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A new insight to vulnerability of Central Odisha coast, India using analytical hierarchical process (AHP) based approach

Mani Murali R.[1] · Ankita M.[1,2] · Vethamony P.[1]

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Abstract

The occurrence of the PHAILIN, HUDHUD cyclones in the Bay of Bengal region highlights the importance of continuous monitoring of this area from the coastal vulnerability perspective. The increase in the magnitude and frequency of coastal disasters is estimated to cause disastrous effects on the ever-increasing coastal population as well as the natural resources that are available in these regions. In this paper, the coastal vulnerability of a part of the Odisha coast, including the districts of Kendrapara and Jagatsinghpur, has been assessed on a relatively finer scale. These districts are reported to be the most vulnerable areas along the Odisha coast. A set of Physical–geological parameters and socio-economic factors are used to derive the vulnerability using AHP, and vulnerability maps are prepared to demarcate areas with different vulnerability. The Coastal Vulnerability Index (CVI) finally is grouped into the three vulnerability classes for the final coastal vulnerability map. Depending on this classification, approx. 35% of the coastline comes under high vulnerability, 39% under Medium and 26% under low vulnerability class. The coastline adjoining, Teisimouza, Barunei, Paradip, are the highly vulnerable zones whereas the shoreline between Jatardharmohan and Saharabedi comes under intermediate vulnerability zone. The results obtained can be used for prioritization of the most sensitive areas in this coastal belt for better strategic management.

Keywords Climate change · Physical vulnerability index · Socio-economic vulnerability index · Coastal vulnerability index · Analytical hierarchical process

Introduction

The intensification of both natural and human-induced climate change impacts demands a more objective perspective towards recognizing the critical vulnerabilities associated with the occurrence of natural hazards along the coastal regions. Some of the appropriate climate changes and their impacts include sea-level rise, the increase in the frequency and intensity of storms, coastal inundation associated with increased precipitation and shoreline erosion. Tide-gauge data reports values between 1 and 2 mm $yr.^{-1}$ for the twentieth century sea-level rise (Church et al. 2001). Further, IPCC (2007) estimated a warming of 0.2 C per decade. In turn, it would lead to an increase in sea level by as much as 1.5 m (Strohecker 2008). These projections have serious ramifications on coastal environments in the form of changes in the geomorphic characteristics of the shoreline, loss of land, salinization of soils and ground water as well as loss of flora and fauna.

Moreover, these vulnerable coastal regions face serious threats from the developmental activities that are carried out in these areas. Socio-economic pressures, intensive human alteration, and over-exploitation of coastal environments have reduced the resilience of the coastal system to a great extent, making it more susceptible to damage by natural calamities. IPCC (2007) reports that nearly 7 million people will be affected by a 1 m rise in sea level. Considering, the already large yet growing population of coastal residents, the increase in the frequency of natural hazards will thus have grave consequences in the form of loss of life and property (Pendleton et al. 2005), apart from the adverse effects on the coastal ecosystems.

From this perspective, understanding coastal hazards and managing risk exposure are essential pre-requisites for decision making for mitigating the impact of potential disasters and ensuring sustainable coastal zone management. The

✉ Mani Murali R.
mmurali@nio.org

1 CSIR-National Institute of Oceanography, Dona Paula, Goa, India

2 Present address: Indian Institute of Technology, Bombay, Mumbai, India

evaluation of the hazard potential of the natural as well as anthropogenic event involves identification as well as quantification of factors that contribute to risk and vulnerability (Boruff et al. 2005; Romieu et al. 2010). Turner et al. (2003) defined vulnerability as the degree to which a system is likely to experience harm by exposing to a hazard. In the present context, the coastal vulnerability can be described as the susceptibility of the natural system and coastal societies (persons, groups or communities) to coastal hazards. Therefore, vulnerability is a composite of multiple interacting factors emerging from the social, economic and environmental spheres of an exposed unit (Turner et al. 2003; Birkmann 2006). An efficient way of quantifying vulnerability is by constructing a vulnerability index based on several sets of indicators that result in the vulnerability of a coastal region. Formal vulnerability indices are an essential step towards realistic assessment of risk as they provide consistent and rapid characterizations across a various scale. However, coastal vulnerability assessments to climate change are mainly centered on sea-level rise and less focused on other climate change scenarios and even less on socio-economic changes (Nicholls 1995). This is restricting, as with the increase in human-induced climate change, such assessments need to address both climatic and non-climatic drivers. However, considering that climate change impacts and risks are very dependent on regional geographical features, climate and socio-economic conditions, it is desirable that impact studies should be performed at local or at the regional level (Torresan et al. 2012). Hence, over a period, there is an urgent necessity for suitable techniques for assessing vulnerability on a regional basis so that areas susceptible to various natural hazards can be identified within a coastal region and priorities can be set to ensure management on a finer scale (Nicholls 1995).

Coastal vulnerability study, particularly for sea level rise, was initially developed by Gornitz and Kanciruk (1989) for the United States. Subsequently, similar studies were carried out by several researchers along various coastal regions around the world (Thieler and Hammar-Klose 1999; Anfuso and Martinez 2009; Pendleton et al. 2005; Diez et al. 2007; Szlafsztein and Sterr 2007, Doukakis 2005a, b; Gorokhovich et al. 2014;). In India, coastal vulnerability studies have been carried out for the majority of coastal states of the country, mostly using physical variables as an input to the Coastal Vulnerability Index(CVI). Potential vulnerability for coastal zones of Cochin for sea- level rise scenario was calculated (Dinesh Kumar 2006; Mani Murali and Dinesh Kumar 2015). Dwarakish et al. (2009) estimated vulnerability of Udupi coast from few parameters. Kumar et al. (2010) studied the coastal vulnerability of the entire shoreline of Odisha using eight variables along with an additional parameter of Tsunami run-up. The vulnerability to multiple hazard scenarios along the coast of Chennai and Cuddalore–Villupuram was assessed by Mahendra et al. (2011) respectively. In a majority of these studies, CVI is expressed as a product derived as the square root of the ranking factors divided by the number of factors (Thieler 2000). On the other hand, Hegde and Raju (2007) used the sum of the value of each variable divided by the number of variables. Rao et al. (2008) calculated the CVI for Andhra Pradesh coast by taking the summation of the variables considered in the ranks of each multiplied by their corresponding weights on the Andhra Pradesh coast. Sudha Rani et al. (2015) reviewed many coastal vulnerability studies along the Indian coast.

The major constraint in the above studies is that most of these focus mainly on the physical factors affecting coast rather than on socio-economic or ecological parameters (Boruff et al. 2005; Gorokhovich et al. 2014); moreover, the weights calculated for the indices are deduced using an individual's judgment. Adger (1996) suggests the addition of Socio- economic indicators is an important consideration, as it makes a significant contribution to the vulnerability analysis and also provides valuable comparative information for policy makers and emergency managers. Combining physical as well as socio-economic factors provides an over-all estimate of the vulnerability of the community and is termed as place vulnerability (Cutter 1996; Cutter et al. 2003).

Few studies have been carried out recently that include socioeconomic indicators in their vulnerability index. Boruff et al. (2005) computed the overall vulnerability score by considering socio-economic variables. McLaughlin and Cooper (2010) developed a three sub-indices, including a socioeconomic sub-index to assess the infrastructure potentially at risk to coastal hazards. Willroth et al. (2012) studied the vulnerability of coastal communities in southern Thailand. Duriyapong and Nakhapakorn (2011), considered socio-economic parameters along with physical factors for the vulnerability of the Samut Sakhon coast of Thailand and found that the socio-economic variables contributed more to the spatial variability of the CVI than the physical variables. Similar studies on social vulnerability were carried out by Szlafsztein and Sterr (2007), Thatcher et al. (2013) for the state of Pará in Brazil and Gulf of Mexico coast respectively. Kunte et al. 2014 studied the coastal vulnerability of Goa on the west coast of India by including two socio-economic parameters: population and tourist density data, along with the other physical factors. Mani Murali et al. (2013) added four socio-economic factors: population, land use/land cover (LU/LC), roads and location of tourist areas along with seven physical -geological parameters to calculate the CVI for the Puducherry coast. The weight of each parameter in this analysis was derived using the Analytical Hierarchical Process(AHP). A similar study was carried for the South Gujarat coast by Mahapatra et al. (2014).

In this paper, we have tried to calculate the coastal vulnerability index for a part of the coastline of the state of Odisha, East Coast of India, to multi- hazard scenarios. We have followed a procedure similar to Mani Murali et al. (2013), wherein we have used Analytical Hierarchical Process

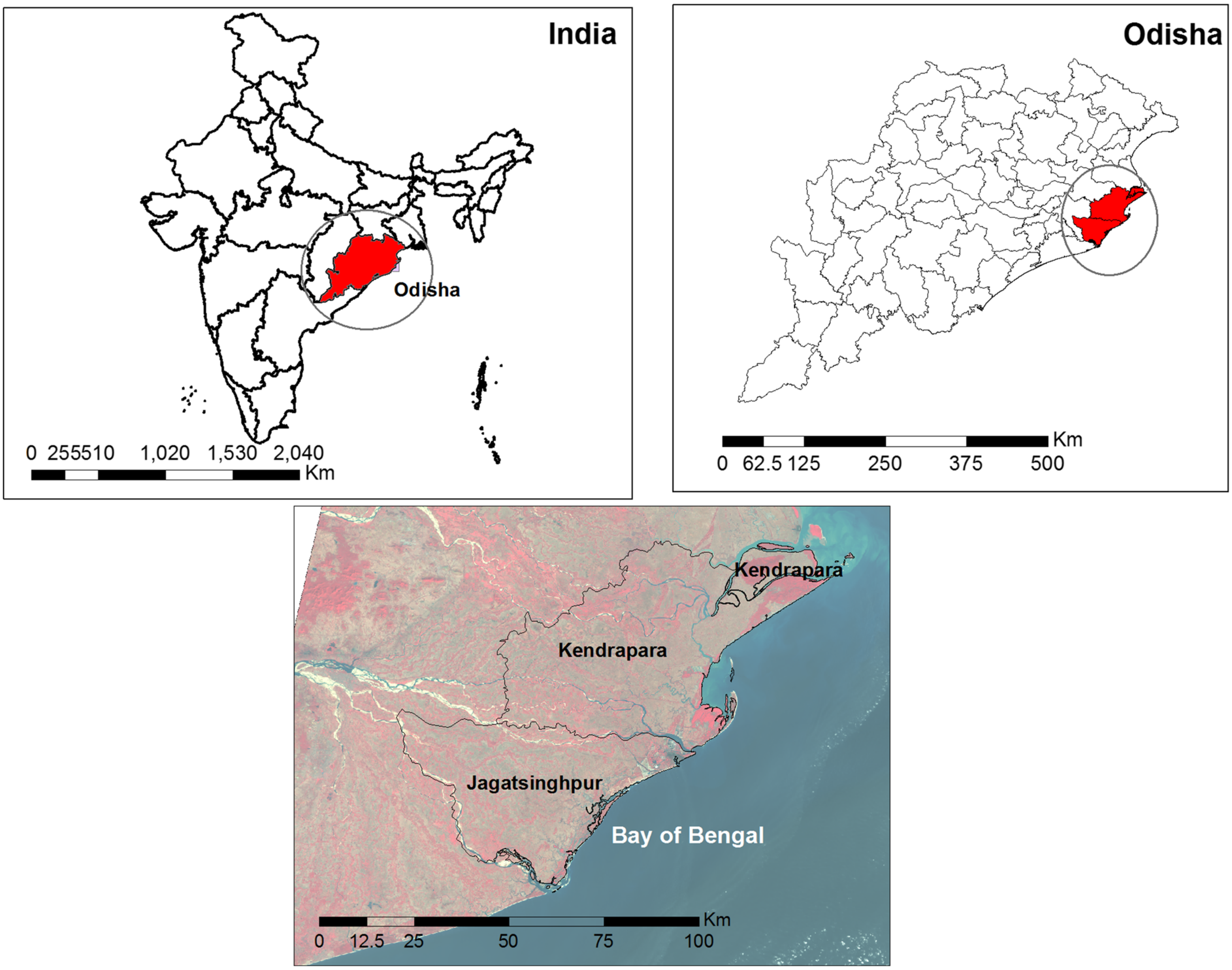

Fig. 1 Map showing location of study area

(AHP) for deriving the calculation of Physical Vulnerability Index (PVI), Social Vulnerability Index (SVI) and subsequently the Coastal Vulnerability Index (CVI). AHP (Saaty 1977, 1980; and Saaty and Vargas 1991) is a multi-criteria decision analysis method that allows a better understanding of the complex decisions by decomposing the problem into a hierarchical structure. According to Ju et al. (2012), AHP aids in arriving at a scale of preference amongst the available alternatives by employing a pair-wise comparison between the decision elements and ranking them based on their relative importance. They performed a GIS-based suitability assessment for Laoshan district wherein they have used AHP as a method to derive weights. Mani Murali et al. (2013) suggested that there are several advantages of this method over the traditional methods of calculating the weights for vulnerability. First, in the case of deriving coastal vulnerability where the data is highly variable in case of its spatial and temporal scale, AHP enables one to take expert opinion into consideration as well as to convert qualitative information to total weights. Moreover, AHP allows pair -wise comparisons which ensure prioritization of various variables depending on the region under consideration. Finally, AHP derived weights are relatively more logical by the test of consistency that helps to check the effectiveness of the judgments, further making the study more reliable.

However, although extensively used as a decision-making tool in landslide studies and research related to flood hazard zonation, AHP has been limitedly used in coastal vulnerability studies. Ozyurt et al. (2010) assessed the coastal vulnerability using AHP for the Turkish Coast. Chang et al. (2012) and Yin et al. (2012) used AHP to prioritize the protection of the Miaoli coast, Taiwan and assess the coastal vulnerability to sea level rise from the Chinese coast respectively. Le Cozannet et al. (2013) discuss the nuances of using AHP for coastal vulnerability at a regional scale. In this study, the approach mainly consists of using this method to convert the information from experts, simple models, and data into comparable quantitative data and to aggregate this data into a single mapping framework. Our main aim through this research is to

Table 1 Data used for the study (modified from Mani Murali et al. 2013)

Parameter	Source	Period
Physical and geological parameters		
Coastal slope	Modified Etopo5 from a data repository of National Institute of Oceanography. (Sindhu et al. 2007)	NA
Geomorphology	LISS III	2014
Elevation	SRTM - 30 m resolution	2014
Shoreline change	Landsat MSS, TM, ETM, IRS LISS III	1990, 2000, 2009, 2014
Sea level change	Unnikrishnan and Shankar 2007, Kumar et al. 2010	40, 100 years
Significant wave height	ECMWF Re-Analysis Interim (ERA-Interim) in Netcdf format (source: http://apps.ecmwf.int/datasets/data/interim_full_daily/)	1979–2012
Tidal range	Prediction tool and reported values in the National Assessment of Shoreline Change: Odisha Coast 2011	2011
Socio-economic parameters		
Population	Census 2011 report, http://censusindia.gov.in/	2011
Land-use/land-cover	Landsat OLI	2014
Road network	GIS-generated data (Source)	NA
Tourist places	GIS-generated data (Source)	NA

contribute to the process of continuous assessment of this region of coastal vulnerability. The final result of the analysis includes the identification of the vulnerability hotspots and prioritization of these areas for intervention. This part of the coast frequently experiences storm surges that are triggered by cyclones and other atmospheric disturbances that develop over the Bay of Bengal or in the Andaman Sea. The recent cyclone “Hudhud” was a very severe cyclonic storm in the North Indian Ocean which caused a landfall near Vishakhapatnam on October 12, 2014. During this period, the Odisha government placed 16 districts, including Kendrapara and Jagatsinghpur, on high alert. The region experienced high winds (90 km/h) and heavy rainfall, with some parts of Southern Odisha facing a power disruption. It is predicted that with the increase in sea-surface temperature due to global warming, the frequency and intensity of cyclonic activity and storm surges would increase (Unnikrishnan et al. 2006) resulting in the greater destruction of life and property. Thus, the maps prepared can be used by the government as well as private coastal zone managers for better disaster mitigation and management. Additionally, we also intend to highlight the efficiency of this methodology in calculating coastal vulnerability on a regional scale for the various regions of the country.

Study area

Odisha is a state on the eastern coast of India located at 17° 49′ - 22° 34’ N Latitude & 81° 29′ - 87° 29′ E Longitude bordering the state of West Bengal in the north and Andhra Pradesh at the

Table 2 Vulnerability ranking criteria (modified from Mani Murali et al. 2013)

Parameter	Coastal vulnerability ranking			
	Very Low (1)	Low (2)	High (3)	Very High (4)
Coastal slope (degrees)	>1	>0.2 and < =1	>0.1 and < =0.2	>0 and < =0.1
Geomorphology	Rocky coast	Embayed / indented coast	Dunes/estuaries and lagoons	Mudflats, mangroves, beaches, barrier, spits
Elevation (m)	>6	>4 and < = 6	>2 and < =4	>0 and < =2
Shoreline change (m/yr)	Accretion >1	Accretion <1	Erosion <1	Erosion >1
Sea level change(mm/yr)	<0	> 0 and < =1	> 1 and < =2	>2
Significant wave height(m)	<0.55	>0.55 and < =1	>1 and < =1.25	> 1.25
Tidal range (m)	<1	>1 and < 4	> 4 and < 6	>6
Population (number)	< 50,000	>50,000 and < = 100,000	>100,000 and < =200,000	>200,000
Land-use/land-cover	Barren Land	Vegetated land or open spaces	Agriculture/ fallow land	Urban, ecological sensitive regions
Road network (distance from)	2 km buffer	1 km buffer	500 m buffer	250 m buffer
Cultural heritage (tourist places)	Absent	NA	NA	Present

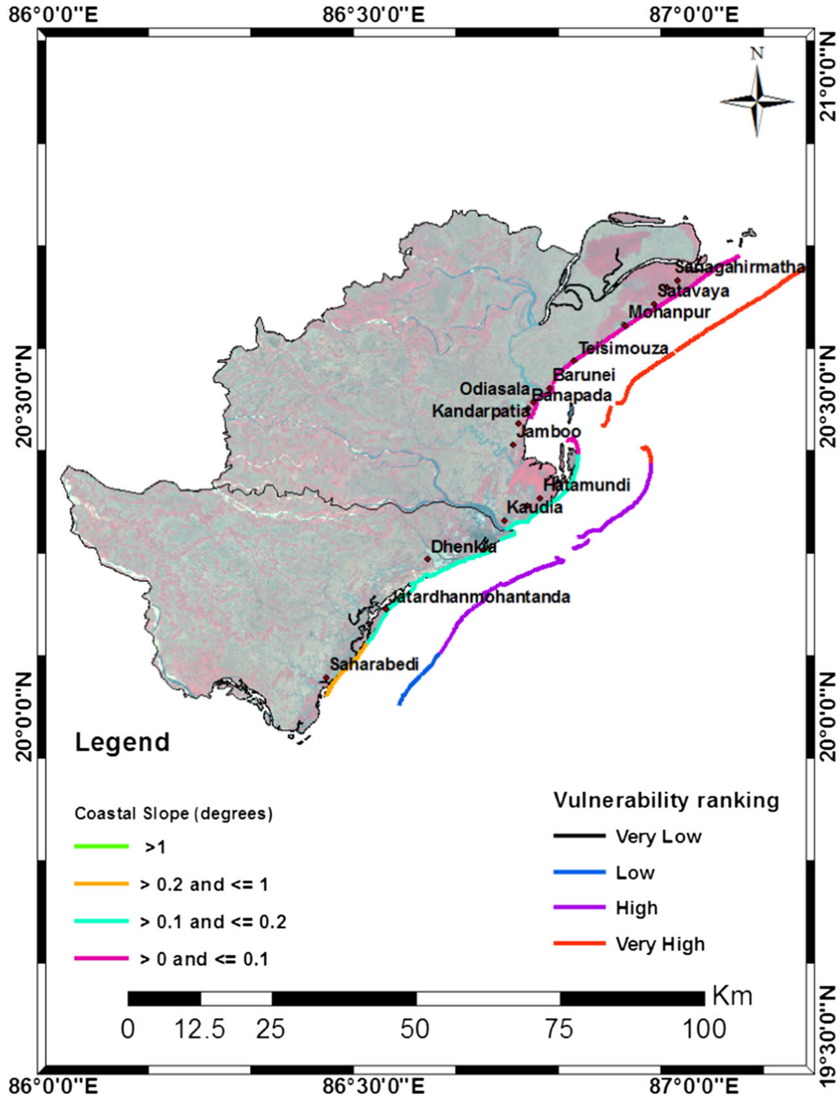

Fig. 2 Vulnerability ranking of coastal slope

southern tip. The coastline of the state of Odisha is approximately 480 km long and consists of six coastal districts.

The study area (Fig. 1) consists of 2 coastal districts of the state of Odisha, namely Kendrapara (68 km) and Jagatsinghpur (67 km) located between 87.1 E 20.758 N and 86.373 E 19.958 N. The climate of Odisha is tropical with three major seasons- summer, rains, and winter. The average rainfall is measured to be about 1482 mm (varies between 1200 mm to 1700 mm.) Tides in the state are of a mixed type, predominantly semi -diurnal in nature with an average spring tidal range of 2.39 m and neap tidal range of about 0.85 (Kumar et al. 2010). The tidal range along the coastal stretch under consideration is between 2.5 m and 3.5 m. The mean significant height ranges between 1.25 and 1.40 m, mostly plunging from June–December and surging from January to May. The combined delta of Baitarani, Brahmani, and Mahanadi form the coastal plains of these regions. The Hukitola bay is formed near to the north of Mahanadi Estuary, and other depositional islands are Shortt's Island and Wheeler Islands.

The Bay of Bengal is prone to severe tropical cyclones; moreover, past records suggest that the state of Odisha has witnessed multiple disasters such as storm surges and tsunamis, which have affected the local population as well as the state's economy. This region also experiences flooding events almost every year by the Mahanadi River, which overflows its banks during the monsoon. Previous work on the coastal vulnerability of Orissa, by Kumar et al. 2010 reports that a significant part of the Jagatsinghpur- Kendrapara coastal stretch comes under medium to high vulnerability category. Therefore, it is imperative to monitor the vulnerability of this region continuously at a finer spatial scale for better disaster preparedness, mitigation, and management.

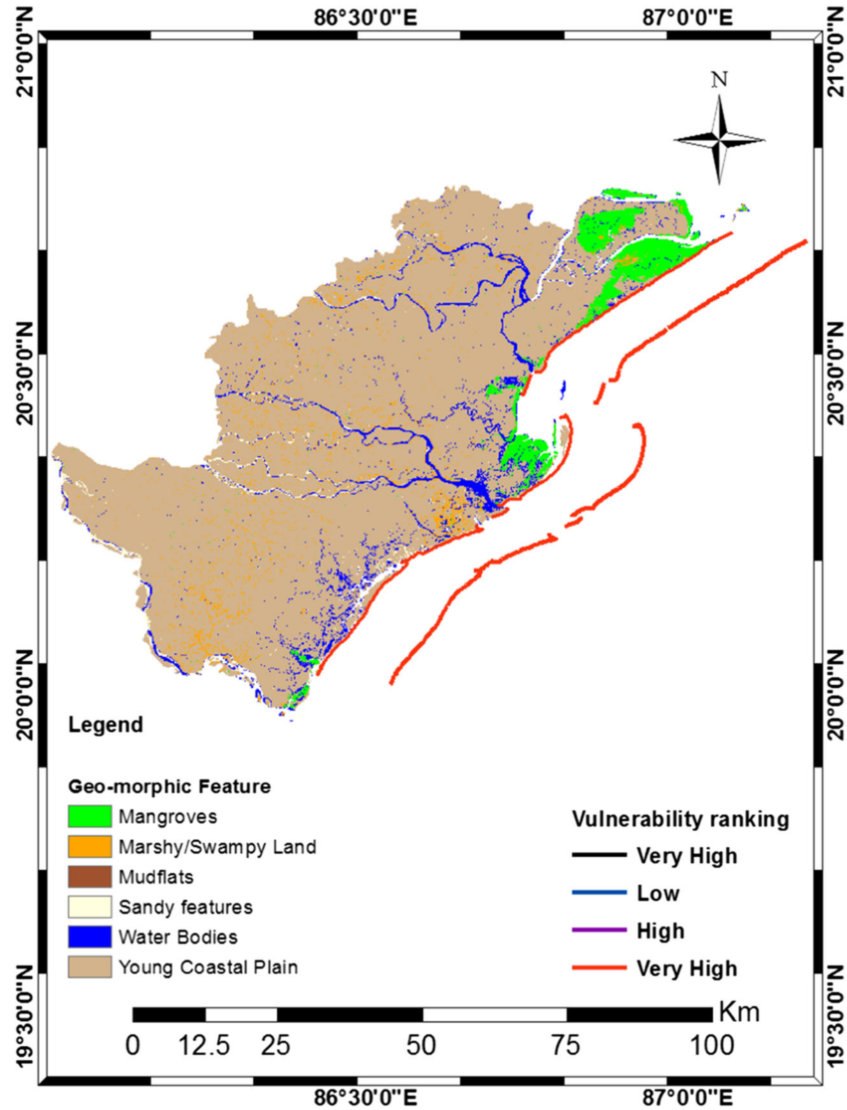

Fig. 3 Vulnerability ranking of geomorphology

Methods and procedures

The IPCC defines vulnerability to climate change as a function of a system's exposure and sensitivity to climate(IPCC 2007). Considering that parameters affecting the vulnerability of an area differ region wise within a country, it is imperative to devise a methodology which can be applied to a varied scope of areas. The standard method of quantifying vulnerability is by using a set or composite of indicators (Moss et al. 2002; Kaly et al. 2002). Indices are an effective way to monitor trends and explore the conceptual framework of vulnerability. According to Klein et al. (2003) indicator approach is an advantageous method as it combines a coastal system's vulnerability to alteration, to its ability to regulate itself to the ever-changing environmental conditions and hence gives an estimate of the system's vulnerability to climatic events. Index-based tools are particularly useful to make an initial assessment of the vulnerability of different coastal areas to climate change, and support adaptation planning and regional integrated coastal zone management (ICZM) strategies (Torresan et al. 2012).

In the present study, the coastal vulnerability index (CVI) is calculated by combining the Physical Vulnerability Index (PVI) as well as Social Vulnerability Index (SVI). Seven variables are used to calculate the PVI: coastal slope, coastal geomorphology, regional elevation, shoreline change rate, the sea- level change rate, mean tidal range, and significant wave height. The Social Vulnerability Index (SVI) is calculated using four parameters such as population, land-use/land-cover, road network and cultural heritage (tourist locations). Although mostly similar to the index based approach used by Pendleton et al. (2005), Thieler and Hammar-Klose (1999),

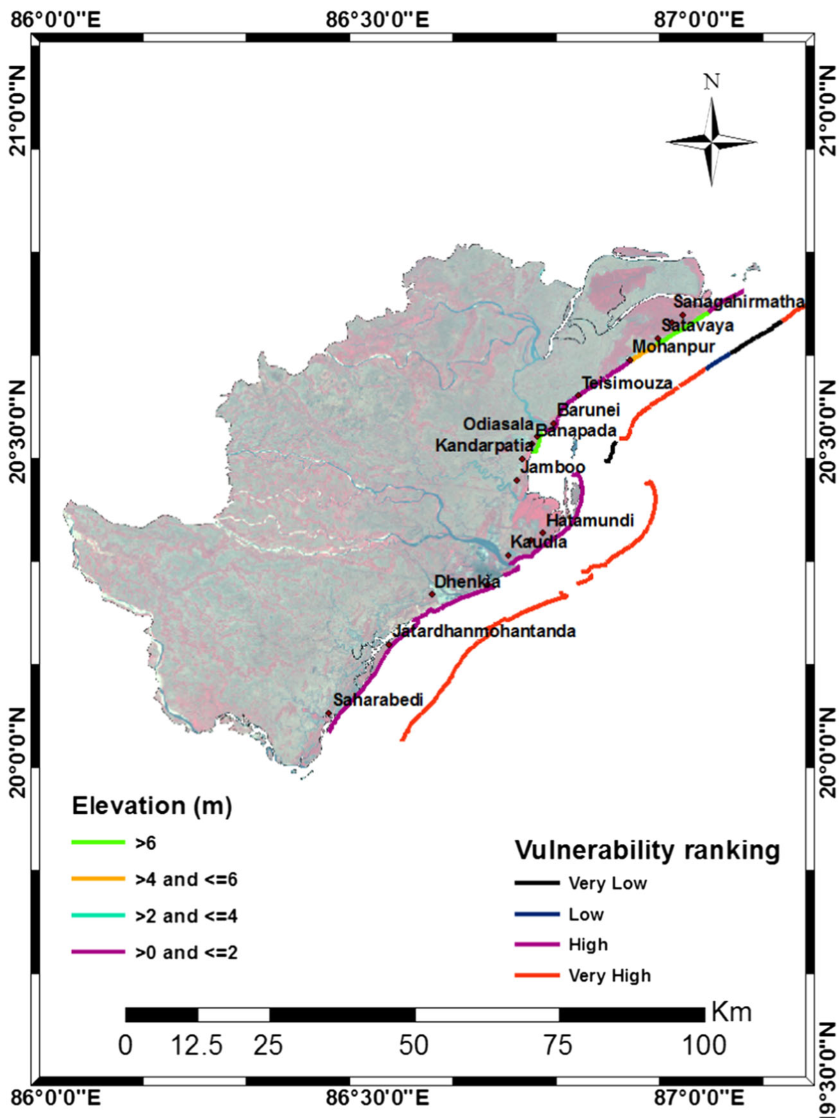

Fig. 4 Vulnerability ranking of elevation

and Thieler (2000), it differs significantly in the process used to calculate the weights for each parameter. Here, Analytical Hierarchical Process (AHP) has been used to calculate the weights (Mani Murali et al. 2013) which are eventually used for estimating the indices. The data for each parameter are procured from several sources such as satellite datasets, GIS databases, numerical modeling, etc. (Table 1) and further processed and analyzed for final classification into vulnerability classes. A scoring method is used to define relative rankings within the vulnerability classes using a 1–4 range (Very low, low, high, and very high). The most significant advantage of using the process of AHP is the incorporation of expert judgment in the decision-making of the scores and weights for the study. A four member interdisciplinary panel of experts (consisting of a geologist, one oceanographer, an environmentalist and an ocean engineering specialist) was set up to give scores for each parameter to deduce the weights for the vulnerability assessment. The final vulnerability classes and scores assigned are Geomorphology, Land-use/Land-cover, Road network, Cultural heritage or quantitative such as coastal Slope, elevation, Shoreline change, Sea level change, significant wave height, tidal range, population in nature. An overall Coastal Vulnerability Index (CVI) is computed for each 5 km segment (total of 23 segments) of the shoreline.

The following section discusses the significance of the parameters considered, as well as the ranking criteria (Table 2) obtained, based on expert judgment and literature survey.

Physical and geological parameters (PVI)

Seven physical–geological parameters: coastal slope, geomorphology, regional elevation, shoreline change, sea level rise, significant wave height and tidal range are considered for studying the PVI index.

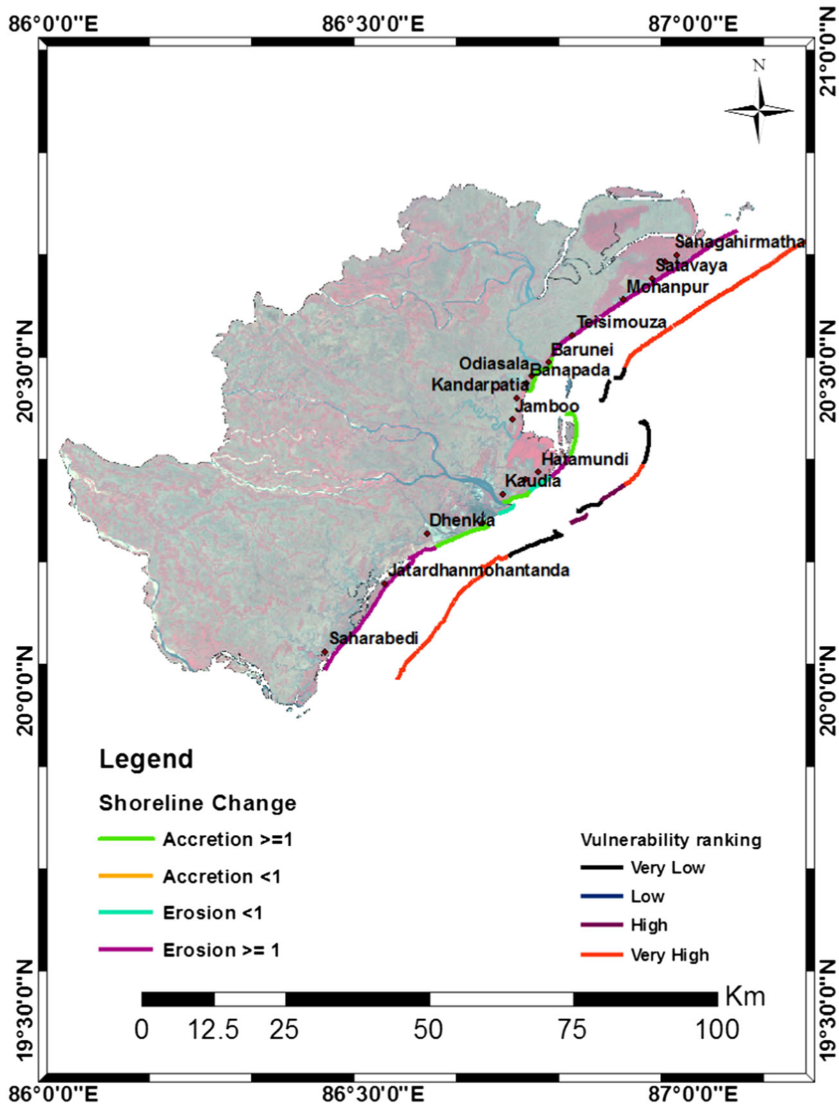

Fig. 5 Vulnerability ranking of shoreline changes

Coastal slope

The coastal slope parameter provides an understanding of the susceptibility of the coast to inundation and rate of shoreline retreat (Aboudha and Woodrofe 2006; Thieler 2000). The extent of inundation is controlled largely by the slope of the land: a gently sloping coast would be more vulnerable to any rise in sea level would inundate large extents of land; on the other hand, on a steep coast, the consequence of sea-level rise would be insignificant. The coastal slope is the ratio of altitude change to the horizontal distance between any two points on the coast, perpendicular to the shoreline, and coastal slope can be estimated using nearshore bathymetry. The term "bathymetry" refers to water depth below sea level, from the coast to the open ocean. In this study, an improved shelf bathymetry derived from Sindhu et al. (2007) is used for estimating the coastal slope for this region. This data is from the National Institute of Oceanography, India, data repository and the slope is computed using the ArcGIS 10.1 slope tool. The slope layer (Fig. 2) is classified according to the ranking criteria. Only two classes are significant in this region, high and very high. The majority of the coastal stretch falls in the range of >0.1 and < 0.2, i.e. the high vulnerability category. The extent of shoreline from Badagahirmatha to Mohanpur and from Karanjia to Jamboo belongs to the very high vulnerability class.

Geomorphology

Geomorphology is the study of landscapes and entails the systematic description of landforms and the analysis of the processes that create them. Thieler and Hammar-Klose (1999) suggests that geomorphology is a significant parameter that determines the response of the coast to sea level rise. The study of geomorphology provides the relevant

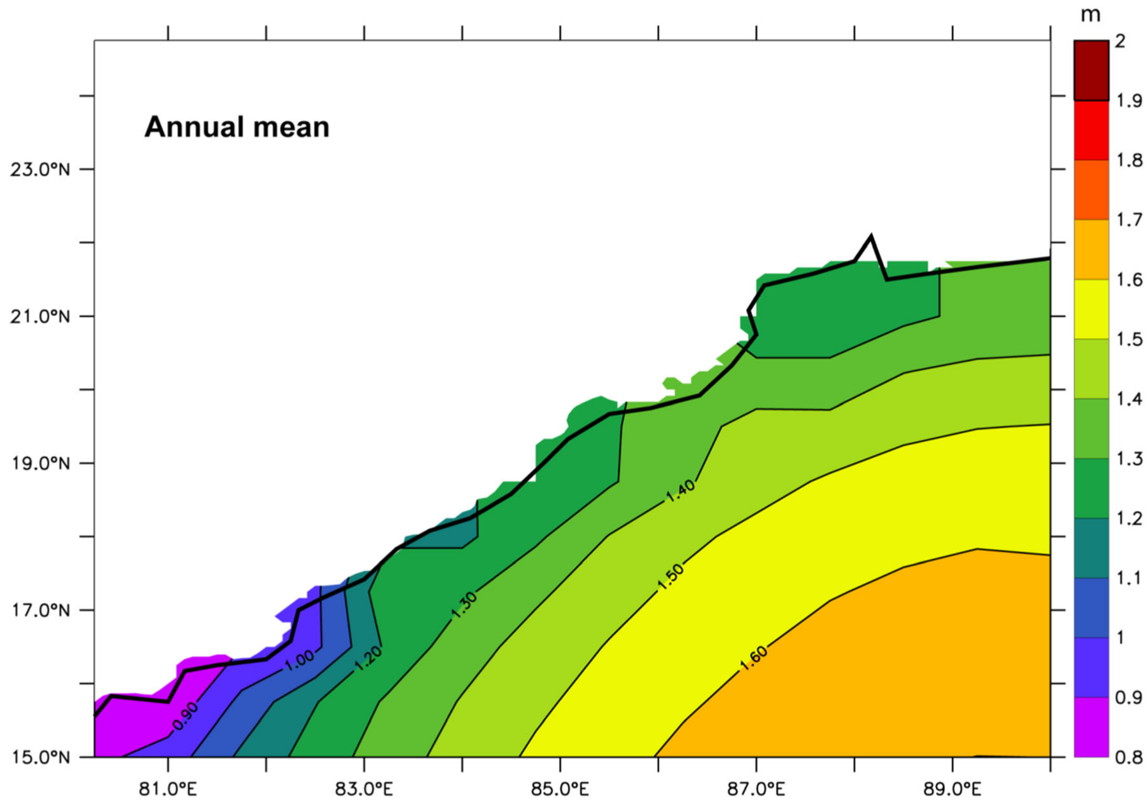

Fig. 6 Map of annual Significant Wave Height (SWH)

information regarding the features that are extremely vulnerable to the current scenario and would be increasingly susceptible to future climatic events. According to Kumar et al. (2010), Coastal geomorphology is a result of prevailing geomorphic processes that were forced to attain the present morphology. Hence, these features act as indicators of the coastal processes that act on it.

The detailed geomorphological map (Fig. 3) for the study region was prepared using Landsat imagery obtained from the USGS Earth explorer. The major landforms of the Odisha coast are mangroves, marshy/swampy lands, mudflats, and beaches or shoreline features. Odisha is characterized by river deltas. The study region mainly forms the middle coastal plain and comprises the compound deltas of Baitarani, Brahmani, and Mahanadi. There are two islands off the Odisha coast, off the Mahanadi Estuary, which are depositional islands. They are Shortt's Island and Wheeler Island, off Maipura and Dhamra river mouths. Only one bay, the Hukitola bay of the Jambu Dweep has been formed because of the huge complex spit built to the north of the Mahanadi Estuary. Mangrove patches can be seen along the Gahirmatha Coast, between Dhamra River and Maipura Nadi (Bhitarkanika Mangroves) along the Mahanadi River. Due to the presence of extensive coastal features this region mainly comes under very high vulnerability Zone.

Regional elevation

Regional elevation can be defined as the average height of a particular area above mean sea level. It is a critical factor in assessing potential impacts in the areas that are vulnerable to the inundation response to rising seas. The primary goal of evaluating this parameter is to quantify the various effects of sea-level rise. Coastal areas at higher elevation provide more resistance to inundation due to rising sea levels, tsunamis and storm surge and hence are considered less susceptible while regions having low elevations are considered highly vulnerable.

A commonly used approach to identify and quantify the extent of land vulnerable to sea-level rise is the use of elevation data such as topographic maps of digital elevation models. In the current study, the regional elevation is derived using the Shuttle Radar Topography Mission (SRTM) data, which is readily available from Earth explorer Site (http://earthexplorer.usgs.gov/). This data has been used to generate a digital topographic map (Fig. 4) of the Earth's land surface with data points spaced every 1 arcsec (approx. 30 m).

This extent of Odisha coast covers all the four vulnerability classes of regional elevation. However, the majority of the shoreline comes under very high class, making this region very vulnerable to sea-level rise and coastal inundation.

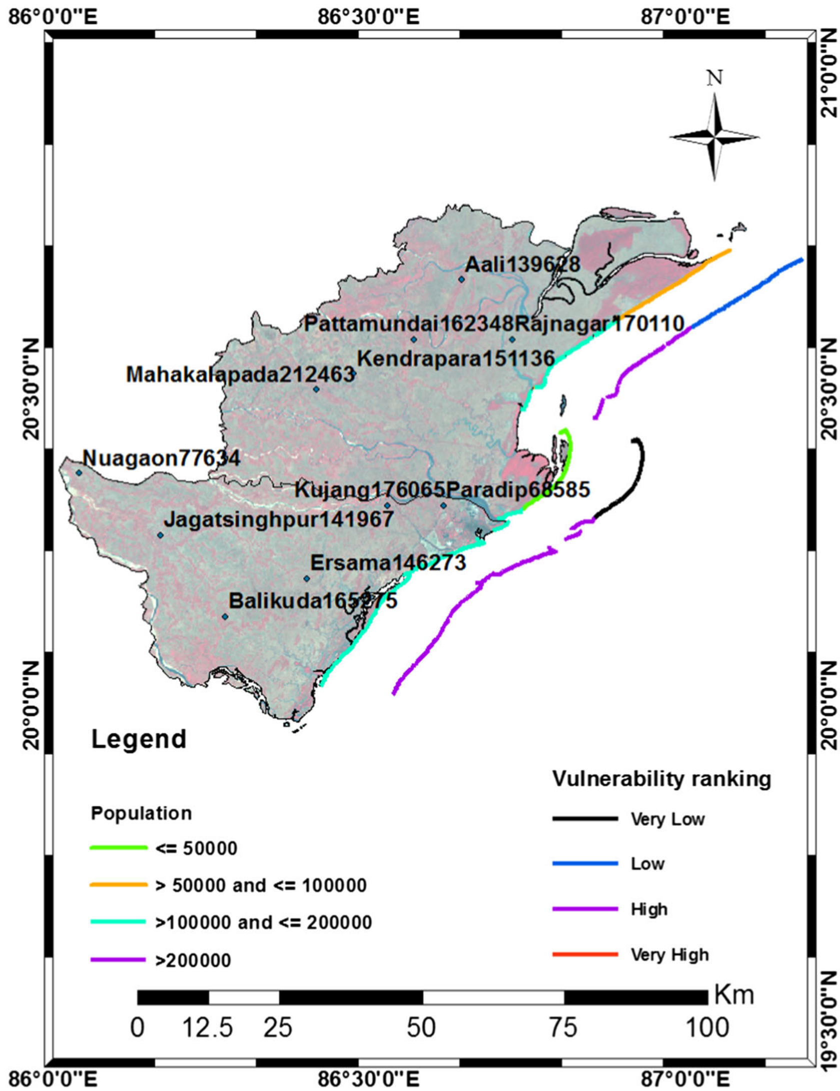

Fig. 7 Vulnerability ranking of population

Shoreline changes

According to an idealized definition provided by Dolan et al. (1991) shoreline is defined as the physical interface between land and water. Coastlines/shorelines are sensitive ecosystems that provide various services and have ecological value. Shoreline positions change continuously temporally, because of cross-shore and alongshore sediment movement in the littoral zone due to the dynamic nature of water levels at the coastal boundary (e.g. waves, tides, groundwater, storm surge, setup, run up, etc.) (Boak and Turner 2005). Shoreline changes result from the breaking of waves and currents in the nearshore zone which are responsible for the transport of shoreline sediments. From the vulnerability point of view, eroding coastlines are considered highly vulnerable because of the resultant loss of natural as well as anthropogenic resources linked to them, whereas accreting coastlines are considered less vulnerable, as they result in the extension of land areas by moving towards the ocean. Coastal management and engineering design require pertinent information about where the shoreline is, where it has been in the past. Mani Murali et al. (2009), (2015) reported shoreline movement in this region. For the coast of Odisha, the shoreline change has been done using temporal data from LANDSAT MSS, TM, ETM and LISS III data of the years - 1990, 2000, 2009, and 2014 which were further processed using ERDAS software. Further, the extracted shorelines are vectorized to calculate the shoreline change using the DSAS tool(USGS 2005). The transects are maintained at an interval of every 250 m. The DSAS tool calculates several statistics which are useful for understanding the shoreline trends from a temporal perspective. End Point Rate (EPR) and Net Shoreline Movement (NSM) were used for finding out the changes on the shore. The shoreline has been ranked based on whether they are accreting and eroding into four classes. For this coast, all the four categories, very high, high, low and very low, can be observed. The shoreline

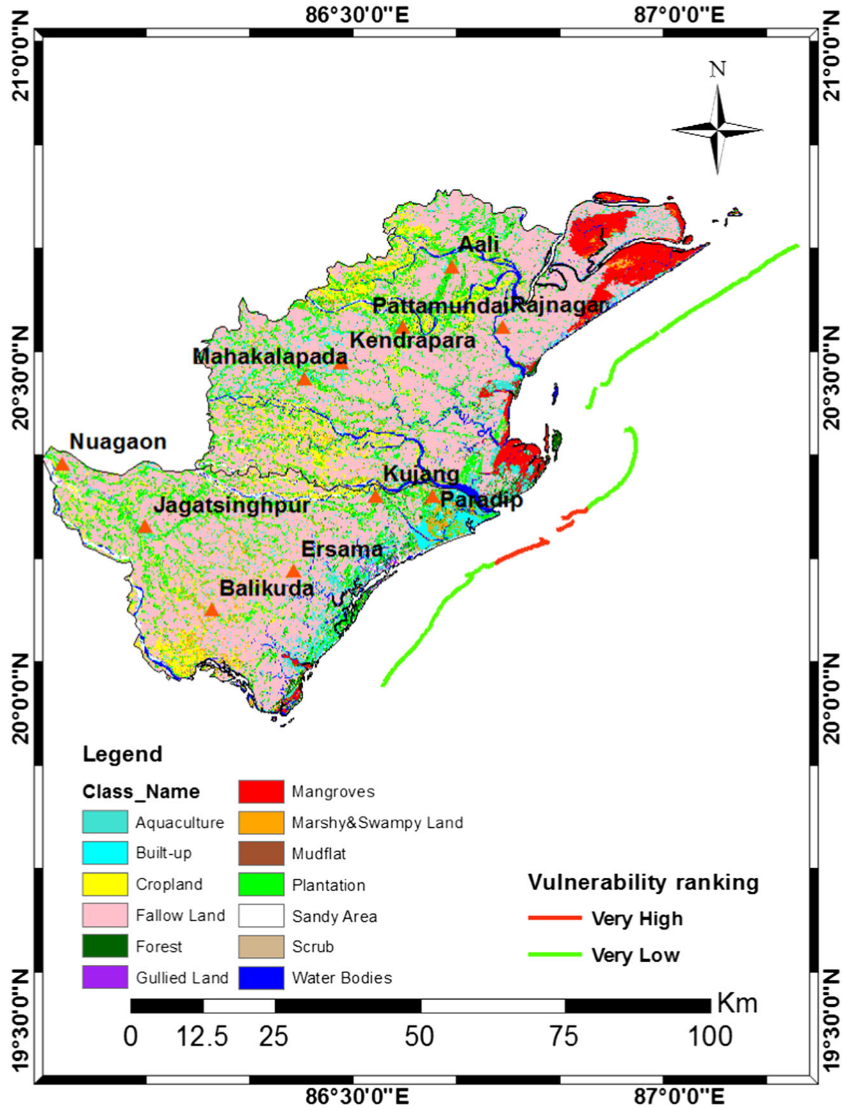

Fig. 8 Vulnerability ranking of land use/land cover

extent from Sanagahirmatha to Odiasala, Jatardharmohan to Saharbedi shows very high erosion. The south of Paradip port shows very high accretion (Fig. 5).

Sea- level changes

Mean sea level is described as a tidal datum that is the mean of hourly water elevations observed over a specific 19 yr. cycle. Sea level behavior is an important signal for tracking climate change. Sea Level Rise (SLR) is contributed by thermal expansion of sea water and land ice melting (IPCC 2007). Apart from being a threat to coastal habitation and environments, sea level rise corroborates other evidence of global warming.

According to a previous study on sea level rise for the Odisha coast done by Kumar et al. (2010), the sea level change rates along the coastal stretches of Kendrapara and Bhadrak districts is between 0.1 and 1.0 mm/y. However, for our study, we have considered the value estimated by Unnikrishnan and Shankar (2007) for the North Indian Ocean coasts i.e. a regional average of 1.29mmyr − 1. As the scoring in the study varies in between 1 and 4, we have assigned the coast a risk rating of 3, the high vulnerability class. Mani Murali (2014) assessed the inundation regions in this area due to different sea level rise scenarios.

Significant wave height (SWH)

SWH is defined as the average of the highest one-third (33%) of waves that occur in a given period. Significant wave height (SWH) is used as a proxy to wave energy and is essential for studying the vulnerability of shorelines. Further, Wave energy is directly related to the square of wave height by the following formula:

$$E = 1/8\rho g H^2,$$

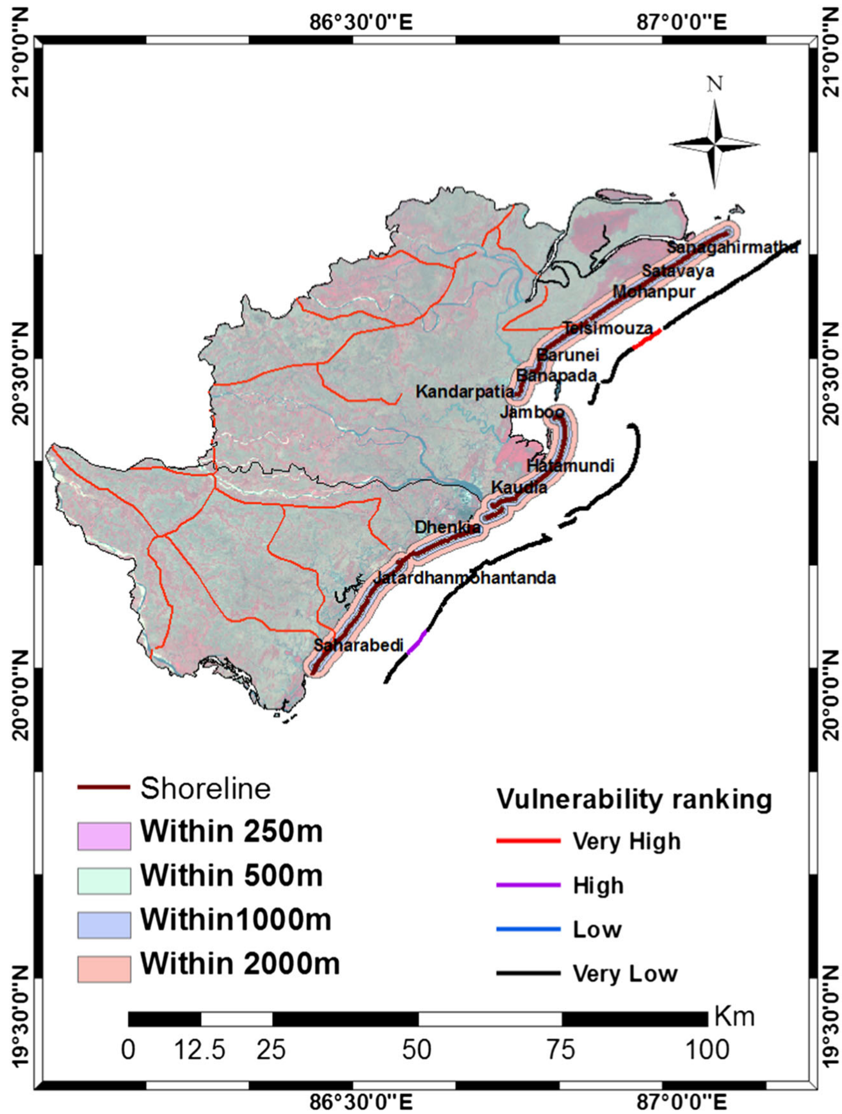

Fig. 9 Vulnerability ranking of road network

An increase in wave height triggers erosion and inundation along the shore, causing loss of land. Hence, concerning vulnerability coastline experiencing greater wave heights are considered more vulnerable that those who are exposed to low wave heights. Four times daily significant wave height values with spatial resolution 0.75-degree latitude × 0.75-degree longitude for the period January 1979 to December 2012 was extracted from ECMWF Re-analysis Interim (ERA-Interim) in NetCDF format (Source: http://apps.ecmwf.int/datasets/data/interim_full_daily/). Then annual mean has been calculated to understand the average wave height in the study region. Fig. 6 shows the annual significant wave height; wherein this region falls in the range of 1.2 m to 1.4 m. The entire shoreline falls in the very high vulnerability class.

Tidal range

The longest oceanic waves are those associated with tides and are characterized by the rhythmic rise and fall of sea-level over a period of half a day or a day by the effects of forces of the moon and the sun. The tidal range is described as the vertical difference (in m) between the high tide and consecutive low tide. Strong waves associated with high tidal ranges lead to greater erosion and sediment transport (Gornitz et al. 1994; Kumar et al. 2010). Hence, according to Gornitz (1991), macro- tidal regions are more vulnerable than micro-tidal areas. Tides in the Odisha coast are characterized by "mixed type" predominantly semi-diurnal. The average spring tide range is 2.39 m, and the average neap tidal range is 0.85 m. The shoreline along the coastal stretches of northern Puri, Jagatsinghpur,

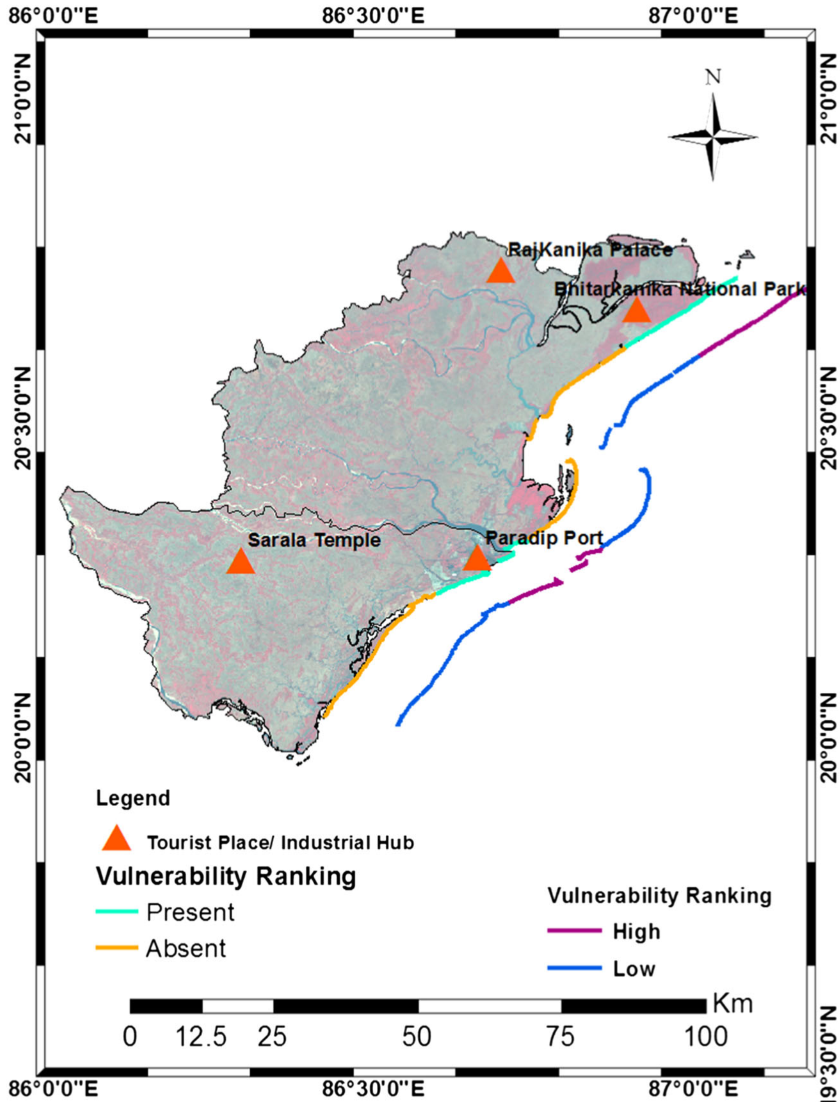

Fig. 10 Vulnerability ranking of road network

Kendrapara, Bhadrak and Southern Balasore fall in the tidal range of 2.5 m and 3.5 m (The National Assessment of Shoreline Change: Odisha Coast 2011; Ramesh et al. 2011, Kumar et al. 2010). According to the ranking adopted by us, the study area falls under the category of low vulnerability.

Table 3 Comparison matrix of physical-geological variables

	Tidal range	Sea level	Significant wave height	Shoreline changes	Elevation	Geomorphology	Slope
Tidal range	1.00	0.50	0.33	0.20	0.14	0.11	0.11
Sea level	2.00	1.00	0.33	0.25	0.20	0.13	0.11
Significant wave height	3.00	3.00	1.00	0.33	0.25	0.17	0.14
Shoreline changes	5.00	4.00	3.00	1.00	0.33	0.20	0.17
Elevation	8.00	5.00	4.00	3.00	1.00	0.33	0.25
Geomorphology	9.00	8.00	6.00	5.00	3.00	1.00	0.33
Slope	9.00	9.00	7.00	6.00	4.00	2.00	1.00
Column total	37.00	30.50	21.67	15.78	8.93	3.94	2.12

Table 4 Comparison matrix of socio-economic variables

	Cutural heritage	Road network	LU/LC	Population
Cutural heritage	1.00	0.33	0.20	0.11
Road network	2.00	1.00	0.25	0.11
LU/LC	5.00	4.00	1.00	0.20
Population	9.00	9.00	5.00	1.00
Column total	17.00	14.33	6.45	1.42

Socio-economic parameters

Population

The magnitude of a coastal disaster is often represented according to the effect it has on the population residing in it. Therefore, the population is one of the primary socio-economic variables influencing the vulnerability of a region which is essential to understand the dimension of a calamity. In the present study, the census data of 2011 is considered to find areas with a higher population distribution in comparison to others. A population map (Fig. 7) is prepared in the GIS environment where the individual polygons represent the two districts of Kendrapara and Jagatsinghpur, and the individual point features represent the sub-districts with their corresponding population.

Land use/land cover

Accurate and current Land Use/Land Cover (LU/LC) change information is necessary to understand the environmental consequences (Giri et al. 2007). An LU/LC map is essential to demarcate the various LU/LC classes in a region and assess their role in accelerating or diminishing the vulnerability of an area. The primary consideration here is the urban class, which is given the high vulnerability ranking from the socio-economic point of view. The other classes are given lesser priority; the general types are taken into consideration under the geomorphology parameter. An LU/LC map (Fig. 8) is generated using supervised classification techniques in ERDAS Imagine software on a 23.5 m resolution LISS III image of 2014 by applying the maximum likelihood algorithm.

Road network

The response is an important part of disaster management, which depends immensely on the accessibility of the affected regions through the road network. The impact of a calamity increases significantly in the event of lack of timely supply of resources. Hence, this is an important parameter for consideration in this study. The road network data (Fig. 9) was

Table 5 Normalized matrix of physical-geological variables

	Tidal range	Sea level	Significant wave height	Shoreline changes	Elevation	Geomorphology	Slope	Sum	Mean	Weights derived
Tidal range	0.03	0.02	0.02	0.01	0.02	0.03	0.05	0.17	0.024	2.40
Sea level	0.05	0.03	0.02	0.02	0.02	0.03	0.05	0.22	0.032	3.21
Significant wave height	0.08	0.10	0.05	0.02	0.03	0.04	0.07	0.38	0.055	5.49
Shoreline changes	0.14	0.13	0.14	0.06	0.04	0.05	0.08	0.64	0.091	9.07
Elevation	0.22	0.16	0.18	0.19	0.11	0.08	0.12	1.07	0.153	15.28
Geomorphology	0.24	0.26	0.28	0.32	0.34	0.25	0.16	1.85	0.264	26.39
Slope	0.24	0.30	0.32	0.38	0.45	0.51	0.47	2.67	0.382	38.15

Table 6 Normalized matrix of socio-economic variables

	Cultural heritage	Road network	LU/LC	Population	Sum	Mean	Weights derived
Cultural heritage	0.06	0.02	0.03	0.08	0.19	0.05	4.78
Road network	0.12	0.07	0.04	0.08	0.30	0.08	7.61
LU/LC	0.29	0.28	0.16	0.14	0.87	0.22	21.72
Population	0.53	0.63	0.78	0.70	2.64	0.66	65.89

generated from LISS III data and Google maps. Road network has been considered for 250 m, 500 m, 1 km, 2 km or beyond buffers from the shoreline. It is found that the closeness of a particular road makes it more vulnerable. The section of the road joining Teisimouza is classified under very high vulnerability class and the segment joining Saharabedi comes under the high vulnerability class. The rest of the shoreline falls under very low class.

Cultural heritage (tourist areas/industrial hub)

Cultural heritage consist of tourist places attracts huge masses of the population. Further, damage caused due to a disaster on a monument or tomb can lead to economic losses (Mani Murali et al. 2013). Thus, the location of tourist places is one important parameter of concern for estimating the socio-economic vulnerability of a region. For the present study region, we have also considered Paradip as an important tourist place as the famous Paradip Port is situated here; moreover, it also is a hub of immense industrial activity. Two classes are used as two if a tourist area is absent or three if it is present (Fig. 10). The shoreline along Bhitarkanika reserve and Paradip are classified under high vulnerability class.

Calculation of vulnerability index using AHP

The Analytic Hierarchy Process (AHP) or the Saaty method (Saaty 1977) was mainly developed to calculate the weighting factors, selecting the best alternatives by taking into consideration both the objective and subjective factors. This is achieved by constructing a preference matrix, where all identified relevant criteria are compared against each other with reproducible preference factors. In this analysis, the given general protocol for AHP computation is followed to calculate the weights for both PVI and SVI. The main steps of the methodology can be found in the published paper (Mani Murali et al. 2013). The significance values of different scales are given as comparison matrix of physical – geological variables (Table 3), socio – economic variables (Table 4), normalised matrix (Tables 5 and 6) random index (Table 7) and consistency ratio (Table 8). In this study, the main criteria have been compared, and the weights have been reported. Consistency ratio (CR) is also used in the process of formulation of the AHP (Saaty 1977). This is to ascertain that the matrix judgments were generated randomly (Mani Murali et al. 2013).

Table 7 Showing values of RI (Saaty and Vargas 1991), with n = order of the matrix

N	2	3	4	5	6	7	8
RI	0.00	0.52	0.90	1.12	1.24	1.32	1.41

The vulnerability rank values are multiplied by the corresponding weights of the respective variables to obtain the value of each parameter for the entire coast, represented as a linear feature in which every 3 km is analyzed for its vulnerability. In the present study, PVI and SVI have been calculated by using the method of summation based on the methodology followed by Mani Murali et al. (2013). As it is considered that both physical and socio-economic factors have equal contribution in coastal vulnerability, the above formula (6) has been used to calculate the CVI. The PVI, SVI and CVI values for the different segments of the coastline are further classified into low (less than 25th percentile), medium (between 25th and 50th percentile) and high vulnerable (greater than 50th percentile) classes. All the computations of the analysis are performed as well as represented in the GIS environment.

Results and discussion

Vulnerability assessment using AHP

Indices need to be simple, robust and comprehensive to be an effective way to monitor trends and explore the

Table 8 Computation of Consistency Ratio (CR)

Parameters	Physical- geological variables	Socio-economic variables
λmax	7.7	4.24
n	7	4
CI	0.12	0.08
RI	1.32	0.09
CR	0.09	0.09

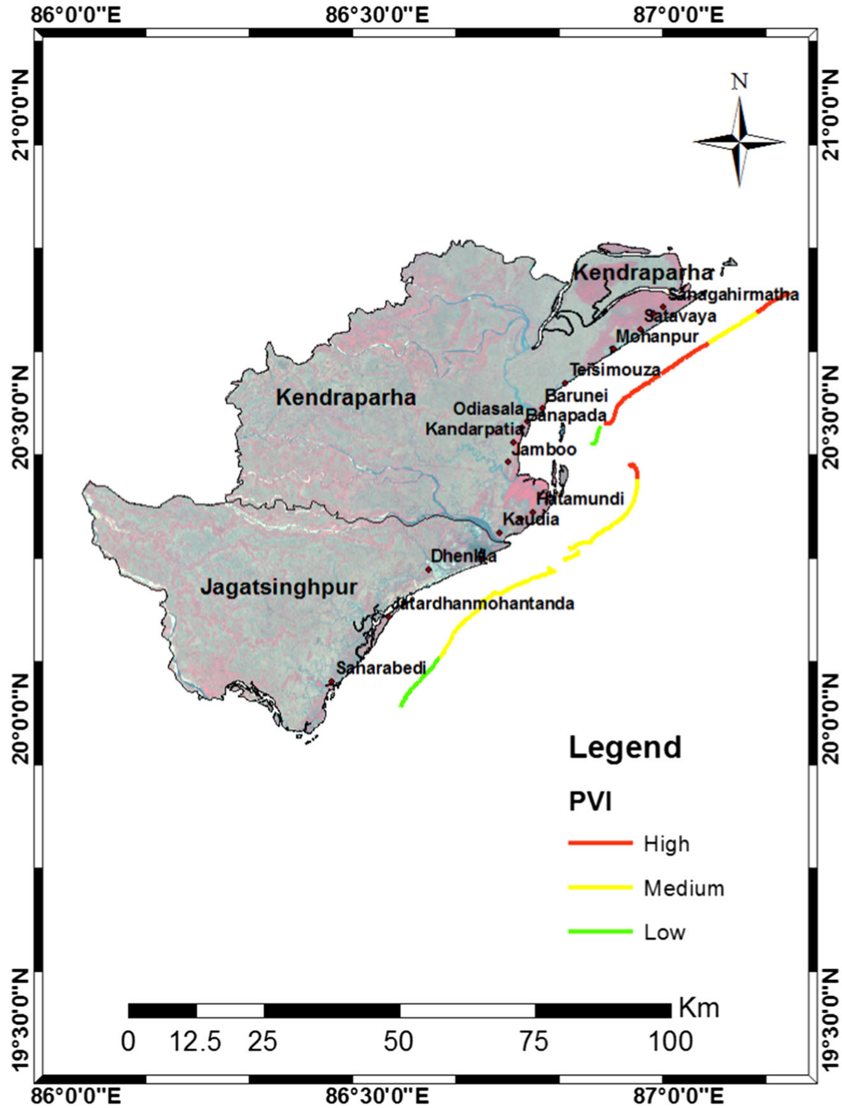

Fig. 11 Map of physical vulnerability index

conceptual framework of vulnerability. While the indicator approach is valuable for monitoring trends and exploring conceptual frameworks, indices are limited in their application due to the considerable subjectivity involved in the selection of variables, their relative weight, the scale of the data, etc. Moreover, the limitation in most of the studies is that the weights are assigned randomly, based on the researcher's discretion. Also, the limited inclusion of socio-economic parameters makes the study incomplete. In this study, we have addressed these drawbacks by using AHP process and calculating the socio-economic vulnerability index along with the physical- geological vulnerability index and giving them equal priority in the calculation of coastal vulnerability index. An inclusion of both these aspects enables greater specificity in addressing issues about managing the coastal disaster. AHP is beneficial as it is flexibly altered based on the prevailing conditions in a particular region (Mani Murali et al. 2013). This ensures better assessment of coastal vulnerability at a regional level, which is important especially in the case of India, as the east coast differs significantly from the west coast.

Physical vulnerability index (PVI)

PVI (Fig. 11) presented in this study has been calculated by using seven variables. The variability of an index depends on the extent to which the contributing variable differs spatially. For the coast of Odisha, the parameters that varied the most are coastal slope, regional elevation, and shoreline change. Regional elevation is used as it provides an estimate of the extent of land susceptible to Sea level rise, flooding events, etc. (Kumar and Kunte 2012; Kumar et al. 2010). On the contrary Rao et al. 2008 considered slope as a better parameter

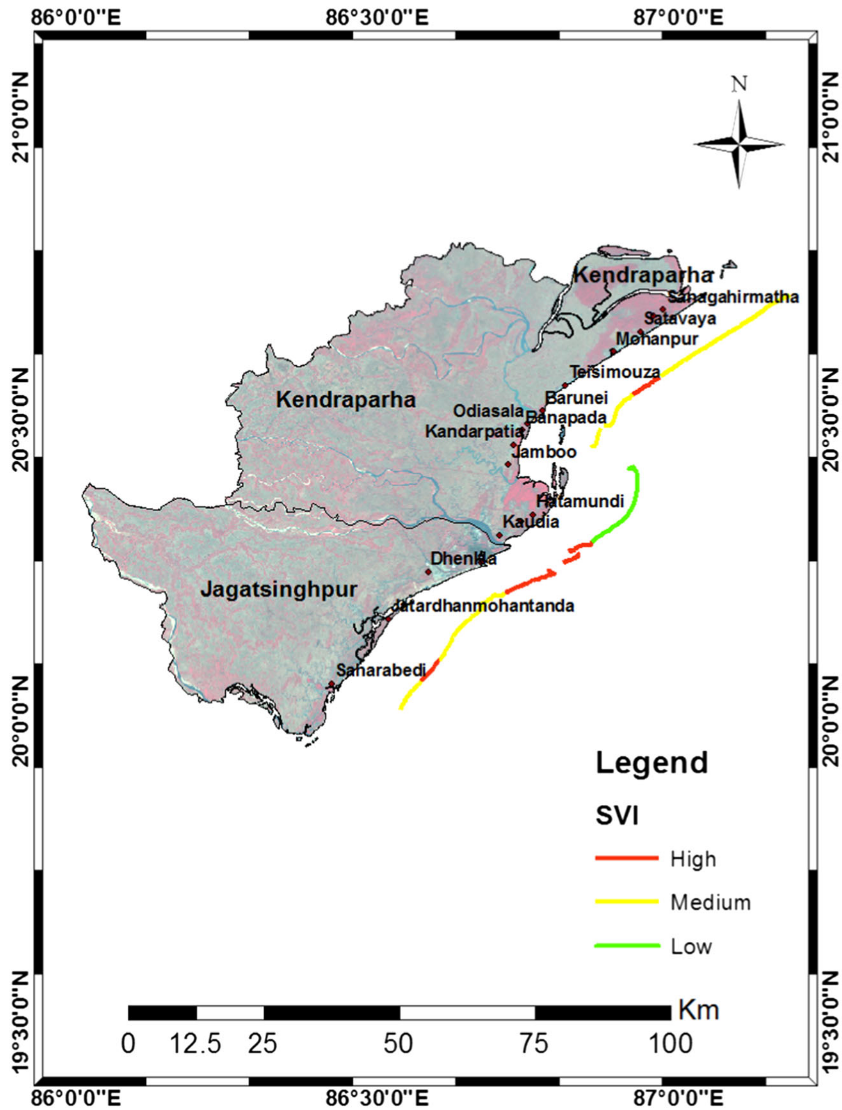

Fig. 12 Map of socio-economic vulnerability index

than elevation. However, in the present study, both these parameters are considered, as the former represents the vertical level of the terrain, and the latter refers to the bathymetric changes. Here, the coastal slope is considered as the most important variable contributing to the Physical vulnerability, followed by geomorphology and regional elevation. The geomorphic features of this coastal belt include, sandy beaches, deltas, creeks, mangroves, etc. making it an extremely vulnerable coastline. Shoreline change is considered as the fourth most important parameter; this is because, although it is an indicator of the general nature of the coastline, it cannot be used as a predictor of future vulnerability (Rao et al. 2008). However, this parameter depicts the influence of natural sediment transport as well as the impact of anthropogenic influence (Paradip Port) in shaping the dynamics of the shoreline. A change in the location of the shoreline is an indicator of coastal erosion which also has socio-economic relevance in the form of negative impact on tourism. The remaining parameters including the significant wave height, sea level change, and tidal range are considered in this order based on expert judgment, as for each of these values were obtained to the extent envisaged for the study is relatively small to result in changes in the values spatially.

Fig. 10 shows the vulnerability map prepared based on the Physical vulnerability index. The PVI values ranged from 326.59 to 391.95. It is observed that the region between Kanakpur and Banapada as well as the extent between Barunei and Odiasala is highly vulnerable. Based on the PVI calculation, almost 30% of the shoreline comes under the high vulnerability zone whereas 57% of the coastline has medium and 13% has a low vulnerability.

Socio-economic vulnerability index

Social Vulnerability Index (SVI) has been derived from four parameters. These factors, although not exhaustive,

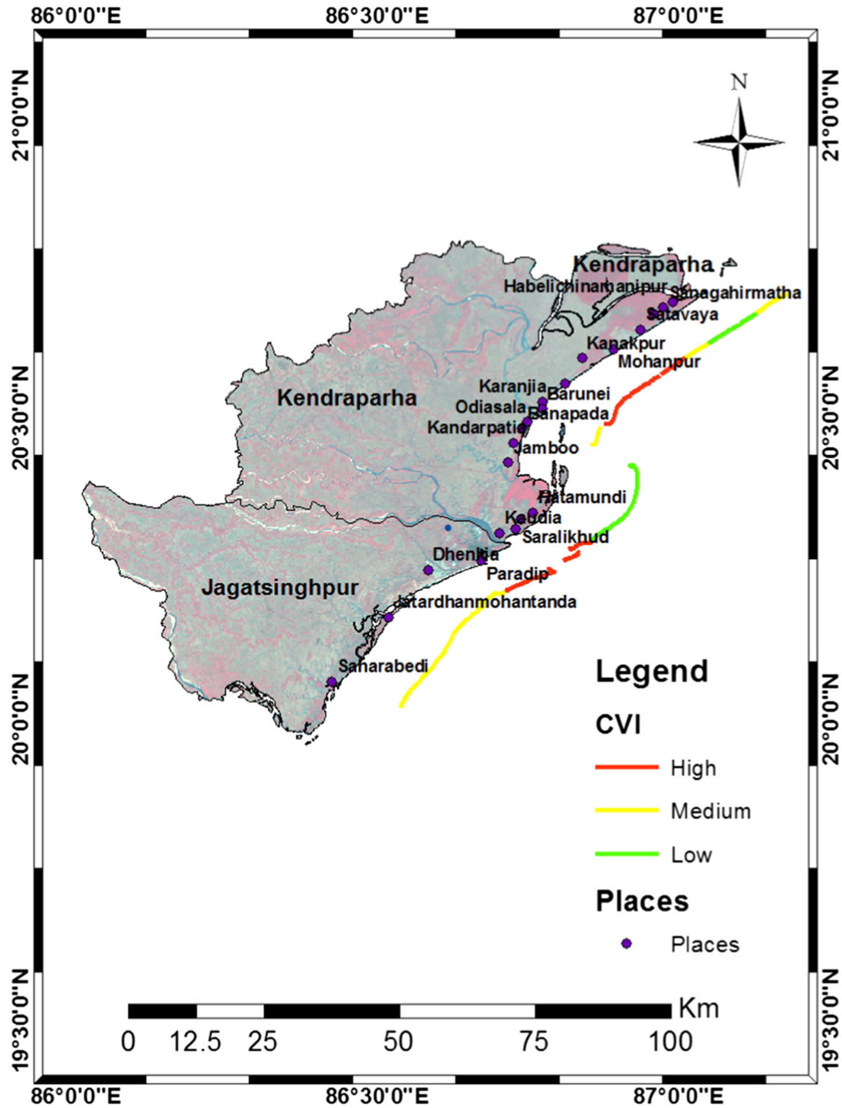

Fig. 13 Map of Coastal Vulnerability Index (CVI)

can be useful in assessing the vulnerability situation along the Kendrapara and Jagatsinghpur coast qualitatively. The devastation a natural disaster causes to human, natural and infrastructural resources is often the indicator of its magnitude and extent. Hence, it becomes necessary to consider socio-economic data [McLaughlin et al. 2002] to enhance the understanding of the vulnerability of an area to natural calamities. Moreover, these parameters are more dynamic over a period than the physical factors (Szlafsztien 2005). The population is one of the major socio-economic variables influencing the vulnerability of a region to coastal hazards. The LU/LC is also considered as it highlights the urban areas near the coast which are highly susceptible. The major drawback of including socio-economic data is the inconsistencies associated with scale; the physical attributes are generally considered at a segment level whereas these parameters are at a regional level. Moreover, Physical-geological data are at larger temporal scales in comparison to socio- economic data which represent a shorter span of time, such as in the case of population.

Fig. 12 shows the socio-economic vulnerability map wherein about 17% of the shoreline comes under low, 56% under medium and 26% of high vulnerability class. The shoreline from Teisimouza to Barunei and the adjoining Paradip Port come under the high vulnerability category.

Coastal vulnerability index (CVI)

In this study coastal vulnerability index is calculated using both physical-geological as well as socio- economic parameters by giving equal weight to both. The former can be considered as the causal parameters which regulate the intensity and extent of the disaster; the latter describes the impacts. The

CVI calculated through this methodology ranges from 264.29 to 325.15. Accordingly, the final coastal vulnerability map (Fig. 13) for the Odisha coast is generated by grouping various coastal segments into the three risk classes. Depending on this classification, 35% of the coastline comes under high vulnerability, 39% under Medium and 26% under low vulnerability class. The coastline adjoining Kanakpur, Mohanpur, Teisimouza, Brunei, and Paradip Port is the highly vulnerable zone. The shoreline between Jatardharmohan and Saharabedi come under medium vulnerability zone. This approach provides a better indication as it considers both the physical as well as socio-economic aspect equally.

Conclusion

The state of Odisha is prone to tropical cyclone and storm surges, which have led to the great destruction of life and property in this region. According to Ramesh et al. (2011), the cyclones that have occurred between 1877 and 1988 hit the Odisha coast somewhere along the shoreline joining Dhamra and Paradip. Moreover, the latter was the landfall point for the most devastating 1999 Odisha super cyclone. This paper uses an Analytical Hierarchical based approach to analyze and illustrate the coastal vulnerability of the Odisha coast, specifically the Kendrapara and Jagatsinghpur districts adjoining the Bay of Bengal. Here, seven relative physical–geological (geomorphology) and four socio-economic parameters have been selected to understand the sensitivity to natural hazards, of the adjoining coastline. To improve the efficiency of the vulnerability assessments of this nature, it is imperative to choose methods which enable better multi-criteria decision making. In this study, we have used the analytical hierarchical process (AHP) proposed by Saaty (1977) to derive the quantitative weights for each parameter used to estimate the physical and socio-economic vulnerability and have subsequently calculated the coastal vulnerability index. The main strength of this methodology is its capability to convert expert opinions into numerical values and to integrate quantitative and qualitative data in an organized way. Further, the vulnerability maps produced in this research work are a contribution to the process of continuous monitoring of this area which is extremely vulnerable to coastal disasters. These can be used by the coastal managers and decision- makers to devise better coastal management plans to diminish the losses during the various extreme events.

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