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Coastal vulnerability assessment of the predicted sea level rise in the coastal zone of Krishna–Godavari delta region, Andhra Pradesh, east coast of India

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Abstract The Krishna–Godavari coastal region in east coast of India has a 525.15-km-long coastline with low-lying tidal mudflats, beaches, mangrove swamp, creek and tidal channels. Recently, the increasing frequency of tropical cyclones in the Bay of Bengal, i.e., Phylin and Hudhud in Andhra Pradesh coast, and the devastating impact of the 2004 tsunami in India increased the significance in assessing the vulnerability of the coastal lands to inundation and flooding, notably in the context of climate change-induced sea level rise. This study aims to estimate a coastal vulnerability index (CVI) for the coastal subregion of Krishna–Godavari delta and to use the calculated index to evaluate the vulnerability of 14 coastal talukas of the Krishna–Godavari delta region. This CVI is calculated by using four geological and three physical parameters characterizing the vulnerability of the study coastal region, including regional slope, coastal elevation, geomorphology, significant wave height, mean tidal range and relative sea level using different conventional and remotely sensed data. Using a composite coastal vulnerability index based on the relative risk rating of those parameters, each of the 14 coastal talukas was classified according to their vulnerability. The CVI results depict that coasts are least and most vulnerable to inundation, flooding and erosion of coastal lands where geological parameters are more efficient to CVI. The paper alerts to decision makers and planners to mitigate the natural disaster and manage the coastal zone and is a primary step toward prioritizing coastal lands for climate change adaptation strategies in the view of increased storminess and projected sea level rise.

Keywords Coastal vulnerability index · Krishna–Godavari delta · Sea level rise · Coastal geomorphology · Significant wave height

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1 Introduction

Coastal zones have changed significantly during the twentieth century, due to increasing populations, increasing urbanization, industrialization and other development activities. In 1990, 1.2 billion people (23 % population) of the world lived both within a 100-m elevation of the coast, and the densities are about three times higher than global mean population densities (Small and Nicholls 2003). So within this context, the coastal area and its inhabitants are at risk or more vulnerable to storm events, flooding (Rao 1990) particularly due to significant rising in sea level (Unnikrishnan et al. 2004; Unnikrishnan and Shankar 2007). In the twenty-first century, millions of people will be affected and respond to coastal erosion and flooding incidences per year due to the projected sea level rise. The sea level rise will also contribute to increased storm surge events (Gilman et al. 2006), even if storm magnitude and intensities do not increase in response to the warming of the world oceans (Murty and Neralla 1996).

In India, about 25 % of the human population live within 50 km of the coast (Mahapatra 2010). The Indian coastal regions are under significant threat of tsunamis (observed tsunami December 2004) and tropical cyclones (Chaudhuri et al. 2013), whose destruction force and threats to human life can be basically attributed to a storm-surge-induced coastal flooding (Sindhu and Unnikrishnan 2012). Both the Bay of Bengal and the Arabian Sea areas along the coastlines are mostly affected by tropical cyclones and related hazards (Chaudhuri et al. 2013) and with an estimated 1-m sea level rise could displace about a million inhabitants from their living place along the coastline (IPCC 2001). The eastern coast of India is mostly affected by tropical cyclones originating from both Southeast Arabian Sea and Northern Bay of Bengal where 1–2 tropical cyclones form every year along the coasts (Evan and Camargo 2011). The eastern coast is also affected by the several storm surges of the Bay of Bengal. However, these storms and tropical cyclones weaken after traveling a long distance across the Indian subcontinent after making landfall along the coastal regions. Recently, two tropical cyclones that formed in the Bay of Bengal are Hudhud (October 13, 2014) and Phylin (October 11, 2013), and devastating impacts on the eastern coast had reminded the country has lack of preparedness to cyclone, storm surge and related natural hazards. This sea level rise will also contribute to beach recession where 70 % of the sandy beaches have been a likely retreating in the past century. The east coast of India had also experienced the rising tendency of the sea level not in an equal perception, but it varies differently throughout the coastal areas (Nayak 2005). However, increasing coastal population, recent observed cyclones and storm surges, and climate change-induced sea level acceleration stressed the importance of the scientific studies on coastal vulnerability and the collect appropriate information for government decision makers, community residents (Kumar and Kunte 2012). In addition, to addressing this issue, stakeholders need to classify the coastal areas according to their resilience and sensitivity to coastal flooding, inundation and coastal erosion. In the past, the prime barrier in understanding vulnerability analysis has been a lack of information and data (Sterr et al. 2003). However, recent development in image processing techniques and spatial data gathering, including geographic information system (GIS) and satellite remote sensing, have helped to overcome this constraint.

According to Intergovernmental Panel for Climate Change (Van Aalst et al. 2012) vulnerability is a function of sensitivity, adaptive capacity and exposure to climatic event (Das2012). Vulnerability incorporates a set of process and conditions resulting from socioeconomic and environmental factors that accelerate the susceptibility to hazards of a community and may encompasses the icon of coping capacity to respond to the disasters of the community (Mahendra et al. 2011). The coastal vulnerability assessment is strongly related to the socioeconomic conditions assigned to coastal elements. The changes to these conditions will assist in the interpretation and selection of probable responses to the sea level rise, climatic changes and human interferences (Michele et al. 1999). The final outcomes of the vulnerability evaluation will be most useful in ICMP (Integrated Coastal Zone Management Plan) (Snoussi et al. 2008). The coastal vulnerability index (CVI) was used for the assessment of the relative vulnerability of the coast in the future sea level rise within the study coasts. Thieler and Hammer-Klose (1999) have completed the integrated assessment of coastal vulnerability along different coasts based on the factor of Gornitz (1991). They have included six physical coastal variables: geomorphology, shoreline change rate, mean tide range, sea level rise, coastal slope and significant wave height. In India, Dwarakish et al. (2008, 2009) constructed a coastal vulnerability index for the Udupi coast in Karnataka, Southwest India. They included six variables which are coastal slope, mean tidal range, wave height, geomorphology, sea level rise and shoreline change. Joevivek et al. (2013) and Sheik Mujabar and Chandrasekar (2011) used the same physical and geologic variables as proposed by Dwarakish et al. (2008, 2009) to identify the vulnerable zone of southern Tamil Nadu coast to erosion and sea level rise, while Nageswara Rao et al. (2009) applied five of six variables omitting the rate of sea level rise to construct the vulnerability and their development in the Andhra Pradesh coast, India. For the application and development of coastal vulnerability in India, many researchers have used different kinds of geological and climatic parameters that are given in Table 1. The basic objectives of the present study were to construct a coastal vulnerability index for coastal erosion and sea level rise and then use this index to signify the impact along the coast of Krishna–Godavari delta, with a view to quantifying and identifying the low-lying coastal vulnerable areas, susceptible to coastal erosion (increase land loss) and sea level rise.

2 Description of the study area

The study coasts stretch for 525.15 km along the coast of the Krishna–Godavari delta region in Andhra Pradesh, which is located in the eastern part of India (Fig. 1). The study deltaic coastal region lies between 15°3′ and 17°30′ north latitude and 79°41′ and 82°32′ east latitude, covering an area 11,756 km^2 from the coastline. The area covers five districts and 14 talukas along the coastline of Andhra Pradesh from east Godavari (Tuni taluka) district to Prakasam district (Kundukur taluka). The coastal area has rich agricultural land and abundant water supply, owing to the deltas of Krishna and Godavari rivers. The main economic activities include agriculture and fishing. However, the regional variation in slope, elevation, geomorphology and rate of shoreline changes is more significant that affects their economic activities of the Krishna–Godavari delta region. The temperature of the region continuously increases from 33 °C (February–May) and over 45 °C in the interior of the region. The temperature of the coldest month (January) has been recorded as 25 °C in the coastal regions. The annual rainfall of the coasts is 1137.6 mm with uneven distribution. Most of the rainfall occurs during June–September (the southwest monsoon season) and contributes about 72 % rainfall and over 57 rainy days annually.

The Krishna–Godavari coastal tract is situated in the central part of the passive eastern continental margin (Peri cratonic rift basin) of India (Rao 2001) and which is mostly covered by alluvial sediments, beach sand, gravel, kankar soils and colluvial deposits with

Table 1 Previous study about coastal vulnerability index and parameters used in the coastal areas of India

Study/Variables	Study area	Shoreline change	Coastal elevation	Coastal slope	Geomorphology	Sea level change	Significant wave height	Mean Tidal range	Storm surge	Tsunami wave	Population	Socioeconomic characteristics
Hegde and Reju (2007)	Mangalore Coast	*		*	*						*	
Dwarakish et al. (2008, 2009)	Udupi coast	*		*	*		*	*				
Kumar et al. (2010)	Orissa coast	*	*	*	*	*	*	*		*		
Sheik Mujabar and Chandrasekar (2011)	Tamil Nadu (southern part)	*		*	*	*	*	*				
Mahendra et al. (2011)	Cuddalore–Villupuram coast	*	*			*			*			
Kumar and Kunte (2012)	Chennai city	*	*	*	*	*	*	*	*			
Joevivek et al. (2013)	Southern Tamil Nadu coast	*		*	*	*	*	*				
Kunte et al. (2014)	Goa coast	*	*	*	*	*	*	*				*

a very gentle slope (Gupta 2006). The sedimentary region of the coasts contains a large extent of geologic and geomorphologic settings, such as delta, shelf-slope apron, tidal mud flat, mangrove, deepwater fan complex, costal basin and deep-sea channel. The study coasts are characterized by graven and horst systems.

3 Materials and methods

The methodology used in the present study followed the procedure of the USGS (United States Geological Survey) published in Thieler and Hammer-Klose (1999, 2000a, b). Accordingly, to calculate the coastal vulnerability index (CVI) eight variables were selected, each of which represented a specific characteristic of coastal vulnerability. The selected variables were ranked into four categories on the basis of the level of risk that include low, medium, high and very high risk. The value indicates the relative risk of the coastal land due to future sea level rise and related physical changes. Most of these variables are dynamic in nature along the coastal region and require a vast amount of data and information to be acquired from different sources, processed and analyzed. Table 2 shows the data used and their sources for the vulnerability analysis. The character of vulnerability parameters for the Indian coastline is classified into three categories:

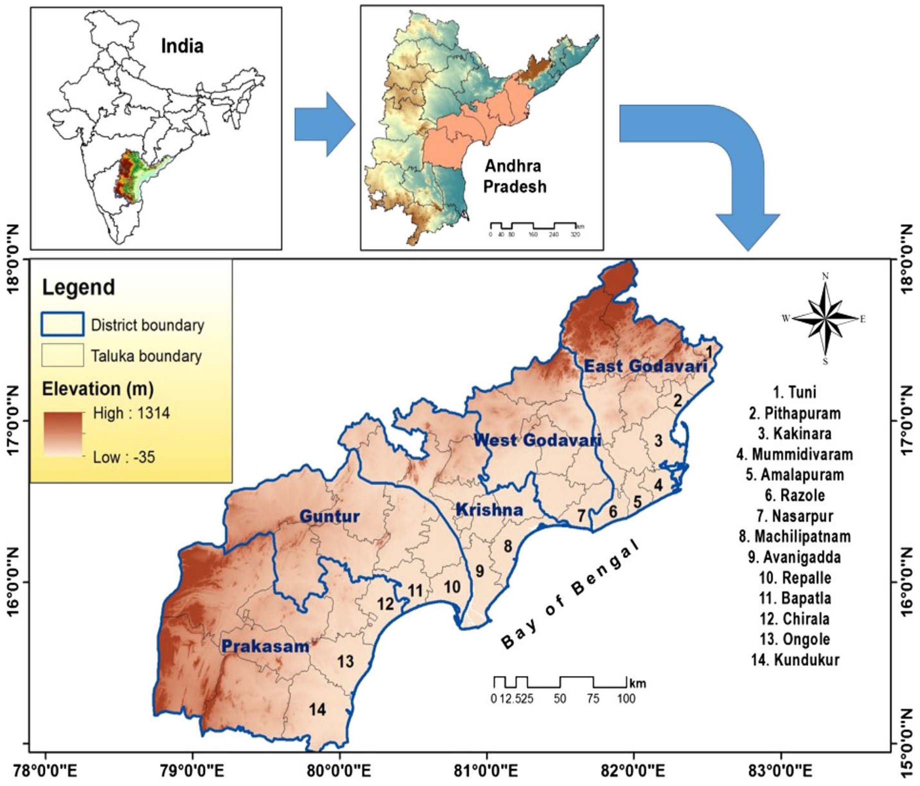

Fig. 1 Location map of the study area

Table 2 Parameter used in the construction of coastal vulnerability index and their types, details and sources

Parameters	Data type	Sources of the data	Details about data	Period
Rate of shoreline change	Spatial	Toposheet and Landsat TM (Path & row—142/49, 141/48, 141/49), ETM images (142/49, 141/48, 141/49)	USGS satellite images (30 m resolution)	1957, 1987 (3.6.1990, 27.5.1990, 5.2.1990), 2010 (27.12.2010, 20.12.2010, 20.12.2010)
Coastal elevation	Spatial	SRTM DEM and Arc GIS	3-ARC (90 m)	2000
Coastal slope	Spatial	SRTM DEM and DGH for bathymetry	3-ARC (90 m)	2000
Geomorphology	Spatial	IRS LISS-P6 images	High-resolution satellite images	January, 1999
Sea level rise	Conventional	PSMSL	Yearly sea level	1937–2009
Significant wave height	Conventional	NIO	Pre- and post-monsoon season	2013
Mean tidal range	Conventional	Extracted from WXTide software	Predicted tidal range	2015

1. Geological variables—shoreline changes, regional elevation, bathymetry and coastal slope, geomorphology.
2. Physical variables—sea level rise, significant wave height, mean tidal range.

These parameters include both the quantitative and qualitative information about the coasts. Table 3 signifies the vulnerability variables and its ratings for calculating the coastal vulnerability index. In the present study, vulnerability ranking of these parameters was assigned for 14 coastal talukas of four districts of Andhra Pradesh to obtain the comprehensive information about the vulnerable coastal areas. The parameters used and their sources for the coastal vulnerability index are discussed in the following parts (Sects. 3.1 and 3.2).

3.1 Geological parameters

3.1.1 Coastal shoreline change

The shoreline is the boundary between sea and land which continuously changes due to accretion, erosion, tidal processes, and topography and sea level changes. Shoreline changes may occur due to man-made and natural processes. Natural processes refer to the wave characteristics, sediment transport and their characteristics, beach forms, nearshore circulation, etc. Anthropogenic activities include the relative sea level change, sand mining and coastal other resources extraction.

The coastal shoreline was digitized using toposheet for the years 1957 and Landsat satellite image for the year of 1990 (TM) and 2010 (ETM) with 30-m resolution obtained

Table 3 Ranking of risk assigned to the different coastal vulnerability index parameters

Parameter used	Low-risk rating (1)	Medium-risk rating (2)	High-risk rating (3)	Very high risk rating (4)
Shoreline change (m/year)	>5 m/year accretion	<5 m/year accretion	<5 m/year erosion	>5 m/year erosion
Coastal elevation (m)	>9	6–9	3–6	<3
Coastal slope (%)	>0.9	0.9–0.6	0.6–0.3	<0.3
Geomorphology	–	–	Headland and low extended mudflat	Extended mudflat and beach ridge complex, mangrove.
Sea level rise (mm/year)	–	0.58	–	–
Significant wave height (m)	–	0.5–2.5	–	–
Mean tidal range (m)	–	0.1–1.4	–	–

from United States Geological Survey (USGS) (Table 2). These images were processed using ERDAS Imagine software, which included geo-referencing, band extraction and image enhancement, and Arc GIS was used for the vectorization of contours and coastline. These digitized vector files were used to calculate the rate of shoreline change and their trend on the basis of reference baseline. The shoreline change rate and ratings of associated risk were computed by drawing perpendicular transects to the coastal baseline (Hegde and Reju 2007) for each coastal taluka of the study coasts. The rate greater than 5 m per year is considered a very high risk rating. Table 3 shows the shoreline change rates corresponding to the very high, high-, medium- and low-risk rating categories.

3.1.2 Coastal elevation

Coastal regional elevation refers to the mean elevation of a particular coastal land above MSL (mean sea level). Coastal elevation is a significant parameter for use in the analysis of coastal vulnerability, which helps to estimate the threatened area and sensitivity to coastal flooding by projecting sea level rise (Diez et al. 2007; Kumar and Kunte 2012). With respect to vulnerability, the areas with low elevation are considered more vulnerable and vice versa. The elevation of the coast of the Krishna–Godavari delta was determined using Shuttle Radar Topography Mission (SRTM) Global digital elevation model (DEM) data with 3-ARC 90-m resolution (Table 2). The mean elevation of the entire coastal area was estimated of each taluka. Vulnerability ratings were assigned by comparing the mean elevation for each taluka of the coastal stretch.

3.1.3 Coastal slope and bathymetry

The coastal slope is an important parameter to be considered in estimating the effect of sea level rise on the study coast. On a low-lying coast, the sea level rise effect would be significant contrary to a steeply sloping coast where a short rise in water level would inundate a large extent of coastal land (Sterr et al. 2003) and mostly affected by tsunamis and storm surges (Kumar et al. 2010). Thus, coastal lands that have gentle slopes have high vulnerability, while the lands of the steep slope may be considered as a low-risk rating. The global digital elevation models (DEM) of the Krishna–Godavari coastal area available from the USGS Web site are downloaded (Table 2), and estimated contours at 0.3 % intervals are interpolated using ArcGIS 3D analyst toolbox.

Bathymetry signifies the depth from the coastline toward the open oceanic region. It is the significant baseline for all forms of wave, hydrodynamic and inundation modeling, while nearshore bathymetry depicts the wave's fate as they approach the coastline (Kumar and Kunte 2012). However, it is an important factor to consider in estimating the effect of sea level rise. Bathymetric images were obtained from the Directorate General of Hydrocarbons (DGH) under the Ministry of Petroleum and Natural Gas (Government of India). The procedure for estimating the ocean bathymetry consisted of first vectorizing the contours from the collected bathymetric map (Fig. 4) and after geo-referencing the data using the WGS-84 (World Geodetic System) datum.

3.1.4 Geomorphology

The morphological configuration of the coastal area plays a significant role in estimating the effect of sea level rise. Coastal landforms and the resistance capacity reflect their relative responses to sea level rise where every landform signifies a certain degree of erosion along the coastal region (Thieler and Hammer-Klose 1999, 2000a, b), while the wave cut benches and the rocky cliffs offer maximum resistance capacity and represent very less vulnerable where the muddy and soft sandy form such as mangroves, sand dunes and mudflats which offer less resistance and extremely vulnerable to sea level acceleration. The Krishna–Godavari delta coastal area is very low lying where beaches, mangrove swamps, mudflats, and creeks and tidal channels are main geomorphological landforms in this micro-tidal coastal environment. The spring high tide reaches up to 35 km upstream in the distributaries of Godavari and Krishna rivers up to the maximum Holocene transgression boundary, which is demarcated by the landward limit of the former shorelines (beach ridges) (Nageswara Rao and Sadakata 1993). Table 3 indicates the vulnerability and risk level assigned with respect to the geomorphological structure of the coasts.

3.2 Physical parameters

3.2.1 Rate of sea level rise

In the context of coastal vulnerability, high rate of sea level acceleration is considered as a high vulnerable coastal area and vice versa. The official record of the mean sea level sea level rise data of the study coast is not available. So, the nearest station with available sea level data in the present study coastal area is Visakhapatnam Sea. The rate of sea level changes has calculated for 73 years from 1937 to 2009 which indicates a 0.73 mm per year. This rate is a risk of the low-lying coastal area that has been affected by inundation as well as increases the vulnerability of the coastal region.

3.2.2 Significant wave height

Significant height of waves indicates an average height of the one-third highest waves in 12-h time period. Average significant wave height is used as a proxy for wave energy, as an indicator to assess the coastal vulnerability, which helps to transport the coastal sediment

(USGS 2005). Wave height of the coastal regions recorded by scientists of NIO (National Institute of Oceanography) using directional wave rider buoy that used to calculate the significant wave height. The relationship between wave height and wave energy is calculated by the following formula:

$$E = \frac{1}{g}\rho g H^2 \tag{1}$$

where E indicates energy density, g is the gravitational acceleration, ρ is the density of water and H indicates the height of the wave. Increasing wave height gradually increases the wave energy as the subsequent results in increased erosion of the coastal area (Kumar et al. 2010). Low wave height is considered as less vulnerability, and the areas of high wave height indicate the more vulnerability along the coastal region. The mean significant wave height of the region varies between 0.5 and 2.5 m.

3.2.3 Mean tidal range

The range of tide is calculated by the vertical difference between the lowest low tide and the highest high tide and is also linked to flood hazards (Doukakis 2005; Diez et al. 2007; Kumar et al. 2010). In the context of vulnerability, high tidal range signifies the highly vulnerable (Gornitz et al. 1994; Doukakis 2005; Diez et al. 2007; Kumar et al. 2010; Di Paola et al. 2011; Yin et al. 2012; Addo 2013), while others described coastal areas with low tidal range are most vulnerable in the coastal region (Pendleton et al. 2005; Dwarakish et al. 2008; Ozyurt and Ergin 2010; Sheik Mujabar and Chandrasekar 2011; Joevivek et al. 2013; Gorokhovich et al. 2014). In the present study, predicted tide data (Fig. 5) extracted from WXTide software for the year 2015 are taken from the base data, and the maximum and minimum amplitudes of the tide in the study coastal locations are Sacramento shoal (0.2–1.4) and Cocanada (0.1–1.3), and vulnerability rates are assigned.

3.3 Calculation of coastal vulnerability index (CVI)

The selected 14 talukas within the coastline of the Krishna–Godavari region were assigned a risk rating for each variable, and then, CVI was calculated as the square root of the results of the ranked variables divided by the total number of variables (Pendleton et al. 2005):

$$CVI = \sqrt{\frac{a \times b \times c \times d \times e \times f \times g}{7}} \tag{2}$$

where a = rate of shoreline change, b = coastal elevation, c = coastal slope, d = geomorphology, e = rate of sea level rise, f = significant wave height and g = mean tidal range.

The composite index of the selected coastal taluka was calculated by their weighted averages by combining the individual parameters (Hahn et al. 2009). In the present vulnerability analysis, equal weight was used for every selected variable, an approach that is the commonly used in the literature (Pendleton et al. 2005; Boruff et al. 2005; Hegde and Reju 2007; Dwarakish et al. 2008; Dwarakish et al. 2009; Özyurt and Ergin 2009; McLaughlin and Cooper 2010; Gaki-Papanastassiou et al. 2010; Di Paola et al. 2011; Sheik Mujabar and Chandrasekar 2011; Clavano 2012; Karymbalis et al. 2012; Addo 2013; Joevivek et al. 2013; Gorokhovich et al. 2014).

Equation 2 is calculated for 14 talukas, and the output coastal vulnerability index values were ranked into four classes as very high, high, medium and low risk depending on their total level of vulnerability of the Krishna–Godavari coastal region.

4 Results and discussion

4.1 Rate of shoreline change

The estimations of the rate of shoreline change indicated that the talukas of Pithapuram, Mummidivaram and Avanigadda were the most sensitive due to accelerated rate of coastal erosion, which signifies a very high risk rating (Fig. 2), with calculated erosion rates of more than 5 m per year. The coastline of Tuni, Amalapuram and Machilipatnam had lower erosion rates, less than 5 m per year, thus having rated high-risk level. The coast of the Kakinada, Repalle, Chirala, Ongole and Kundukur experienced both low erosion and accretion rates and was therefore ranked as a medium-risk category. The coastal area of Razole, Narsapur and Bapatla which had higher accretion rates of more than 5 m was ranked as lower-risk level.

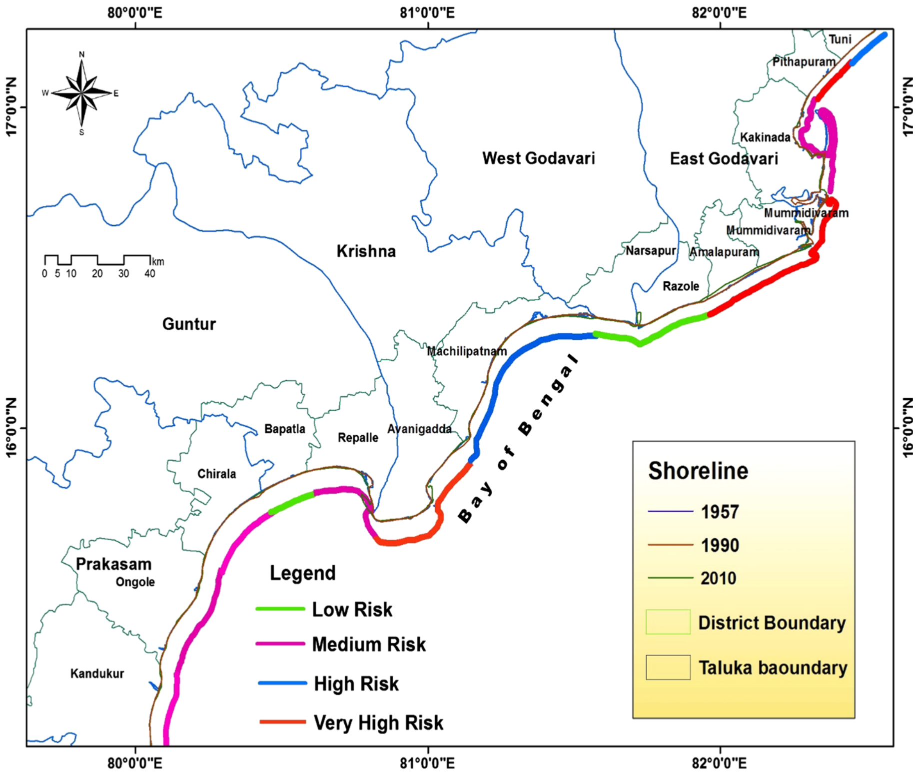

Fig. 2 Shoreline positions of 1957 (toposheet), 1990 (Landsat TM), and 2010 (Landsat ETM) with Shoreline change risk ranking

4.2 Coastal elevation

The coastal regional elevation in the Krishna–Godavari delta region ranges between 0 and 632 m. Accordingly, talukas with a beach elevation of less than 3 m were categorized as very high risk zone, while those areas with a coastal regional elevation of more than 9 m were categorized as low-risk zone (Table 3).

The study signifies that the talukas of Mummidivaram and Avanigadda have an elevation of 3 m from the coast, which were assigned a very high risk rating and the talukas of Pithapuram, Kakinada, Amalapuram, Machilipatnam, Repalle, Bapatla and Chirala situated within 3- to 6-m elevation zone along the coast were assigned to a high-risk category (Fig. 3). The coastal talukas of Tuni, Razole and Narsapur had a very high coastal elevation from 9 to 632 m and were therefore marked as low-risk rating.

An inundation map was created for the present study coastal areas that show the inundation-based potential risk zone based on different sea level rise scenario (Fig. 7). As Fig. 7 signifies, the major river system of study coastal areas is main corridors for the increase in inundation rate as they permit the flood water through upstream rivers, resulting in flooding along the river side. During high tide, the ocean water can reach up to 35 km upstream. Figure 7 also illustrates the vulnerability of a number of coastal areas to submergence due to sea level rise, and generally, the parts of Kakinada, Mummidivaram,

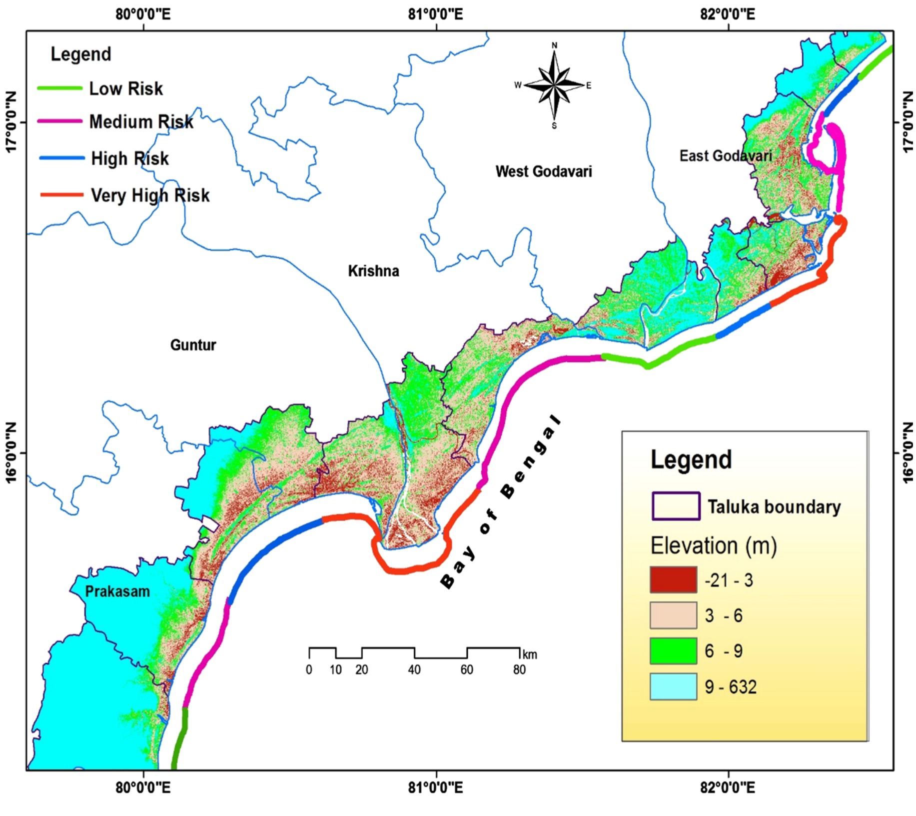

Fig. 3 Areas of risk ranking-based coastal regional elevation

Narsapur, Machilipatnam, Avanigadda and Repalle talukas are mostly affected by the lower (0–6) elevation.

4.3 Coastal slope

The study revealed that the talukas of Mummidivaram and Avanigadda have a very high risk rating due to their lower slopes along the coastal region which is about 0–0.3 %, and the coastline of Pithapuram, Kakinada, Amalapuram, Machilipatnam, Repalle, Bapatla and Chirala was assigned a high-risk category (Figs. 4, 5) with the coastal slopes between 0.30 and 0.60 %. The shoreline of Ongole and Kundukur situated in the 0.6–0.9 % slope represented medium-risk category with a slope of more than 0.9 % which rated as a low-risk category for the Tuni, Razole and Narsapur talukas.

4.4 Coastal geomorphology

Geomorphologically, the region was mostly sensitive due to the muddy and soft sandy forms such as mudflats, mangroves and dunes which offer less resistance and were extremely vulnerable to sea level acceleration. So, the region was categorized into two types of risk level where headland and high slope, but the lower amount of low-lying mud

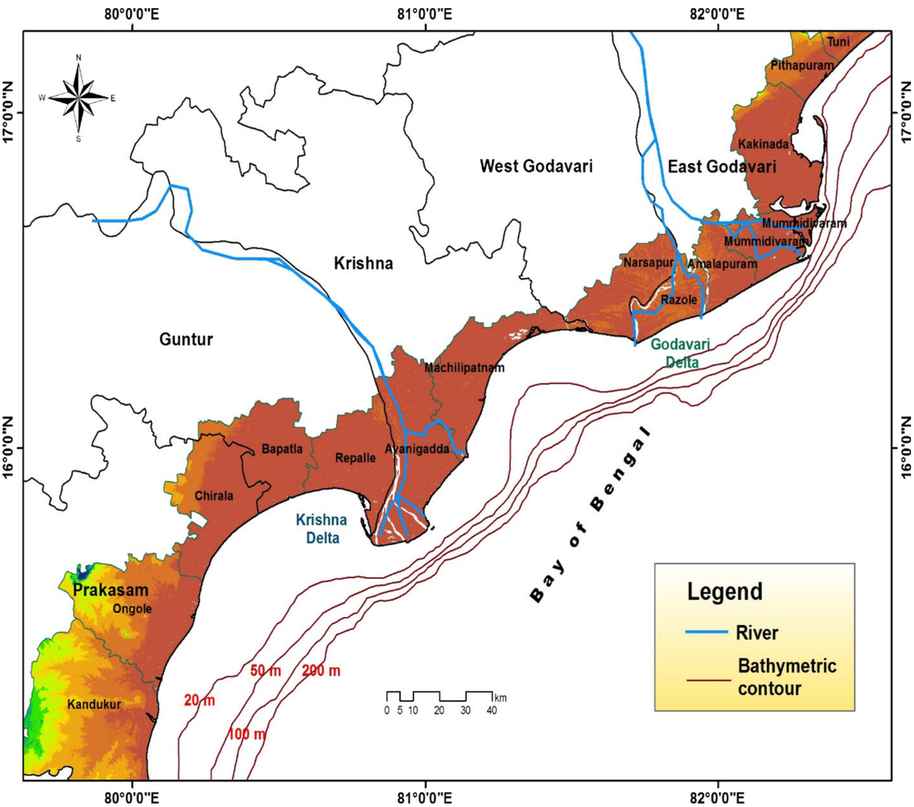

Fig. 4 Nearshore bathymetric map of the Krishna–Godavari delta region

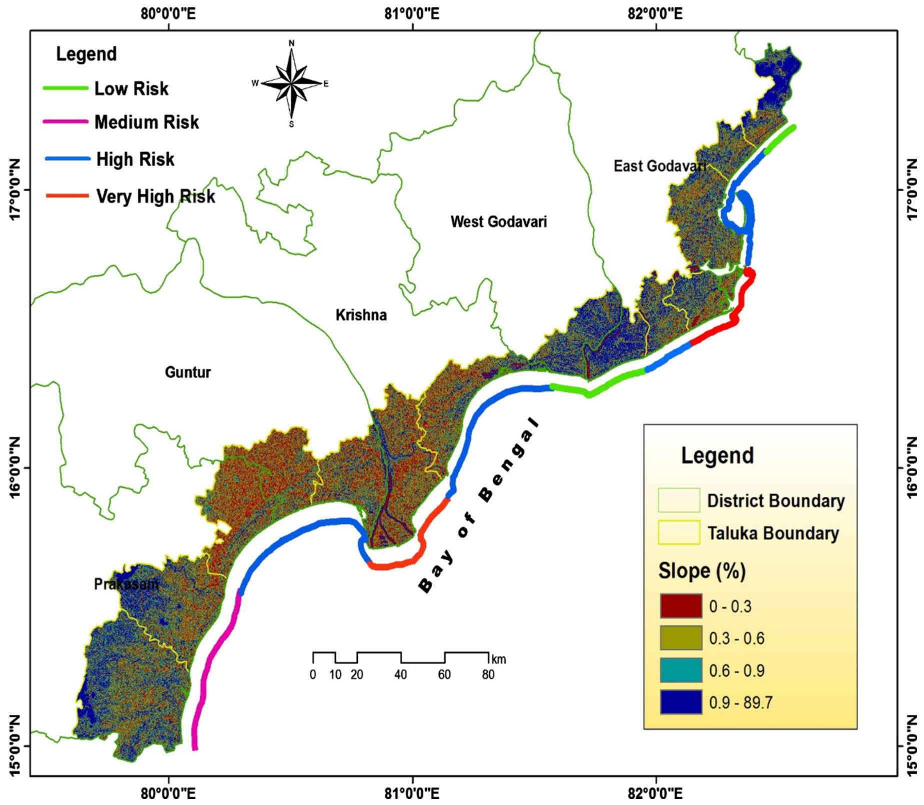

Fig. 5 Coastal regional slope with the ranking of coastal vulnerability

flat has assigned as a high-risk category. The coastal talukas of Tuni, Pithapuram, Razole, Narsapur, Machilipatnam, Bapatla, Chirala, Ongole and Kundukur fall under this category (Fig. 6). However, the region of mangrove forest, long beach ridge complex and long mudflat dominated areas has represented very high risk category where Kakinada, Mummidivaram, Avanigadda and Repalle talukas fall under this category (Fig. 6).

4.5 Rate of relative sea level rise

Recently, climate change-induced sea level rise has a great impact on both for the environment and for societies. Mean sea level refers the height of the sea with respect to the local benchmark of the coast for a year or a month averaged over a certain period of time. Changes in average sea level as measured by tide gauge stations are called relative sea level rise (Church and Gregory 2001).

In the nearest station (Visakhapatnam) of the study area, sea level has increased gradually at the rate of 0.58 mm per year in between 1937 and 2009, where the estimated regional average is 1.29 mm/year, depending on the a global isostatic adjustment correction and tidal gauge recording site (Unnikrishnan and Shankar 2007). However, this regional average of global sea level rise varies between 1 and 2 mm/year for the past 100 years, as estimated by the Inter-governmental Panel for Climate Change (IPCC)

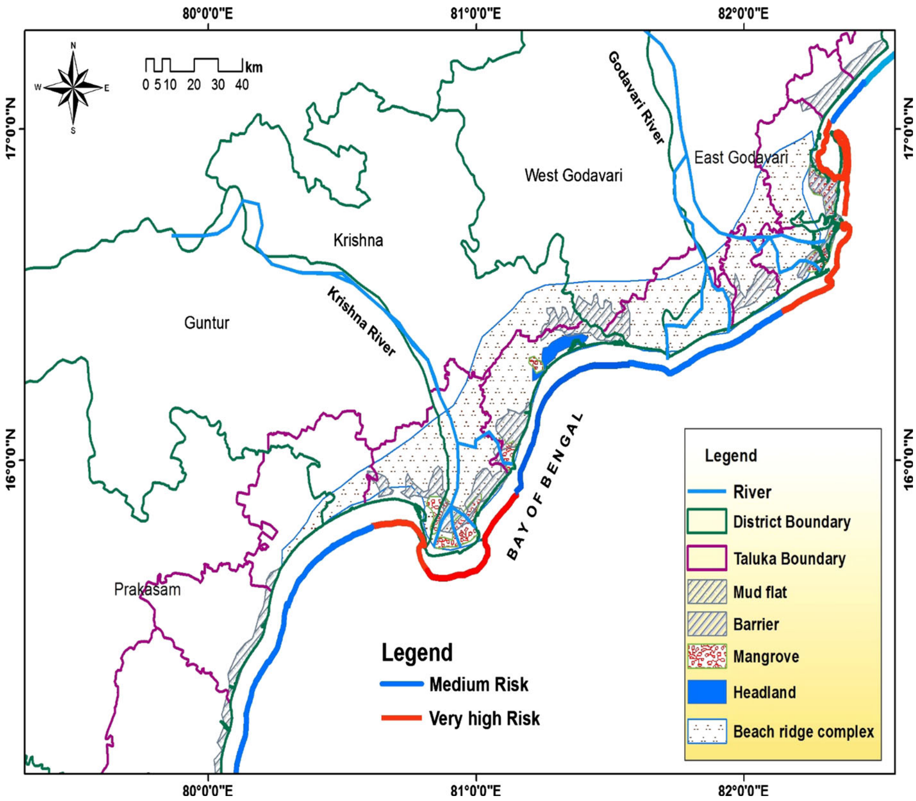

Fig. 6 Geomorphology of the study area with risk level

(Hegerl et al. 2007). If the sea level rise continues due to the projected emissions of greenhouse gases at the end of this century, the sea level will be increased approximately 4 mm per year (Unnikrishnan et al. 2004). In addition, the variations across the Krishna–Godavari delta region are minimal, and the rate of the sea level rise is below the IPCC scenario (Fig. 7). Accordingly, it is not surprising for the study region with a relatively small coastal area, and one could categorize the total 525.15 km coastline in the medium-risk ranking category.

4.6 Significant wave height

During monsoon months (June to September), the significant wave height varies between 1 and 2.5 m, but in the northeast monsoon season the height reaches within 1 m in the Kakinada coastal area and during the February to May (fair weather) the height ranges between 0.5 and 1.0. Dwarakish et al. (2009) considered that the coastlines are moderately vulnerable when the magnitude of significant wave height ranges from 1.6 to 2.8 m, and accordingly, significant wave heights of the Krishna–Godavari region were classified in the medium-risk ranking category, which ranges between 0.5 and 2.5 m (Kakinada). For a small region of the Krishna–Godavari delta, significant wave height does not vary significantly. So, the entire coastline of the delta was given the same risk ranking category.

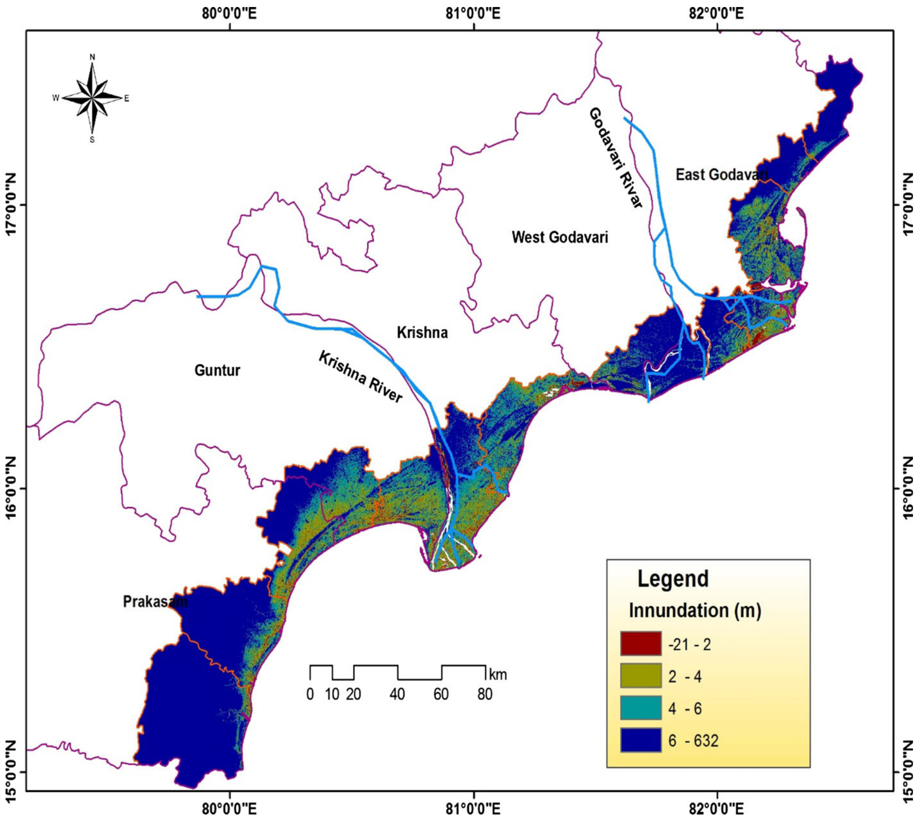

Fig. 7 Inundation map of the Krishna–Godavari delta region on different sea level rise scenarios

4.7 Mean tidal range

The tidal range for a small coastal region of Krishna–Godavari delta does not fluctuate much within a year (Kumar and Kunte 2012). The tide range below 2.5 m is considered in the same risk category (Kumar et al. 2010). In the study region, two tidal stations are present, which are Sacramento shoal and Kakinada. The mean predicted tidal level was extracted as 0.1–1.3 m in Kakinada and 0.2–1.4 m in Sacramento shoal (Fig. 8) for the year 2015. However, the entire 525.15 km coastline of Krishna–Godavari region was classified under the same and with moderate-risk category as considered by Kumar et al. (2010).

4.8 Coastal vulnerability in the Krishna–Godavari region

Table 5 shows the coastal vulnerability results for 14 coastal talukas of the Krishna–Godavari delta region, and the relative ranking and percentile-based vulnerability of each parameter are depicted in Table 4 and Fig. 9. The classification of the vulnerability was based on sensitivity and exposure of the coast to seven geological and physical parameters. The coastal vulnerability index (CVI) for the 14 coastal talukas of Krishna–Godavari delta region varied from 1.84 to 17.25. The 25th, 50th and 75th percentiles of the calculated CVI

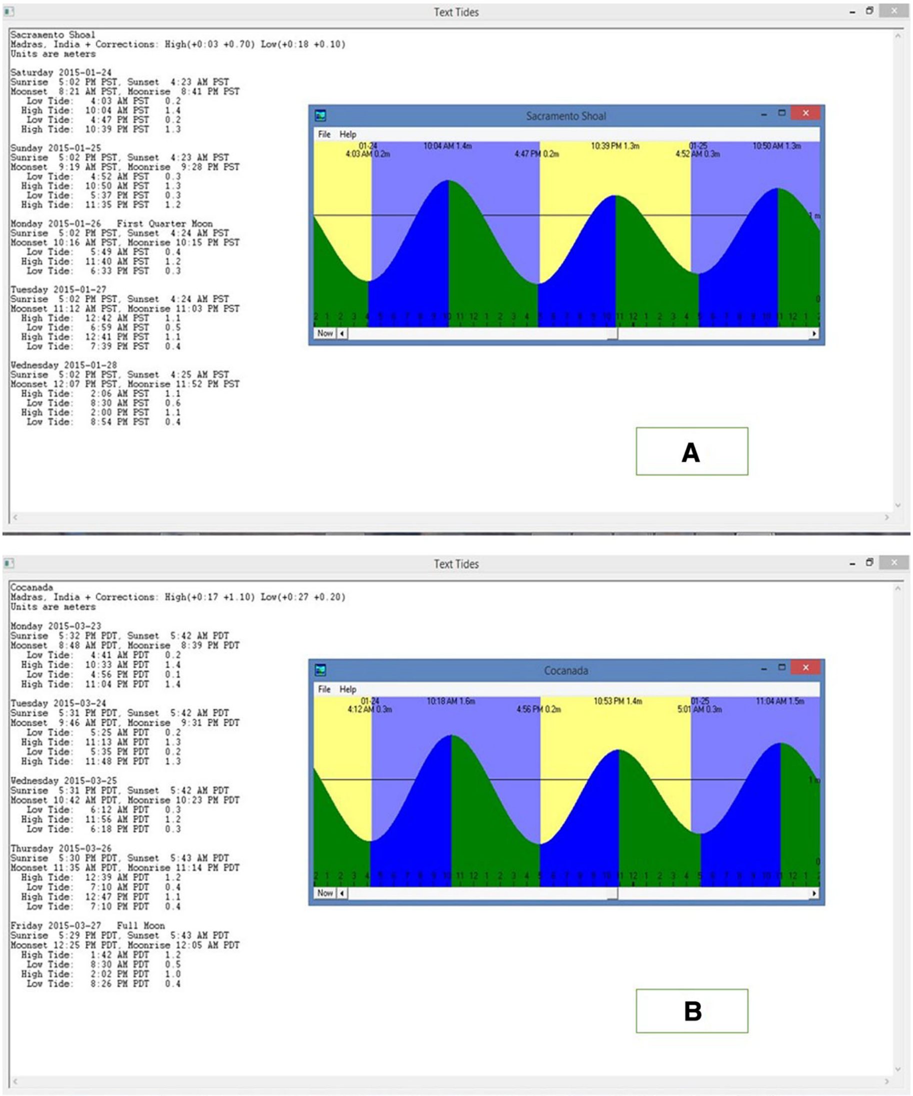

Fig. 8 Tide data extraction of the study area from WXTide software for January, 2015, **a** Sacramento shoal, **b** Kakinada station

values are 3.75, 7.63 and 11.95, respectively. Hence, the coastal talukas of Tuni (northernmost), Razole, Narsapur (middle portion) and Kundukur (southernmost) of the study region are considered to have lower vulnerability category due to the presence of a number of rocky cliffs or rock headlands. The coast of Kakinada, Machilipatnam, Bapatla and Ongole to have a medium coastal vulnerability index which are non-deltaic dune front category. The talukas of Pithapuram, Amalapuram and Chirala have CVI values of 9.07, 11.01 and 7.86, respectively. These regions fall within the high vulnerability category where the slopes, landforms and elevations, however, are of moderate category, the strong

Table 4 Relative risk ranking of 14 talukas for all parameters

Sl. no.	Talukas/variables	Rate of shore line change	Coastal elevation	Coastal slope	Geomorphology	Sea level rise	Significant wave height	Mean tidal range
1	Tuni	3	1	1	3	2	2	2
2	Pithapuram	4	2	3	3	2	2	2
3	Kakinada	2	2	3	4	2	2	2
4	Mummidivaram	4	4	4	4	2	2	2
5	Amalapuram	4	3	3	3	2	2	2
6	Razole	1	1	1	3	2	2	2
7	Narsapur	1	1	1	3	2	2	2
8	Machilipatnam	3	2	3	3	2	2	2
9	Avanigadda	4	4	4	4	2	2	2
10	Repalle	4	4	3	4	2	2	2
11	Bapatla	1	3	3	3	2	2	2
12	Chirala	2	3	3	3	2	2	2
13	Ongole	2	2	2	3	2	2	2
14	Kundukur	2	1	2	3	2	2	2

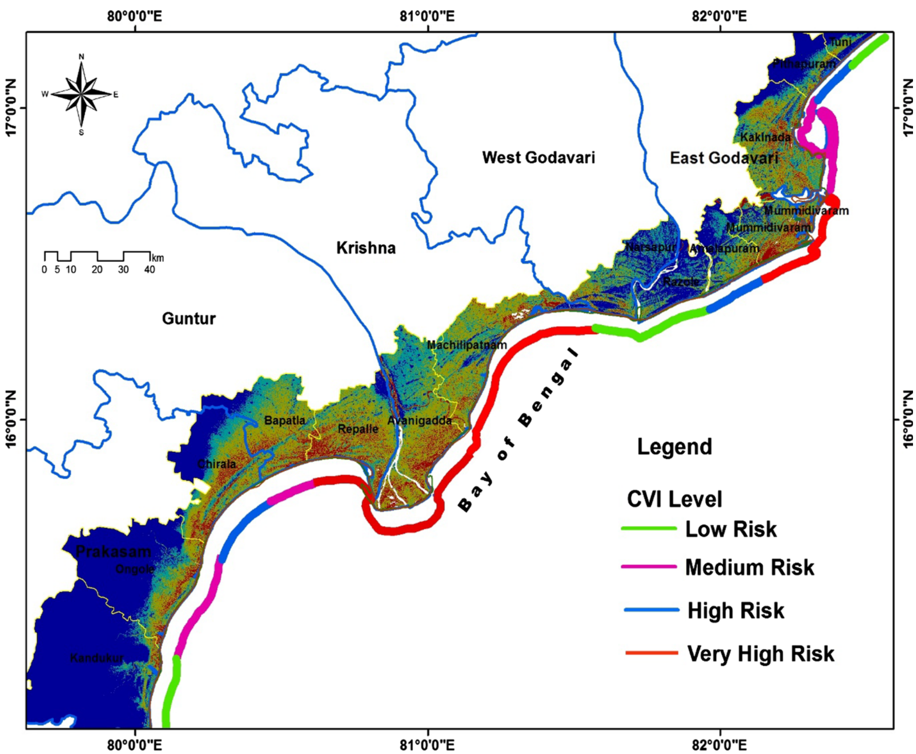

Fig. 9 Overall coastal vulnerability index of the Krishna–Godavari delta region

Table 5 Coastal vulnerability index values for the 14 coastal talukas and their vulnerability ranking of the Krishna–Godavari delta region

Talukas	Coastal vulnerability index (CVI)	CVI ranking according to percentile
Tuni	3.21	Low
Pithapuram	9.07	High
Kakinada	7.40	Medium
Mummidivaram	17.25	Very high
Amalapuram	11.01	High
Razole	1.85	Low
Narsapur	1.85	Low
Machilipatnam	7.86	Medium
Avanigadda	17.25	Very high
Repalle	14.77	Very high
Bapatla	6.23	Medium
Chirala	7.86	High
Ongole	5.24	Medium
Kundukur	3.70	Low

wave energy and comparatively high rate of shoreline erosion make the coast high vulnerable. While the talukas of Mummidivaram, Avanigadda and Repalle are classified as the very high vulnerable due to the presence of almost flat and low-lying surface with mudflats, backwaters/lagoons and mangrove swamp. Moreover, these coastal talukas are experiencing higher erosion rates for the last two decades. Even the small tidal range can reach far inland areas since the coastal gradient is extremely gentle of these coastal talukas.

Since the physical variables of the coastal vulnerability index, i.e., mean tidal range, significant wave height and sea level rise, were given the same risk value across the study coastal region, the risk-based relative vulnerability of all 14 talukas was consequently evaluated on the basis of geological variables, i.e., coastal regional elevation, coastal slope, geomorphology and rate of shoreline change. The talukas of Mummidivaram, Avanigadda and Repalle were considered as a very high vulnerable, which have experienced high erosion rates of more than 5 m per year and lower slope along the coastal region. In addition, these three coastal talukas are also vulnerable to coastal inundation and flooding due to their lower elevation, and extended mudflat and beach ridge complex with low-lying topography and mangrove forest, while the talukas of Tuni, Kundukur, Razole and Narsapur were considered as low vulnerability due to their high elevation, lower erosion rates and steep coastal slope along their coastal region. The slopes of the regions are very steep due to the presence of exposed rocks, rocky cliffs and mesas. So, the talukas of Tuni, Razole, Kundukur and Nasarpur signify as relatively lower vulnerable than the talukas of Repalle, Avanigadda and Mummidivaram.

5 Conclusion

In the light of the climate change-induced rising sea levels, a coastal vulnerability assessment is necessary to take some appropriate measures and adaptation strategies to protect the coastline with property and living inhabitants. Construction of vulnerability index of the coastal areas has various advantages. A coastal vulnerability index brings a qualitative assessment that helps to prioritize most significant issues that need to be addressed. The construction of this index enhances the analysis of subjective attributes, and it is useful in communicating and summarizing the vulnerability assessment results to stakeholders and decision makers. A coastal vulnerability index was developed for the 14 coastal talukas of Krishna–Godavari delta region by ranking four significant geological variables such as coastal slope, coastal geomorphology, rate of shoreline change, coastal elevation, and three physical variables including significant wave height, relative sea level rise and mean tide range indicating the risk level of the study coast. The study addressed that the geological variables are mostly significant than the physical variables that classify the talukas as a low, medium, high and very high vulnerability category. The coastal vulnerability index revealed that three (Mummidivaram, Avanigadda and Repalle) low-lying coastal taluka and three (Pithapuram, Amalapuram and Chirala) highly sensitive erosion-prone talukas are under very high risk zone, which calls for some protective measures and adaptation strategies to prevent the inundable coastal areas and inhabitants who, are hut-dwelling and socioeconomically more vulnerable. Recently, in the context of predicted climate change and sea level rise, the coastal vulnerability assessment of this type is more necessary for a proper and integrated coastal zone management. It is also expected that the vulnerability analysis and inundation scenario under climate change will be more useful in land use planning to protect community resources and for developing emergency management plans for coastal natural disasters like inundation as a result of sea level rise and tropical storms. This study of coastal vulnerability analysis provides reliable information to other researchers and planners to estimate the vulnerability index of their coastal regions. However, the integrated assessment of vulnerability along the coastal regions, considering a dynamic and valuable interaction between processes and sectors which makes an integrated assessment models, will be more useful for decision and policy making at different spatial scales.

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