal range refers to the vertical distinction between the most elevated and least elevated tides. The beachfront

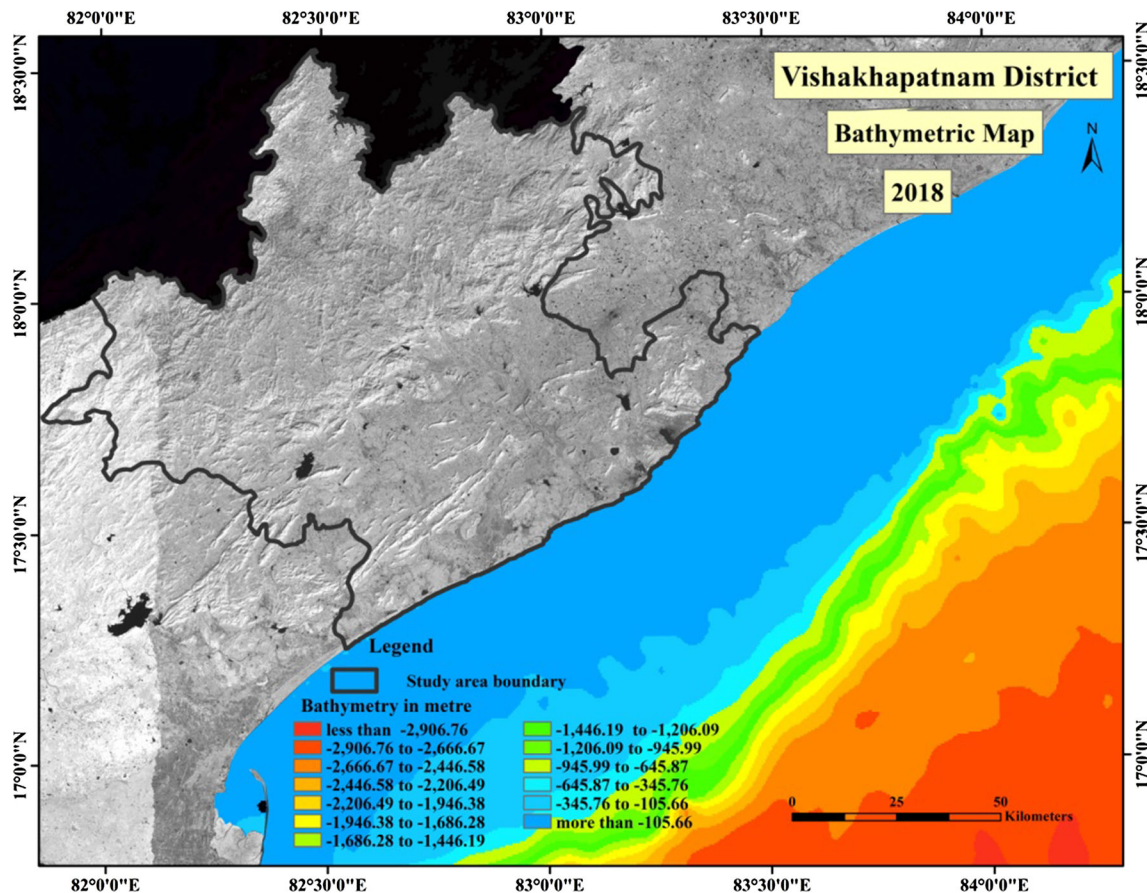


Fig. 5 Bathymetric map of the Vishakhapatnam district

Fig. 6 Contour map of the Vishakhapatnam district

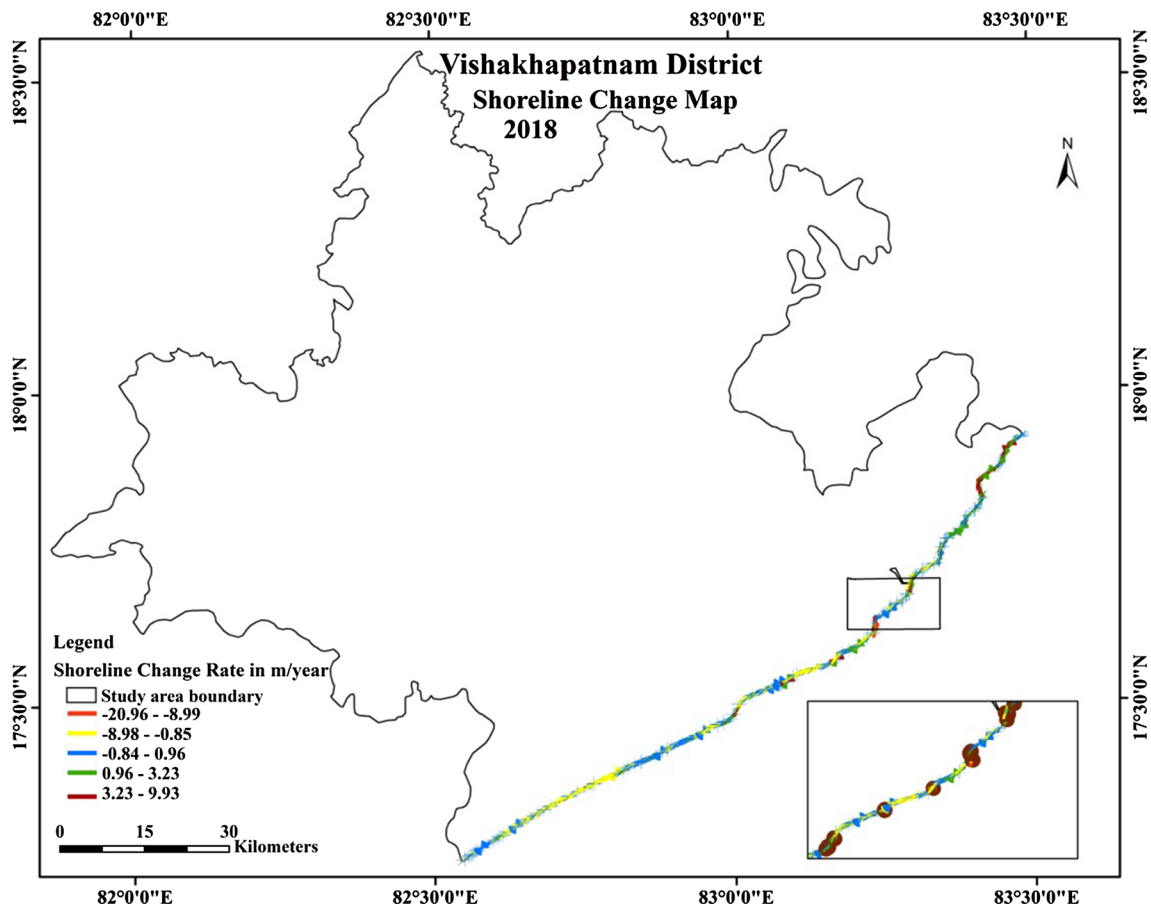
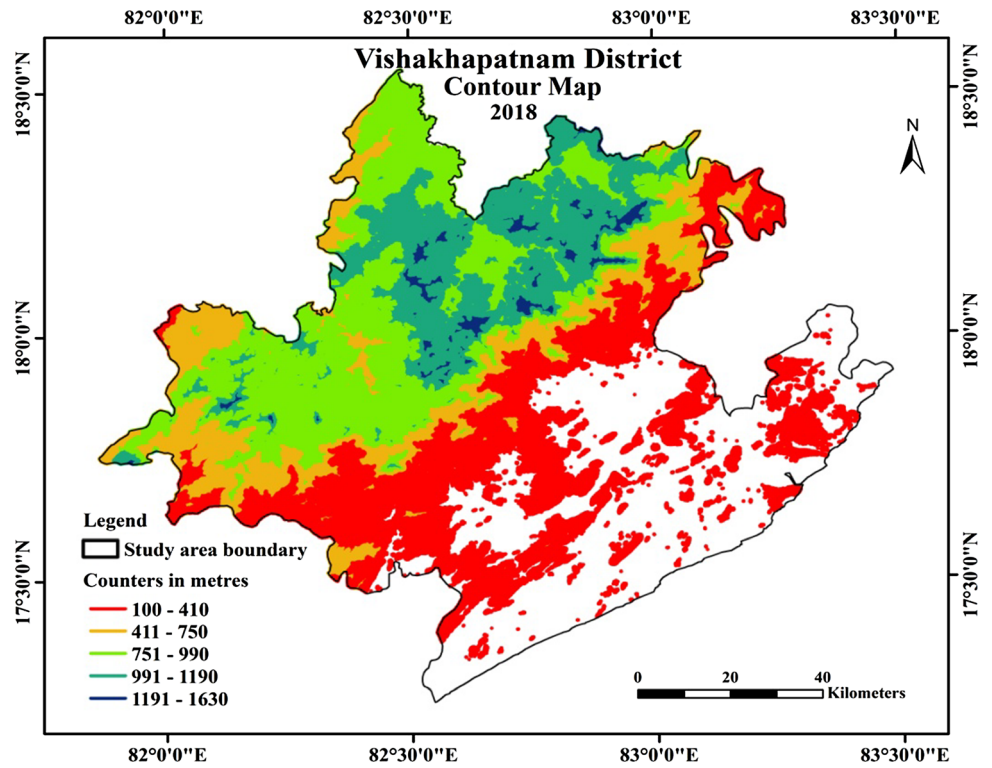


Fig. 7 Shoreline change map of the Vishakhapatnam district



territories with a high range of tide are considered as highly vulnerable, while the territories with a low range of tide are considered as less vulnerable. In the study of ebb and flow, anticipated tide information from the WX Tide programming for 1991 was used as the base information, to determine the most extreme height of tide in the beachfront areas of Vishakhapatnam, and thus the rate of the hazard was doled out (Fig. 8).

AHP has been applied as an assessment tool in numerous studies like landslide vulnerability assessment, flood vulnerability assessment, as well as the soil erosion mapping, etc. (Rincón et al. 2018). Overall, the various parameters as discussed above like LU/LC, geomorphology, bathymetry, contours and coastal slope, rate of shoreline change and mean tidal range have been given vulnerability indices for calculating vulnerability through AHP technique (Table 2).

A relative value ranging between 1 and 9 (Table 3) has been rated against each factor, and the values were assigned to the cell concerned (Table 4). After comparative matrix (Table 4), the priority vector was calculated which was normalized eigenvector of matrix and it was done by dividing each column by their corresponding sum (Tables 4 and 5). At the final step, the mean value of each row has been calculated and used as weights in the objective

pecking order for computation of CVI. AHP permits both sub-criteria just as primary criteria correlation; nonetheless, for the current investigation the last has been utilized and the loads have been accounted for further calculation.

For the vulnerability studies, CVI was examined by using the square root of the product of the ranking of indicators divided by the number of indicators used. But as per Gornitz (1991), even though CVI may be computed as a sum of the indicators, the CVI deliberated as the product of indicators has the benefit of intensifying the sort of values. Further, according to Diez et al. (2007), the CVI is the sum total of differentially weighted indicators that signify the variability of the environment more suitably. In this study, the CVI was calculated by applying both these techniques and it was found that the technique using the square root of the product of the ranking indicators divided by the number of indicators suitably expresses the better results in this region.

To obtain weights in this study is different from the previous studies on the vulnerability assessment studies in India. For example, Rao et al. (2008) used varying weights for the indicators by developing the rank for vulnerability by random multiplication factors based on the relative significance of five indicators used. They ranked slope and geomorphology as additional significant indicators in

**Fig. 8** Mean tidal range data for the Vishakhapatnam District collected from WX Tide software

Vizagapatnam  
 Madras, India + Corrections: High (+0:06 +0.90) Low (+0:05)  
 Units are meters, initial time zone is IST  
 April 2018 low is -0.0m, high is 1.4m, range is 1.4m.  
 Predicted historical low is -0.3m, high is 1.8m, range is 2.1m.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	04-01	04-02	04-03	04-04	04-05	04-06
L0308 0.0	L0340 0.0	L0409 0.0	L0439 0.1	L0508 0.1	L0539 0.2	H0009 1.0
H0918 1.3	H0952 1.4	H1025 1.3	H1058 1.3	H1132 1.2	H1209 1.2	L0615 0.3
L1522 0.1	L1556 0.1	L1631 0.1	L1705 0.2	L1741 0.3	L1823 0.3	H1254 1.1
H2128 1.4	H2200 1.3	H2231 1.3	H2302 1.2	H2334 1.1	H2335 1.4	L1919 0.4
	04-08	04-09	04-10	04-11	04-12	04-13
H0054 0.9	H0212 0.9	H0419 0.9	H0544 1.0	L0027 0.3	L0101 0.2	L0133 0.1
L0702 0.3	L0822 0.4	L1010 0.4	L1131 0.4	H0633 1.0	H0710 1.1	H0745 1.2
H1357 1.1	H1531 1.0	H1701 1.1	H1800 1.1	L1225 0.3	L1308 0.2	L1346 0.2
L2044 0.4	L2231 0.4	L2342 0.4	L120 0.3	H1842 1.2	H1918 1.2	H1952 1.3
	04-15	04-16	04-17	04-18	04-19	04-20
L0204 0.1	L0236 0.0	L0310 0.0	L0345 0.0	L0421 0.0	L0502 0.1	L0548 0.1
H0819 1.3	H0853 1.4	H0929 1.4	H1006 1.4	H1047 1.4	H113 1.3	H1223 1.3
L1422 0.1	L1458 0.1	L1536 0.1	L1616 0.1	L1659 0.1	L1748 0.2	L1848 0.3
H2025 1.3	H2059 1.3	H2135 1.3	H2213 1.3	H2255 1.2	H2341 1.1	H2385 1.4

**Table 2** Vulnerability indices for various parameters

Variables	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Geomorphology	–	Plateau	Valley	Flood plain	Coastal plain
Land use/land cover	–	Built up	Rangeland	Bare soil	Beaches and wetlands
Bathymetry (m)	> 1000	800–1000	500–800	200–500	< 200
Contours (m)	> 750	411–750	100–410	< 100	–
Shoreline change analysis (m/yr)	9.93–3.23	3.23–0.96	0.96 to – 0.84	– 8.5–0.89	< – 8.9
Mean tidal range(m)	Nil	0.9	1.1	1.4	–

**Table 3** Scale of comparison for AHP

S. no.	Intensity of importance	Description
1	1	Extreme importance
2	3	Very strong importance
3	5	Strong importance
4	7	Moderate importance
5	9	Equal importance
6	2, 4, 6, 8	Intermediate values
7	Reciprocals	Values for inverse comparison

contrast to the others (shoreline change, significant wave height, and tidal range) and, therefore, given it the maximum weight of 4 and then gave 2 to shoreline change and zero weights to the tidal range as well as SWH. The GIS-based suitability approach for assessment for Laoshan District has been used by Ju et al. (2012), wherein they used AHP method to derive weights.

Likewise, in this study, the weights for the different indicators were obtained using the AHP. This is on the ground that, though in virtual terms, a specific indicator can have higher significance than the others; thus, giving fixed

**Table 4** Comparison matrix of variables for AHP

Variables	Shoreline change analysis (m/yr)	Geomorphology	Land use/land cover	Mean tidal range (m)	Contours (m)	Bathymetry (m)
Shoreline change analysis (m/yr)	1	0.33	0.20	0.50	0.33	0.25
Geomorphology	3	1.00	0.25	0.67	0.50	0.33
Land use/land cover	5	4.00	1.00	0.50	0.40	0.29
Mean tidal range(m)	2	1.50	2.00	1.00	0.67	0.50
Contours (m)	3	2.00	2.50	1.50	1.00	0.67
Bathymetry (m)	4	3.00	3.50	2.00	1.50	1.00
Column sum	18.0	11.83	9.45	6.17	4.40	3.04

**Table 5** Normalized matrix variables for AHP

Variables	Shoreline change (m/yr)	Geomorphology	Land use/land cover	Mean tidal range (m)	Contours (m)	Bathymetry (m)	Mean	Percentage (%)
Shoreline change analysis (m/yr)	0.06	0.03	0.02	0.08	0.08	0.08	0.06	5.73
Geomorphology	0.17	0.08	0.03	0.11	0.11	0.11	0.10	10.15
Land use/land cover	0.28	0.34	0.11	0.08	0.09	0.09	0.16	16.47
Mean tidal range(m)	0.11	0.13	0.21	0.16	0.15	0.16	0.15	15.46
Contours (m)	0.17	0.17	0.26	0.24	0.23	0.22	0.22	21.51
Bathymetry (m)	0.22	0.25	0.37	0.32	0.34	0.33	0.31	30.68

weights based on the prudence of investigators extremely destabilizes the individual input of all the variables. For example, geomorphology and the slope are regularly measured important factors in the case of coastal vulnerability; on the other hand, giving them a similar value cannot define their virtual input. In addition, the random values can be used in the case of vulnerability valuation for a scrupulous type of calamity, but for the overall evaluation, they can be ambiguous. Noticeably, AHP demonstrates to be more helpful in the case of a multi-index integrated assessment. To show the probability, the matrix judgment was generated arbitrarily and an index of steadiness known as a consistency ratio (CR) was applied in the procedure of fusion of AHP (Saaty 1977).

$$CR = \frac{CI}{RI} \tag{4}$$

Here, the consistency index (CI) can be expressed as

$$CI = (\lambda_{max} - n) / (n - 1) \tag{5}$$

where  $\lambda_{max}$  refers to the leading or principal eigen significance of the matrix, while  $n$  refers to the order of the matrix. The random index (RI), proposed by Saaty (1977), is the mean of the outcome of consistency index which is dependent on the bid of the matrix (Table 6).

In general, the consistency ratio (CR) value of lower than 0.10 is considered to be relevant (Saaty 1977). In this study, the consistency ratios of the indicators were lower than 0.1 so they can be measured for additional calculation. The weights calculated using AHP were used for the calculation of coastal CVI using Eq. 6:

$$CVI = \frac{\sqrt{A1W1 * A2W2 * A3W3 * A4W4 * A5W5 * A6W6}}{6} \tag{6}$$

where  $W_n$  refers to the weight of each variable, while  $A_n$  refers to the vulnerability score of each indicator.

The values of each indicator for every coastal fragment were acquired by multiplying the values of the rank of vulnerability by the consequent weight factors of respective indicators. The intact coast was accepted as a linear attribute, and then the CVI values for the all the segments of the coastline were re-classified into five subclasses based on the equal interval ranging from very low to very high.

## Results

### Coastal Vulnerability Index

Coastal areas of Vishakhapatnam are vulnerable to frequent disasters due to factors like sea level rise, tidal height, slope, general bathymetry, shoreline change rate, changing land use/land cover, storm, surge, erratic rainfall, temperature, etc. To produce the vulnerability indices for each indicator (Fig. 9), the 500-m grids were buffered out from the Vishakhapatnam coast. Further, based on the indicator features available in the grids, each grid was allotted different variables. CVI was then prepared based on the USGS classification system of 2010. The CVI prepared in this study was validated by comparing it with the coastal vulnerability atlas prepared by INCOIS.

In this study, the CVI values obtained range between 2.6 (min) and 14.39 (max). Based on CVI values (Fig. 9), the coastal tract was re-classified into five vulnerability classes, i.e., very low (0–4.9), low (4.9–7.3), moderate (7.3–9.4), high (9.6–12.0) and very high (12.0–14.39) with equal CVI interval. The very low and low vulnerability classes cover about 42.5 and 29.49 km areas, respectively, while the moderate and high vulnerability classes cover about 23.46 and 34.61 km area, respectively, and the very high vulnerability class covers about 7.5 km area.

### Areas Affected Due to CVI

The result shows that the Yendada Coast, Port area, Tantadi, Beach Road, Pata Polavaram, etc., come under very high vulnerable category due to high rate of shoreline change and soft rock structure, whereas places like Durga Beach, Peedahthala Beach, Yarada Beach, Gangavaram and Sagar Nagar Beach come under high vulnerable zones. Bheemili Beach, Gajuwaka part, Jogannapalem, R.K beach and Rushikonda fall under the moderately vulnerable areas because shoreline change rate is moderate along with medium-height tidal range. Vulnerability is low in areas like Boyapadu, Chattametta, NTPC bridge area, Nerellavalara rural and Jalari Peta, Appikonda Beach, and Polavaram Beach, and the rest of the areas come under very low vulnerability because of hard rock structure and accretion rate higher than erosion as shown in Fig. 9.

There are totally 34 coastal villages in the four taluks (subdivision of the district) of Vishakhapatnam District. Bheemunipatnam taluks have 5 villages and

**Table 6** The random index showing the number of orders of matrix (Saaty and Verges 1991)

No. of orders of matrix (N)	2	3	4	5	6	7	8
Random index (RI)	0.00	0.52	0.90	1.12	1.24	1.32	1.41

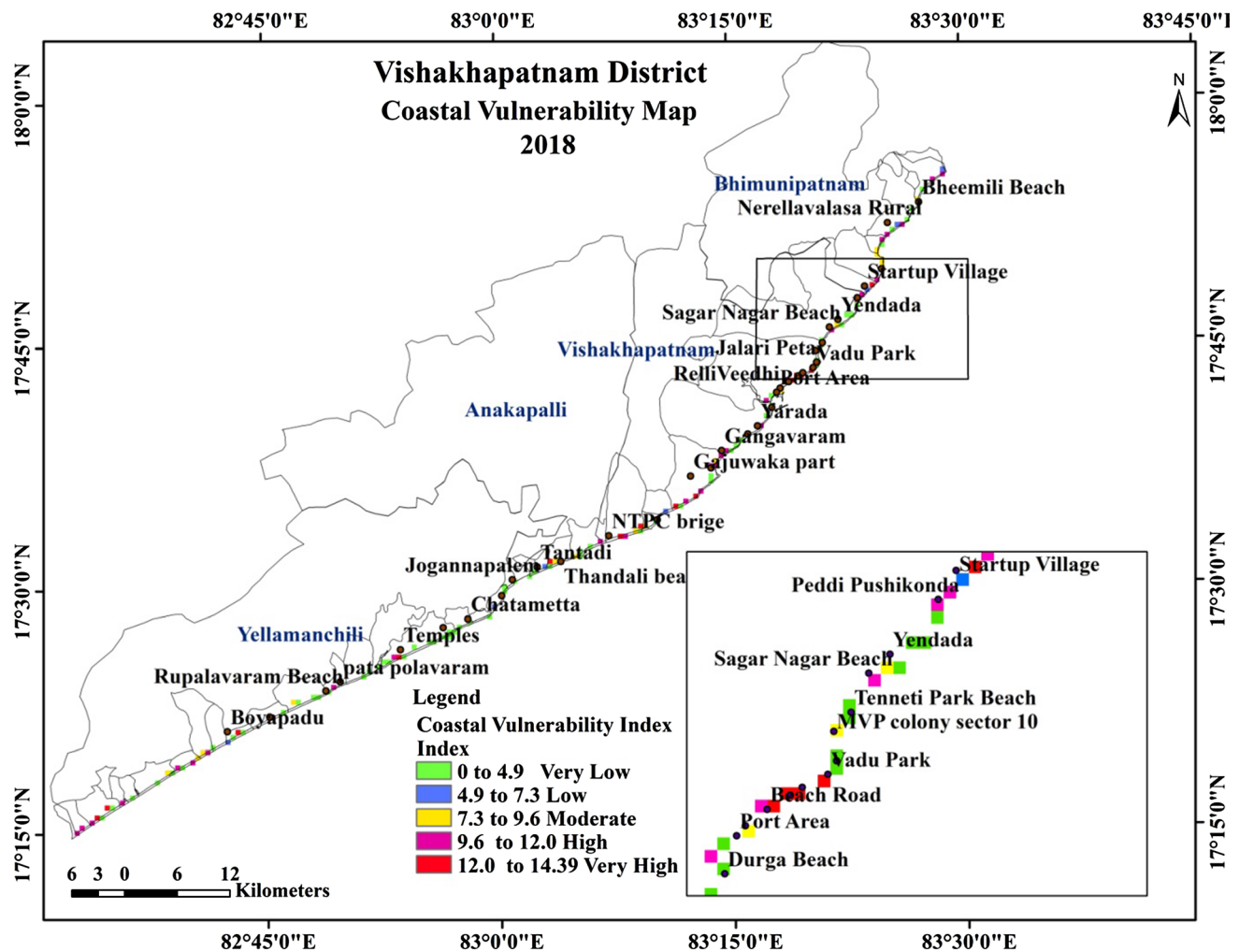


Fig. 9 Coastal vulnerability map of the Vishakhapatnam district

Vishakhapatnam taluks have 7 villages, whereas Anakapalle taluks have only 3 villages. Yelamanchili taluks share the largest coastal boundary, and it has 19 villages. Among villages of Bheemunipatnam taluk, a high vulnerability is found in Kapuluppada village due to high rate of shoreline change rate and loose sand particles along the coast. Moderate vulnerability is seen in Chippada, Chipolapadda and Nerellavasa villages, and low is seen in Bheemunipatnam rural areas. In Vishakhapatnam taluk areas, Vishakhapatnam metropolitan outer growth and forest areas come under moderate vulnerable as the forest is considered as a barrier toward coastal erosion. High coastal vulnerability is seen in Vishakhapatnam urban because of the concrete jungles and high population density, whereas Gangavaram, Gujuwaka, Devada and Appikonda have shown low vulnerability due to low rate of erosion along these coasts. In Anakapalle taluk, Tandati village is highly vulnerable as villages have large agricultural land and vulnerability of erosion is very high and Cheepurupalli village is moderately susceptible to coastal hazards, but

Jogannapalem has only 68 households and also has a low population, so vulnerability is low in terms of overall coastal vulnerability. Yelamanchili taluk shares the largest coastal boundary among coastal taluk of Vishakhapatnam. In addition to this, it has around 19 villages where low vulnerability is seen in villages like Thallepelam, Pudimadaka, Sitapalem, Ziyarati Chintuva, Rajala Agraham, Vakapadu, Gudivada, Pedateenarla, Rajavaram, on basis of parameters incorporated for calculation of CVI like geomorphology, land use/land cover, tidal range, general bathymetry, slope and shoreline change rate. Moderately vulnerable villages are Rambilli, Rajyapetta, Vempadu, Donivanilakshmipuram, Kesavaram and Kumarapuram as shown in Fig. 9.

### Comparison of Four Taluks of Vishakhapatnam

By comparing four taluks of Vishakhapatnam District, it is seen that most of the Bheemunipatnam taluk and Vishakhapatnam taluk's coastal villages are highly

vulnerable as compared to Ankapalle and Yelamanchili *taluk*. Most of the areas of Bheemunipatnam and Vishakhapatnam *taluk* have a coastal vulnerability index of more than 7.3, whereas Ankapalle and Yelamanchili *taluk* has low CVI that ranges between 0–7.3 values. Yelamanchili shares the largest coastal boundary than Vishakhapatnam and Bheemunipatnam *taluk*, and it has low vulnerability values as compared to them. Although, Ankapalle *taluk* has the smallest coastal tract among all *taluks*, it has a higher coastal vulnerability than the Yelamanchil *taluk*.

## Discussion

There are various factors/parameters which directly or indirectly hamper coastal community and livelihood. Among all these parameters, geomorphology and land use/land cover play a key role in coastal vulnerability assessment (Ružić et al. 2019). Therefore, this study is conducted to calculate the CVI of Vishakhapatnam coastal tract using six risk indicators and geospatial techniques. Islam et al. (2016) have done a similar study in the coastal Bangladesh where seven indicators were used to calculate the CVI. Coastal plains are highly vulnerable due to soft nature of the rock, loose sand particles, unconsolidated rock elements and other geological characteristics as in case of the coastal tract of Vishakhapatnam. Erosion is not dominant in areas of mudflats, estuaries, mangrove as these possess resistance to erosion and hence protect coasts (Williams et al. 2018). The results of this study show that the vulnerability to the coastal hazards is high to very high in about one-fourth area of the Vishakhapatnam coastal tract, while more than half of the area falls under either very low or low vulnerability zones. This is because the number of mangrove trees, estuaries and mudflats are very less in the coastal parts of Vishakhapatnam District (ISRO 2012). Most of the beach areas are showing erosion trends as compared to other areas. Beaches are more encroached for various anthropogenic activities, e.g., rest and recreation or for tourism purpose, which somehow impact the level of coastal vulnerability (Ghosh and Dutta 2012). Similarly, Vishakhapatnam coast is also used for commercial and recreational activities, which led to the addition of its community's vulnerability to certain.

In Vishakhapatnam District, the mean tidal range varies with areas and it is considered to be one of the important factors along with other factors in the assessment of coastal vulnerability. Contribution of tidal data in CVI calculation is not significantly important because tidal heights are variable depending on several other factors (Woodworth et al. 2019). At the same time, the bathymetry and surface geomorphology are the main determinants of the coastal

vulnerability in the coastal area of Vishakhapatnam, because of the very low surface bathymetry (− 22.7–217.4 m), presence of low lying flood plains, coastal plains and water bodies in the form of lagoons and lakes in the region. The geomorphologic features such as low elevated plains, mangroves and mudflats have a relatively low confrontation and are vulnerable to the sea level deposition (Parthasarathy and Natesan 2014). The Krishna Godavari delta of Andhra Pradesh has been categorized into two risk levels. The headland and high slope are in low risk category, whereas mud flat low lands have been put into a high risk category (Pramanik et al. 2016).

The coastal vulnerability index of the Vishakhapatnam coast is not uniform but varies from very low to very high vulnerability. This is mainly because of the dynamic pattern of geomorphology, slope, elevation and LU/LC of the Vishakhapatnam coastal tract. A similar pattern of coastal vulnerability in Vishakhapatnam was noted in the CVI prepared by INCOIS 2012. Although the results of this study are not completely identical to the study of INCOIS and there are some variations in the index, this could be due to the types of risk indicators and data used as well as the scale of the study (Koroglu et al. 2019). In this study, the high and very high vulnerability zones cover less than 50% area (23.46 and 34.61 km, respectively) of the Vishakhapatnam District, but in the INCOIS atlas, the area under high and very high vulnerable zones was more than half of the district. Few commercial activities accelerate the trend of coastal erosion, e.g., salt pans, aquafarms and tourist centers, instead of resisters like mangroves, plantation, dunes and mudflats. High exposure to the wind and wave activities causes natural hazards and coastlines changes from Vedaranyam to the north of Muthupet lagoon to a certain degree of vulnerability. Non-conservation agriculture, scrubland and mudflat into salt pans and aquaculture and conservation of wetlands and mangrove should be prioritized for the sustainability of the coastal stretch. To protect the coast from the future degradation, awareness programs should be conducted on coastal resources, environment management, afforestation and environment alertness of local population (Rani et al. 2015; Bama et al. 2020). From the above discussion, it is oblivious that proper assessment of coastal vulnerability and environmental conservation is necessary for conservation and sustainability in the coastal tract of Vishakhapatnam District.

To analyze the vulnerability level of socioeconomic activities to flood and erosion, coastal vulnerability index has been integrated with the LU/LC of lagoon barrier (Maanan et al. 2018). Both physical vulnerability indexes (PVI) and social vulnerability index (SVI) are equally important for calculating overall coastal vulnerability index along with ranking using analytical hierarchy process

(AHP) (Serio et al. 2018). To secure barrier islands, point-by-point field examinations on silt supply (sources and sinks), hydrodynamic powers (tides and waves) and topographical setting (profile of shore face and the structure of substrata) ought to be done in due course of time (Yang et al. 2010). Recently, the coconut garden at RK Beach which is preserved for the beautification of the beach has been declining because of soil disintegration brought about by the ocean's strong waves in the Visakhapatnam.

The National Centre for Coastal Research (NCCR) has done shoreline mapping for the entire coastline of the country on 1:25,000 scale. These maps were being updated every year. A rise in sea level by 3 cm a year was observed at some places, resulting in inundation of low elevation areas alongside the coast (NCCR 2018). These were mostly in the northern Bay of Bengal in Odisha and West Bengal. NCCR has conducted studies on the beach erosion between Rushikonda and Gangavaram port. The report would propose the mediations required to forestall sea shore disintegration on the stretch, especially at R.K. Seashore and Rushikonda (NCCR 2018). The alternative of setting up artificial reefs would likewise be investigated. The thought is to give maintainable arrangements that do not cause an unfavorable effect at different areas because of progress throughout the tide (Krishna et al. 2018), and the present study also shows that R.K. beach, Rushikonda beach, along with other areas are vulnerable to erosion and need to be taken under consideration while planning and developmental activities.

There are certain limitations to the study as the resolution of satellite data restricts at some level, lack of submergence and emergence land information which somehow cause uncertainty of output. There would be a more accurate result if updated value elevation of the coastal areas is available to the public domain which has been also noted by Murali et al. (2019). From this study, it is obvious that CVI and other methods are vital tools for vulnerability identification of coastal areas which should be incorporated adequately. Therefore, a simple step such as selecting a given method might have a strong impact from the management standpoint as hot spots of vulnerability have been identified at various locations. A set of local factors and conditions should be considered before any recommendation, including the use of CVI as a tool to identify the coastal risks and vulnerability for better management and planning and disaster management. The future studies may aim to see how geo-spatial techniques are essential and efficient for coastal research endeavor in terms of accessibility, availability and comfort (Li et al. 2016). This study can provide the database for the future studies, especially micro-level studies of coastal vulnerability as the *Mandal* (subdivision of the district) level analysis has been done in this study and the CVI has been

calculated for the first time for this part of India. Further, it is recommended that in future researches, the integrated vulnerability index (IVI) may be calculated combining physical vulnerability index (PVI) and social vulnerability index (SCI) which may give a holistic view and true representation of overall coastal vulnerability (Guillard et al. 2018) and the criteria that were chosen may differ based on the location of coasts (Koroglu et al. 2019).

## Conclusion

This research has brought out some useful results related to the coastal vulnerability along the Vishakhapatnam coast using the geospatial techniques coupled with the AHP. Based on the study, the overall coastal areas are vulnerable or invulnerable and the degree of vulnerability varies with the time and space and other factors like coastal erosion and accretion, shoreline change, slope, LU/LC, geomorphology, etc. The CVI shows the hazardous impact of erosion, accretion, etc., on the coastal community in terms of physical and social vulnerability. Maximum and minimum CVI value is about 14.39 and 2.6, respectively. Based on the vulnerability, these areas are classified into five categories as very high, high, medium, low and very low. Mostly, beach areas of taluk Vizag, Ankapalle and Yelamanchili are more vulnerable coastal hazards as compared to Bheemunipatnam. Out of the Vishakhapatnam District, Vishakhapatnam urban area being densely populated also lies in the highly vulnerable category. Rural areas people, as well as their livelihood, are vulnerable to sea level rise, coastal erosion, coastal flood and high tidal range. The vulnerability of coastal areas also increases due to encroachment for commercial and tourism purposes.

Therefore, this study can be used as a supplementary document for the planning and developmental activities along the coastal tract of Vishakhapatnam and will also be helpful to the future researchers and policymakers working in the coastal management field. This may also assist scientists and researchers working in the areas of coastal vulnerability and hazards assessment. This study can also help disaster managers, policymakers and planners in the disaster management and risk mitigation strategies. Further, it can be beneficial for the coastal community who are some way or other suffering due to natural hazards since ages.

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## Compliance with Ethical Standards

**Conflict of Interest** There is no conflict of interest on any issue among the authors.

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