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Coastal vulnerability assessment of Puducherry coast, India using analytical hierarchical process

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Abstract

Increased frequency of natural hazards such as storm surge, tsunami and cyclone, as a consequence of change in global climate, is predicted to have dramatic effects on the coastal communities and ecosystems by virtue of the devastation they cause during and after their occurrence. The tsunami of December 2004 and the Thane cyclone of 2011 caused extensive human and economic losses along the coastline of Puducherry and Tamil Nadu. The devastation caused by these events highlighted the need for vulnerability assessment to ensure better understanding of the elements causing different hazards and to consequently minimize the after-effects of the future events. This paper advocates an Analytical Hierarchical Process (AHP) based approach to coastal vulnerability studies as an improvement to the existing methodologies for vulnerability assessment. The paper also encourages the inclusion of socio-economic parameters along with the physical parameters to calculate the coastal vulnerability index using AHP derived weights. Seven physical-geological parameters (slope, geomorphology, elevation, shoreline change, sea level rise, significant wave height and tidal range) and four socio-economic factors (population, Land-use/Land-cover (LU/LC), roads and location of tourist places) are considered to measure the Physical Vulnerability Index (PVI) as well as the Socio-economic Vulnerability Index (SVI) of the Puducherry coast. Based on the weights and scores derived using AHP, vulnerability maps are prepared to demarcate areas with very low, medium and high vulnerability. A combination of PVI and SVI values are further utilized to compute the Coastal Vulnerability Index (CVI). Finally, the various coastal segments are grouped into the 3 vulnerability classes to obtain the final coastal vulnerability map. The entire coastal extent between Muthiapet and Kirumampakkam as well as the northern part of Kalapet is designated as the high vulnerability zone which constitutes 50 % of the coastline. The region between the southern coastal extent of Kalapet and Lawspet is the medium vulnerability zone and the rest 25 % is the low vulnerability zone. The results obtained, enable to identify and

prioritize the more vulnerable areas of the region to further assist the government and the residing coastal communities in better coastal management and conservation.

1 Introduction

In lieu of the disproportionate climate change, the coastal areas constitute the most productive, yet vulnerable ecosystems of the world. These coastal belts often prove to be the hot spots of severe impacts associated with permanent inundation of low-lying areas, increased flooding due to extreme weather events like storm surges, tsunami, greater erosion rates affecting beaches and cliffs and devastation due to calamities like cyclone (Nicholls and Cazenave, 2010; EC, 2005; EEA, 2006; Klein et al., 2003). The greenhouse effect (caused by greenhouse gases released due to pollution) leading to global warming has severe implications on the regions bordering the oceans. According to a recently projected estimate, the global climate will warm by around 0.2 °C per decade in the next 20 yr (IPCC, 2007). Strohecker (2008) estimates that the melting of glaciers, disappearing of ice sheets and warming water could lift the sea level by as much as 1.5 m by the end of this century. The accelerated sea level rise and possible increase in the intensity and frequency of cyclones (Unnikrishnan et al., 2006) related to increase in sea surface temperature, will cause serious ramifications such as flooding, coastal erosion and shoreline retreat (Pye and Blott, 2006). Such projections are adversely linked to sustainable coastal management as they lead to geomorphic changes along the coastline as well as damage to coastal ecosystems and resources.

In addition to threats due to natural hazards, these regions also face immense population and developmental pressures. Creel (2004) reports that approximately half of the world's population live within 200 km of a coastline. Development affects natural coastal functioning, in particular, the equilibrium between terrestrial shoreline environments – the beach and near-shore bathymetry. In extreme cases, this leads to the loss of coastal lands making them highly susceptible to the impacts of sea-level rise, coastal erosion, extreme weather and other coastal hazards (O'Connor et al., 2009). From the

developing country perspective, the present day vulnerability due to natural disasters, the possibility of increase in number and enormity of such events under climate change regime, and their potential high impact on the performance of climate sensitive sectors make a strong case for focus on alternatives as part of the climate change policy. The need for local scale assessments is further highlighted by the several disaster events (McFadden et al., 2007) that take place frequently along the coasts of countries like India, Bangladesh, Thailand etc. In recognition of these risks, there is a need to develop methodologies to assess coastal vulnerability to ensure efficient hazard management and mitigation (Cooper and Mckenna, 2008; McFadden et al., 2007).

The definition of vulnerability in the climate change context falls into two main categories (i) in terms of the damage caused by the natural hazard (Jones and Boer, 2003), and (ii) the inherent existing state of the system before it encounters an event (Allen, 2003). The IPCC fourth assessment report (2007) specifies vulnerability to be a function of the character, magnitude, rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity. However, in this framework vulnerability can be understood to be a composition of multiple interacting factors emerging from the social, economic and environmental spheres of an exposure unit (Turner et al., 2003; Birkmann, 2006). Thus, vulnerability is often expressed in the form of quantitative indices, and this is considered as a key step towards vulnerability assessment and management (Romieu et al., 2010). Indices are applied for various scientific objectives such as for identifying cause–effect relationships, for mapping and ranking to compare vulnerability across regions, for realistic assessment of risks etc (Füssel and Klein, 2006) as they not only provide consistent and rapid characterizations but also provide them at many spatial scales (local to global).

One of the most initial attempts to formulize a coastal vulnerability index particularly for sea-level rise was developed by Gornitz and Kanciruk (1989) for the United States. Coastal slope, geomorphology, relative sea-level rise rate, shoreline change rate, mean tidal range and mean wave height were the main parameters used by Thieler and Hammer-Klose (1999) for assessment of coastal vulnerability of the US Atlantic coast.

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The coastal vulnerability index (CVI) of the Golden Gate National Area to sea-level rise was assessed by Pendleton et al. (2005). These assessments are generally based on remotely sensed data as an input and processed by means of GIS methodology. This method is particularly useful as it does not rely on detailed, precise or long-term data, which when working at a regional scale is rarely available and costly to produce (Bryan et al., 2001). However, a major inadequacy in case of most vulnerability assessments is that they focus only on the physical characteristics of vulnerability with little inclusion of economic and ecological aspects (Boruff et al., 2005). In the Indian context, several vulnerability studies have been taken for the east coast as well as west coast for sea -level rise using physical variables as an input to the coastal vulnerability index. Shoreline movement (Mani Murali et al., 2009) and run up, inundation limits (Jayakumar et al., 2005) were studied along the parts of east coast of India for anthropogenic and Tsunami studies, respectively.

Dwarakish et al. (2009) calculated CVI for coastal zone of Udupi, Karnataka from shoreline change, rate of sea-level change, coastal slope, tidal range, coastal geomorphology. CVI for Orissa was assessed by Kumar et al. (2010) using an additional parameter of tsunami run-up. The multi-hazard vulnerability along the coast of Cuddalore–Villupuram was assessed by Mahendra et al. (2011) by incorporating storm surge parameter along with other physical factors. Kumar et al. (2012) did a vulnerability assessment of Chennai coast using geo-spatial technologies. In majority of these studies the CVI is expressed as the square root of the product of the ranking factors divided by the number of parameters considered (Thieler and Hammar-Klose, 2000). However, Vittal Hegde and Reju (2007) have used the sum of the value of each variables divided by number of variables. Later, Nageswara Rao et al. (2008) calculated CVI by taking the summation of the variables considered with the ranks of each multiplied by their corresponding weights on Andhra Pradesh coast.

The limitation in these studies is that the weightage are deduced using an individual's discretion, moreover socio-economic factors are not taken into consideration. However, Adger (1996) suggests that social vulnerability is a key dimension that shifts emphasis

onto the underlying rather than proximate cause of vulnerability and hence is an important constitution of vulnerability. Boruff et al. (2005) computed the overall Coastal Social Vulnerability score (CSoVI) by considering socio-economic variables in a principal component analysis. Willroth et al. (2012) studied the socio-economic vulnerability of coastal communities in southern Thailand and also discussed that social networks played a crucial role in coping with the disaster. Thus, it is imperative to integrate socio-economic data in these kinds of studies to judge the vulnerability associated with the people living in the coastal areas facing pressure due to coastal hazards. This is because these disasters do not become catastrophes until human lives are affected and hence the addition is essential for overall understanding of the vulnerability of a region.

The main aim of this paper is therefore to present an Analytical Hierarchical Process (AHP) based Coastal Vulnerability Index (CVI) taking both physical-geological (PVI) and socio-economic parameters (SVI) into consideration. The AHP method proposed by Saaty (1977); Saaty and Vargas (1991), provides a better understanding of the complex decisions by decomposing the problem into hierarchical structure. AHP enables to arrive at a scale of preference amongst the available alternatives by employing a pairwise comparison procedure between the decision elements, by ranking them according to their relative importance (Ju et al., 2012). This methodology is suggested as an improvement to the traditional CVI calculations proposed earlier as we argue that AHP deduced weights provide better estimations. The result of this analysis includes identification and relative ranking of vulnerable units based on geological-physical and socio-economic parameters, demarcation of the priority regions in order to aid in regional assessment and to provide suitable information for planning preventive measures. The region chosen for this assessment is the Puducherry coast as, after the devastation caused by cyclone Thane, it is considered as highly vulnerable to natural disasters. Moreover, this particular shoreline is famous for being eroding in nature due to both natural as well as anthropogenic reasons.

2 Study region

The study area (Fig. 1) is the region along Puducherry situated on the east coast of India, between 79.87° E and 79.79° E longitudes and 12.05° N and 11.75° N latitudes. The union territory of Puducherry consists of four unconnected regions of Puducherry, Karaikal, Yanam which lie in the Bay of Bengal and Mahe which lies in the Arabian Sea. The Puducherry region considered in this study is an enclave of Tamil Nadu state of India. There are two rivers draining this region (1) the Gingee river, which traverses the region diagonally from north-west to south-east and (2) the Ponnaiyar (Penniyar) river, which forms the southern border of the region. The three major physiographic units generally observed are coastal plain (younger and older), alluvial plain and uplands (National Assessment of shoreline change: Puducherry coast, 2011). The entire area, except the northeastern corner is mostly covered by sedimentary formations ranging in age from cretaceous to recent. The physiographic map of the area presents more or less a flat land with an average elevation of about 15 m above m.s.l. Puducherry's average elevation is at sea level, and a number of sea inlets, referred to as "backwaters" are present. This coastal zone is largely low-lying with gentle slope, thus making it highly vulnerable to inundation. The coastal erosion or accretion takes place as a part of a natural cycle and there is a balance, annually and seasonally between accretion and erosion. The Bay of Bengal is one of the six regions in the world where severe tropical cyclones originate and this area in particular was one of the worst hit during 2004 Indian Ocean tsunami. In 2011, a very severe cyclonic storm "Thane" with a wind speed of 140 $km h^{-1}$ (85 mph) to 150 $km h^{-1}$ (90 mph) crossed this study region. Thane made a landfall early on 30 December 2011, on the north Tamil Nadu coast between Cuddalore and Puducherry and resulted in extensive damage of life and property. Thus, the susceptibility of this region to natural hazards and their devastating effects highlights the need for a vulnerability assessment to assist the administration (state and district level) in better disaster planning and mitigation.

3 Methodology

According to Füssel and Klein (2006) vulnerability to climate change is the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change. Vulnerability assessments should shift their focus from quantifying the vulnerability of a place to rather evaluating the vulnerability of selected parameters of concern and to specific sets (Luers et al., 2003). From this perspective, although not quantitatively, qualitatively the relative exposure of the different coastal environments to natural hazards can be studied by using information pertaining to various physical as well as geological aspects of the shoreline as an input to estimate the physical vulnerability index (PVI). Klein et al. (2003) suggested that this approach (indices) is desirable as it combines the coastal system's susceptibility to change with its natural capacity to adjust to dynamic environmental conditions and yields a relative estimate of the system's vulnerability to hazardous events. The present approach is comparable to that used by Pendleton et al. (2005) and Thieler and Hammer-Klose (1999, 2000) in terms of the usage of indices for estimation of vulnerability. Seven risk variables are used to calculate the PVI, i.e. coastal slope, coastal geomorphology, regional elevation, shoreline change rate, sea-level change rate, mean tidal range, and significant wave height. Following a similar protocol, 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 the parameters considered for SVI are not exhaustive however, they are indicative of the social vulnerability status of this region. The weights for PVI and SVI are then calculated using the analytical hierarchical process (AHP) which is discussed subsequently. An overall coastal vulnerability index (CVI) is further computed using the calculated indices to understand the relative vulnerability of each 2.8 km segment (total of 12 segments) of the shoreline. The entire procedure of vulnerability assessment involves data obtained from various sources such as remote sensing, GIS databases and numerical modeling which is acquired, analyzed and processed to derive each of the given parameters

(Table 1). The definition of classes and assigning the scores is a necessary step for the normalization and aggregation of indicators (Torresan et al., 2012). Hence, the significance of the parameters considered as well as their rankings criterions are discussed in the following section.

3.1 Physical and geological parameters (PVI)

Seven physical-geological parameters such as coastal slope, geomorphology, regional elevation, shoreline change, sea level rise, significant wave height and tidal range is considered for studying the PVI index. The entire Puducherry coast is segmented into equal lengths of 2.8 km (12 segments) and assigned vulnerability rankings from 1 to 4 representing very low, low, high and very high vulnerability respectively (Table 2).

3.1.1 Coastal slope

The coastal slope (steepness or flatness of the coastal region) is defined as the ratio of the altitude change to the horizontal distance between any two points on the coast. The susceptibility of the coast due to inundation by flooding and the associated land loss is a direct function of coastal slope (Thieler and Hammer-Klose, 2000). Thus, on a steep coast, the consequence of sea-level rise would be insignificant contrary to a gently sloping coast where any rise in sea level would inundate large extents of land (Nageswara Rao et al., 2008). Bathymetry shows the depth from the coast towards the open ocean and hence it can be used to estimate the degree of near-shore slope of a region. In this study, modified ETOPO5 data has been used to generate the coastal slope. ETOPO5 was generated from a digital data base of land and sea-floor elevations on a 5-min latitude/longitude grid. Sindhu et al. (2007) derived an improved shelf bathymetry for the Indian Ocean region (20° E to 112° E and 38° S to 32° N) by digitizing the depth contours and sounding depths less than 200 m from the hydrographic charts published by the National Hydrographic Office, India. The digitized data were then gridded and used to modify the existing ETOPO5 dataset for depths less than

200 m by combining the digitized data with the original ETOPO dataset and applying blending techniques. This data is obtained from the National Institute of Oceanography, India data repository and the slope for the entire study area is computed in the Arc GIS environment. The slope layer (in degree) is further classified according to the ranking criteria (Fig. 2). Three classes are significant in this region, i.e. low, high and very high. Majority of the coastal stretch falls in the range of > 0.2 and < 1, i.e. the low vulnerability category. The stretch along Pondicherry new harbour, Muthiapet falls under very high vulnerability and areas along Manaveli, Dupuyyet, Lawspet, Kottakuppam and Kuilapalayam belong to the high vulnerability class.

3.1.2 Geomorphology

Geomorphology is defined as the study of surface landforms, processes and landscape evolution of the Earth. The morphology of coast is shaped by tectonic and structural features, the nature of the rock forming the coast, depositional and erosive activity. It plays a pertinent role in determining the response of the coast to sea-level rise as it expresses the relative erodibility and the degree of resistance of the different landforms and the materials that compose them (Thieler and Hammer-Klose, 1999). For instance, rocky cliffs and wave-cut benches offer maximum resistance and therefore are very less vulnerable, on the other hand, the soft sandy and muddy forms such as dunes, mudflats, etc., offer least resistance, so are extremely vulnerable to sea-level rise. Thus, the study of geomorphology enables to identify the coastal areas vulnerable to hazards under present circumstances and is likely to become exceedingly susceptible as a result of the global climate change.

Based on the interpretation of satellite image (Indian Remote Sensing Satellite – IRS P6 LISS III), a detailed map of the geomorphology of the region (Fig. 3) is prepared. The major landforms of the Puducherry coast are beaches, sand dunes, tidal flats and estuaries. Along the Puducherry coast, beaches are generally narrow and severe erosion is observed along the northern segment of the coastline. In the southern segment, beaches are comparatively broader and depositional. Barrier dunes/Sand dunes are seen as continuous mounds between Ariyankuppam, Kirumambakkam, Manapattu and Narimedu areas. Estuarine mouths are prominent at Ariyanakuppam, north of Poornankuppam and in the southern segment where both Gingee and Ponnaiyar rivers join the Bay of Bengal. Throughout the landscape, tanks are distributed. Due to the presence of estuaries and beaches this region mainly comes under the high and very high vulnerability zones.

3.1.3 Regional elevation

In the present study, the coastal regional elevation is derived using the Shuttle Radar Topography Mission (SRTM) data. Defined as the average elevation of a particular area above mean sea level, regional elevations plays an important role in identifying and estimating the extent of land threatened by future climate change scenarios. Coastal regions having low elevations are considered highly vulnerable whereas those having higher elevations are considered less susceptible. This is mainly because areas at higher elevations provide more resistance to inundation due to rising sea level, tsunami and storm surge. The stretch of Puducherry coast covers all the four vulnerability classes of regional elevation (Fig. 4). However, the majority of the coast comes under the high and very high vulnerability zones. The coastline along Muthiapet and Dupuyyet has a very high vulnerability factor and areas of Manavelli and Narambai constitutes a high vulnerability zone. The region between Kalapet and Kuilapalayam lies in a very low to low vulnerability zone.

3.1.4 Shoreline change

Shoreline is the interface between land and water. Healthy beaches and shorelines are essential to the quality of life along the coast, and also provide buffers for storms and critical habitats for many species of plants and animals. Shoreline changes are a result of coastal processes, which are mainly controlled by wave characteristics, near shore circulation, sediment characteristics and beach forms. The breaking waves and

currents in the near-shore zone are responsible for the transport of shoreline sediments resulting in shoreline change. This scenario is part of a process called littoral transport, which moves the eroded material in the coastal zone by means of waves and currents. In the context of coastal vulnerability, accreting coastlines are considered less vulnerable as they result in the addition of land areas by moving towards the ocean. On the other hand, eroding coastlines are considered highly vulnerable because of the resultant loss of natural as well as man-made resources associated with it. LANDSAT MSS, TM, ETM and IRS-LISS III images covering the Puducherry coastline for the years 1977, 1991, 2000, 2006, 2008 and 2012 are used for processing in ERDAS software. The extracted shorelines are then vectorized to calculate the shoreline change using the DSAS tool of Arc-GIS (USGS, 2005). The onshore transects are laid at an interval of every 250 m along the coastline. The DSAS tool calculates several statistics which are useful in understanding the shoreline trends from a temporal perspective. Considering the rate of change, vulnerability ranking is assigned to the 12 coastal segments.

The shoreline change map is constructed based on the Net shoreline movement (NSM) and End point rate (EPR) criteria, the zones having positive NSM and EPR are mainly the accreting zones and those depicting negative values are eroding zones (Fig. 5). The northern part of the coastline is mainly erosive and the southern part has accreting trends. The shoreline along Kalapet is an eroding stretch and based on the above mentioned ranking criteria belongs to high vulnerability class. The regions between Gingee and Ariyanakupum river is an accreting coastline and hence has a very low vulnerability. The port plays an important element as north of the port is erosive and south of the port is showing accretion. Consequently, the shoreline along Duppuyet is highly vulnerable.

3.1.5 Sea level changes

Sea level change is one of the most important consequences of climate change. Mean sea level is usually described as a tidal datum that is the arithmetic mean of hourly water elevations observed over a specific 19-yr cycle. “Global sea level rise” refers

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to the increase currently observed in the average global sea level trend, which is primarily attributed to changes in ocean volume due to two factors: ice melt and thermal expansion. Increase in global atmospheric temperature causes a rise in ocean temperature and subsequent melting of glaciers leading to rise in global sea level. The study of global sea-level rise has been studied extensively in last two decades due to the availability of monthly mean sea level data through the Permanent Service for Mean Sea Level (Woodworth and Player, 2003). Unnikrishnan and Shankar (2007) estimated the trends in sea-level rise for the North Indian Ocean coasts by using the tide gauge data available at the PMSL site by correcting them of global isostatic adjustment (GIA). Their results estimated a regional average of 1.29 mm yr^{-1}. Mahendra et al. (2011) calculated the sea level changes using the tide gauge data of Chennai for a period of 54 yr and estimated a value of 0.085 mm yr^{-1}. In this study the average of 1.29 mm yr^{-1} is used. Thus the coastline for Pondicherry region comes under the high vulnerability class.

3.1.6 Significant wave height

Significant wave height (SWH) is used as an alternative to wave energy and is important in studying the vulnerability of shoreline. It is the average height (trough to crest) of one -third of the waves in a wave spectrum for a given period of time.

Wave energy is directly related to the square of wave height by the following formula

$$E = 1/8\rho g H^2 \quad (1)$$

where E is energy density, H is wave height, ρ is water density and g is acceleration due to gravity. Increase in wave height causes an increase in wave energy which subsequently results in increased erosion and inundation along the shore causing loss of land. Hence, coastlines experiencing high wave heights are considered more vulnerable than those which are exposed to low wave heights.

For Puducherry region, spectral wave (SW) model of MIKE-21 is used to compute the significant wave height for the year 2011. By solving the spectral wave action balance equation, this model simulates the growth, decay and transformation of the wind-generated waves and swells in the offshore and coastal regions (Vethamony et al., 2006). Six hourly SWH are generated by forcing the model with NCEP/NCAR Reanalysis wind data of 2.5 × 2.5 resolution available from the site http://www.esrl.noaa.gov. The model is also validated with DS05 buoy data of 2005 and a correlation of 0.87 is obtained with a bias of −0.08. The average values are calculated and considered for assigning vulnerability rating. The significant wave height at Puducherry rarely exceeds an average of 0.9 m. At Puducherry coast, deepwater waves occur from south and southwest during southwest monsoon and from northeast during northeast monsoon. Maximum Significant wave heights of 2.1–2.2 m are observed in the modeled data for 2011 during the period of formation of Thane cyclone. Puducherry coast falls in the low vulnerability class from the point of significant wave height.

3.1.7 Tidal range

Tidal range is defined as the vertical difference (in meters) between the high tide and the consecutive low tide. Tides are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon and the Sun and the rotation of the Earth. Both permanent and episodic inundation hazards are linked to tidal range. A large tidal range determines the spatial extent of the coast that is acted upon by waves. A coastal area is considered highly vulnerable if it experiences high tidal range whereas those with low tidal ranges are designated to be of low vulnerability.

In the current study, WXtide software has been used to predict tide data along the Cuddalore coast for the year 2011. The tidal range for a smaller region will not fluctuate much in a year. The average tide range of this region is between 0.7–0.8 m. The National Assessment of Shoreline Change: Puducherry Coast (2011) reports that tidal range for Puducherry coast is low and the maximum range during a spring tide is around 0.8 m.

Recorded tide levels at Puducherry with respect to chart datum are:

– Mean High Water Spring (MHWS): +1.30 m

– Mean High Water Neap (MHWN): +1.00 m

– Mean Low Water Neap (MLWN): +0.70 m

– Mean Low Water Spring (MLWS): +0.49 m

– (The National Assessment of Shoreline Change: Puducherry Coast, 2011)

Hence in view of both the data obtained from the prediction tool and the literature, the entire coastline is classified into very low vulnerability class.

3.2 Socio-economic parameters

3.2.1 Population

The population data is essential in order to understand the effect and the dimension of the natural calamity. Human beings vulnerability is considered as a social condition, or as a measure of the resilience of society to a disaster. By using census data and the mapping capabilities of a GIS, our goal is to put in place a blueprint with which we can quickly identify areas where populations are disproportionately susceptible to disaster impacts. In the current study, the census data of 2001 is considered for the region to find zones with a higher population distribution in comparison to others. A population map is prepared in the Arc-GIS environment where the individual polygons represent the important towns of Puducherry. The minimum population of a town is 54 430 (Bahour) and the maximum is observed in the Pondicherry town, i.e. 220 865. Ozukarai also has a large population that resides along the coastal belt. Based on the ranking criteria, three vulnerability classes of low, high and very high are obtained for this region (Fig. 6).

3.2.2 Land-use/land-cover

A Land-use/land-cover map is essential to understand the changes in the land-use/land-cover classes in a particular region and how it helps in increasing or diminishing the vulnerability of an area. Changes in LU/LC are attributed to the anthropogenic activities (Mani Murali et al., 2006) in addition to the climate changes. For instance, an urban area along the shoreline such as in the case of Puducherry makes the region more vulnerable to natural calamity. In the current study LU/LC map is generated using supervised classification technique in ERDAS Imagine software on a 23.5 m resolution LISS III image of 2012 by applying the maximum likelihood algorithm. From the land-use/land cover map (Fig. 7, Table 3) it can be seen that the agricultural area and fallow land (49 % of the total land area) comprising of mainly cropland, plantation dominate this region. The forest land is almost nil in Puducherry and most of the vegetation (approx. 3 % of the total land) comprises of those which are along the settlements. Only 0.4 % of the total area comprises of the sandy beaches. The urban area covers about 9.8 % of total land-use/land-cover. The main areas of urban agglomeration are Puducherry, Kalapet and hence have a very high to high vulnerability. Other areas have been ranked as low vulnerability as they have less urban built-up and are not entirely barren.

3.2.3 Road network

Road networks are essential during a natural calamity especially with reference to providing relief work. A disruption in road network due to a natural calamity can lead to a cut-off and increase the impact of the calamity manifold due to scarcity of resources. The road network data was created in the GIS environment using a combination of available LISS III data and rectified Google maps. The classification of the road network has been done by making buffers of 250 m, 500 m, 1 km and 2 km or beyond from the shoreline. It is considered that the proximity of a particular section of the road to the shoreline makes it more vulnerable. Based on this, a short stretch of road from Kalapet

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to Kuilapalayam appears to be vulnerable and is classified under high vulnerability zone. A majority of the road segments are 2 km or beyond and hence are classified under very low vulnerability category (Fig. 8).

3.2.4 Cultural heritage (tourist places)

The distribution of tourist places is considered as it has a pertinent socio-economic implication as the cultural heritage of a region. Damages caused due to a disaster on monument, tomb can lead to economic loss, and moreover more people are considered to collect at these places that can cause huge human loss in case of a natural disaster. Considering Puducherry to be essentially a tourist destination, this parameter has been considered by plotting the location of important places in GIS. Two classes are prepared based on the criteria that whether a tourist place is present or absent near the shoreline (Fig. 9). In order to ensure consistency, the ranking is given as 2 if a tourist place is absent or 3 if it is present. Most of the tourist places are located in Puducherry town and hence the extent along it is considered to be highly vulnerable. Though, the area along Kalapet is not a tourist destination, it has been ranked as highly vulnerable as the University is located here.

3.3 Analytical hierarchical process and calculation of vulnerability index

Analytical Hierarchical Process (AHP) was developed by Saaty (1977) to calculate the needed weighting factors with the help of preference matrix, where all identified relevent criteria are compared against each other with reproducible preference factors. AHP selects the best alternatives by considering both the objective and subjective factors. In this analysis, a general protocol is followed for calculating the weights for both PVI and SVI. In the first step, pair-wise comparisons are carried out for all factors to be considered, and the matrix is completed by using scores based on their relative importance. In the construction of a pair-wise comparison matrix, each factor is rated against every other factor by assigning a relative dominant value between 1 and 9 to

the cell concerned. The significance of the dominant scale values is given in the table (Table 4). Having a comparison matrix (Tables 5, 7), a priority vector is computed which is the normalized eigen vector of the matrix. This is done by dividing each of the columns by the corresponding sum (Tables 6, 8). As the last step, the average values of each row are computed and these are used as weights in the objective hierarchy for calculating the PVI and SVI. AHP allows both sub-criteria as well as main criteria comparison, however, for the present study the latter has been used and the weights have been reported.

CVI in most of the vulnerability studies is expressed as the square root of the product of the ranking factors divided by the number of parameters considered. According to Gornitz (1991), although CVI can be expressed as a sum of the parameters, the CVI computed as the product of parameters has the advantage of expanding the range of values. On the contrary, Diez et al. (2007), suggest that the CVI as the sum of differentially weighted variables represent the environmental variability more appropriately. In the present study, PVI and SVI have been calculated by using both the methods and it is found that the method of summation suitably expresses the conditions in this region.

The approach used here to derive weights is different from the methodologies used previously in the vulnerability studies conducted in India. For instance, Nageswar Rao et al. (2008) obtained the differential weights for the parameters by multiplying the vulnerability rank values by arbitrary multiplication factors based on the relative significance of the five variables considered. They have ranked geomorphology and slope as more important parameters in comparison to others (Shoreline change, SWH, Tidal range) and hence have given them the highest weight of 4 and subsequently 2 to shoreline change and no weights to tidal range and SWH. Ju et al. (2012) performed a GIS based suitability assessment for Laoshan district wherein they have used AHP as a method to derive weights. Similarly in this study, weights for the various parameters have been derived using analytical hierarchical process. This is because, although relatively a particular parameter may have more significance than the other, yet giving absolute weights based on the discretion of the investigators highly undermines the individual contribution of each variable. For instance, coastal slope and geomorphology are often considered significant factors in case of vulnerability to sea level rise; however, assigning them the same value does not define their comparative contribution. Moreover, arbitrary values can be considered in case of vulnerability assessment for a particular type of calamity, however for an overall assessment they can be misleading. Clearly, AHP proves to be more advantageous in case of multi-index integrated evaluation.

In order to indicate the likelihood that the matrix judgments were generated randomly, an index of consistency known as consistency ratio (CR) is used in the process of synthesis of the AHP (Saaty, 1977).

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \quad (2)$$

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

$$\mathrm{CI} = (\lambda\mathrm{max} - n)/(n - 1) \quad (3)$$

where λmax is the largest or principal eigen value of the matrix, and n is the order of the matrix. The random index (RI) is defined as the average of the resulting consistency index that depends on the order of the matrix (Table 9) given by Saaty (1977). Generally, a consistency ratio (CR) of the value of 0.10 or less is considered relevant (Saaty, 1977).

Since the consistency ratio for both the variables (Table 10) is less than 0.1 they can be considered for further calculation.

The weights derived using AHP are used for calculating the PVI and SVI, where

$$\mathrm{PVI} = W_1X_1 + W_2X_2 + W_3X_3 + W_4X_4 + W_5X_5 + W_6X_6 + W_7X_7 \quad (4)$$

physical vulnerability index (physical parameters) Eq. (4), where W_n is the weight value of each variable, and X_n is the vulnerability score of each variable.

$$\mathrm{SVI} = W_1X_1 + W_2X_2 + W_3X_3 + W_4X_4 \quad (5)$$

socio-economic vulnerability index (socio-economic parameters) Eq. (5), where W_n is the weight value of each variable, and X_n is the vulnerability score of each variable.

$$\mathrm{CVI} = (\mathrm{PVI} + \mathrm{SVI})/2 \quad (6)$$

We have used the above Eq. (6) considering that both physical and socio-economic factors have equal contribution in coastal vulnerability.

The values of each variable for each coastal segment are obtained by multiplying the vulnerability rank values by the corresponding weightage factors of the respective variables. These are further processed in the geographic information system (GIS) environment (ArcGIS). The entire coast is considered as a linear feature in which every 2.8 km segment along the coast is analyzed for its vulnerability. The PVI, SVI and CVI values for the different segments of the coastline are further classified into low (lesser than 25th percentile), medium (between 25th–50th percentile) and high vulnerable (greater then 50th percentile) classes.

4 Results and discussions

4.1 Physical Vulnerability Index

PVI presented in this study has been calculated by using seven variables of coastal slope, geomorphology, regional elevation, shoreline changes, sea level rise, significant wave height and tidal ranges. The slope, geomorphology, regional elevation and erosion rate variables are important parameters for physical vulnerability as they vary along the coastline. However, the remaining variables, including sea-level change, significant wave height and mean tide range do not vary with respect to vulnerability. This is because the extent of the shoreline under consideration is small and so only one relevant value is obtained for the data. Nageswar Rao et al. (2008) considered slope as a relatively more appropriate variable as slope represents the area whereas elevation denotes a point. However, Kumar et al. (2010) suggest that addition of regional elevation is equally essential. In this study, coastal slope has been given the maximum priority while assigning weight as it plays a major role in case of disasters like Tsunami, storm surge and flooding. Coastal elevation that represents the vertical level of the terrain has also been included as an additional parameter. An analysis of the synthesis of the PVI maps also shows that geomorphology is a governing factor of vulnerability after coastal slope. Dinesh Kumar (2006) studied the implication of sea-level rise on the coastal zone of Cochin and revealed that the mean beach slope and relief play a vital role in land loss of the region. Most of the Puducherry coast is covered with estuaries, sand dunes and beaches classifying it into a priority zone. According to Nageswar Rao et al. (2008), the rate of shoreline change is only a general indicator of the behavior of the coast and hence cannot be used to predict the subsequent trend of the coastline with time. However in our present study we consider it as the fourth most important parameter as it contributes to a significant variance to the calculated PVI. The national assessment of shoreline change – Puducherry coast (2010) report specifies the role of fetch, and therefore the resultant wave energy in the erosion rates observed in the Puducherry coast. They also mention that emplacement of shoreline protection structures such as seawalls/riprap and revetments can result in both active and passive erosion of the beach. Some of the highest erosion zones are found along the northern side of the Puducherry Port mainly because hard structures often play a defining role in case of shoreline trends. Thus, through PVI, it is possible to indirectly understand the anthropogenic impact on the coastline.

Figure 10 shows the vulnerability map prepared based on the physical vulnerability index. The PVI values range from 215 to 345. It can be observed that the region along Kottakupam, Muthiapet and Pondicherry new harbor, Dupuyyet as well as the region between Poornankuppam and Pudukuppam is highly vulnerable. Based on the PVI calculation, almost 50 % of the shoreline comes under the high vulnerability zone whereas 25 % of the coastline has medium and 25 % has low vulnerability.

4.2 Social Vulnerability Index

Most of the previously developed coastal vulnerability/sensitivity indices acknowledge that the addition of socio-economic variables would assist in defining vulnerable areas (McLaughlin et al., 2002). This proves to be difficult as several problems are encountered in assessing socio-economic vulnerability indicators due to inherent drawbacks involved in ranking socio-economic data on an interval scale. Hence they are generally excluded from coastal vulnerability index (CVI) calculations. However, socio-economic variables are significant factors contributing to coastal vulnerability mainly because socio-economic changes occur more often and more rapidly than physical process changes (Szlafsztien, 2005). It is hence imperative to consider socio-economic data along with physical variables as this would enhance the accuracy and clarity of results related to coastal vulnerability as the magnitude of a natural calamity is often described in terms of the devastation its causes to human, natural and anthropogenic resources.

Here, population, land-use/land-cover, road network and location of tourist places are considered to calculate the social vulnerability index (SVI). The region along Kalapet, Kottakuppam and Ariyanakuppam has high vulnerability and that along Kirumambakkam and Kuilapalayam has a low vulnerability (Fig. 11).

All these factors can be used as indicators that can help in making a qualitative analysis of the vulnerability situation along the Puducherry coast.

4.3 Coastal vulnerability index

The sensitivity of a coastal region to coastal hazards can be effectively assessed by using the CVI index. For the coast of Puducherry, both physical-geological as well as socio-economic parameters have been considered for the calculation of CVI by giving them equal weightage. This is because although the former regulates the intensity and enormity of the disaster, the latter characterizes it consequence and impact.

The CVI calculated through this approach ranges from 211 to 362. The extent to which the contributing variables differ, is an important criteria based on which the CVI index varies (Abuodha and Woodroffe, 2006). Accordingly, the final coastal vulnerability map (Fig. 12) for the Puducherry coast is generated by grouping various coastal segments into the 3 vulnerability classes. Depending on this classification, the entire coastal extent between Muthiapet and Pudukuppam as well as the Northern part of Kalapet is designated the high vulnerability zone which constitutes 50 % of the coastline. The region between the southern coastal extent of Kalapet and Lawspet is the medium vulnerability zone and the rest 25 % of the shoreline is the low vulnerability zone. The maps obtained from this study represent the vulnerable areas based on the 11 parameters considered (physical-geological, socio-economic factors). They highlight the more challenging regions along the Puducherry coast which demand further attention and hence need to be studied more elaborately by utilizing datasets with higher resolution and more information.

It is important to understand here that either singularly or collectively the physical and social indicators only represent the conceptualization of vulnerability as an exposure measure (Boruff et al., 2005). Thus, researchers should consider more spatially and temporally varying socio-economic data along with physical variables (e.g., sediment supply, coastal defenses, climatic, and oceanographic data) in their study. An assessment of vulnerability in each area based upon both groups of variables should be implemented for the purpose of designing policy and mitigation measures to increase their flexibility and specificity. Nevertheless, this analysis of PVI, SVI and CVI results can contribute to the better understanding of the variability and determinants of vulnerability for various regions.

5 Conclusions

The rising number of coastal hazards along the world coastlines throws light on the need of better and efficient methodologies for the assessment of coastal vulnerability. Here, relative physical-geological (geomorphology) and socio-economic parameters have been selected to understand the sensitivity of the coast of Puducherry to natural

hazards. The study encourages the inclusion of socio-economic parameters in vulnerability studies, as well as proposes the use of analytical hierarchical process (AHP) for deriving the weights for this assessment. Socio-economic factors are important as the data related to these aspects vary across the study area since these parameters are associated with humans, land use, transportation, and cultural heritage and hence can prove to be essential in terms of the reaction of a particular area to a natural disaster. The analytical hierarchical process (AHP) proposed by Saaty (1977) is a very popular approach to multi-criteria decision-making (MCDM) that involves qualitative data which is one of the most important reasons of using it for calculating the weight for the coastal vulnerability assessment. This paper presents an objective methodology to analyze and illustrate the vulnerability linked with various coastal hazards and can be used effectively by coastal managers and decision makers to devise better coastal zone management plans as well as to ensure efficient mitigation measures to lessen the losses during disasters. Finally in the social context, the vulnerability maps produced can be used as broad indicators of the susceptibility of the people living along the coastline to coastal hazards.

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Table 1. Data used for the study.

Parameter	Source	Period
	Physical and Geological Parameters	
Coastal Slope	Modified Etopo5 obtained from data repository of National Institute of Oceanography (Sindhu et al., 2007)	NA
Geomorphology	LISS III IRS P6	2011
Elevation	SRTM – 90 m resolution	NA
Shoreline Change	Landsat MSS, Landsat TM, Landsat ETM, LISS III	1977, 1991, 2000, 2006, 2008, 2012
Sea level Change	Unnikrishnan and Shankar, 2007	NA
Significant Wave Height	Model output using spectral wave (SW) model of MIKE-21	2011
Tidal Range	Prediction tool and reported values in the National Assessment of Shoreline Change: Puducherry Coast, 2011	2011
	Socio-economic Parameters	
Population	Census 2001 report http://censusindia.gov.in/	2001
Land-use/Land-cover	LISS III IRS P6	2012
Road Network	GIS data	NA
Tourist Places	GIS data	NA

Table 2. Vulnerability ranking criteria.

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	> 3 and < 6	> 0 and < 3	< 0
Shoreline Change ($m\,yr^{-1}$)	Accretion > 1	Accretion < 1	Erosion < 1	Erosion > 1
Sea level change ($mm\,yr^{-1}$)	< 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)	NA	Absent	Present	NA

Table 3. Areal distribution of LU/LC classes as Percentage Cover.

Class Name	% Cover
Water	22
Barren/Muddy areas	14
Sandy beach	0.4
Agriculture	21.2
Fallow	29.4
Vegetation	3.2
Urban	9.8
Total	100

Table 4. Scale of comparison.

Intensity of importance	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Values for inverse comparision

Table 5. Comparison matrix of physical-geological variables.

	Tidal Range	Significant Wave Height	Sea level	Shoreline Change	Elevation	Geomor-phology	Slope
Tidal Range	1.00	0.50	0.33	0.20	0.14	0.11	0.11
Significant Wave height	2.00	1.00	0.33	0.25	0.20	0.13	0.11
Sea level	3.00	3.00	1.00	0.33	0.25	0.17	0.14
Shoreline Change	5.00	4.00	3.00	1.00	0.33	0.20	0.17
Elevation	7.00	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	36.00	30.50	21.67	15.78	8.93	3.94	2.12

Table 6. Normalized matrix of physical-geological variables.

	Tidal Range	Wave height	Significant Sea level	Shoreline Change	Elevation	Geo-morphology	Slope	Sum	Mean	100.00
Tidal Range	0.03	0.02	0.02	0.01	0.02	0.03	0.05	0.17	0.02	2.41
Significant Wave height	0.06	0.03	0.02	0.02	0.02	0.03	0.05	0.23	0.03	3.23
Sea level	0.08	0.10	0.05	0.02	0.03	0.04	0.07	0.39	0.06	5.53
Shoreline Change	0.14	0.13	0.14	0.06	0.04	0.05	0.08	0.64	0.09	9.13
Elevation	0.19	0.16	0.18	0.19	0.11	0.08	0.12	1.05	0.15	14.97
Geomorphology	0.25	0.26	0.28	0.32	0.34	0.25	0.16	1.85	0.26	26.48
Slope	0.25	0.30	0.32	0.38	0.45	0.51	0.47	2.68	0.38	38.25

Table 7. Comparison matrix of socio-economic variables.

	Cultural Heritage	Road network	LU-LC	Population
Cultural 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

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Table 8. Normalized matrix of socio-economic variables.

	Cultural Heritage	Road network	LU-LC	Population	Sum	Mean	100.00
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

Table 9. 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

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Table 10. Computation of Consistency Ratio (CR).

Parameters	Physical Variables	Socio-economic variables
λmax	7.68	4.24
n	7.00	4.00
CI	0.11	0.08
RI	1.32	0.09
CR	0.09	0.09

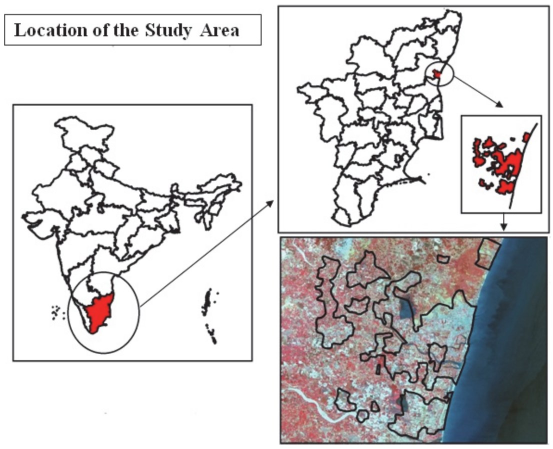

Fig. 1. Map showing location of study area.

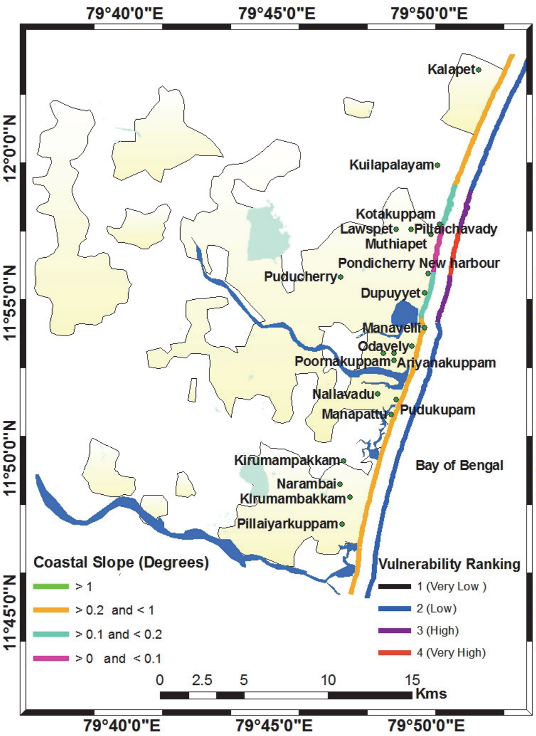

Fig. 2. Vulnerability ranking map of coastal slope.

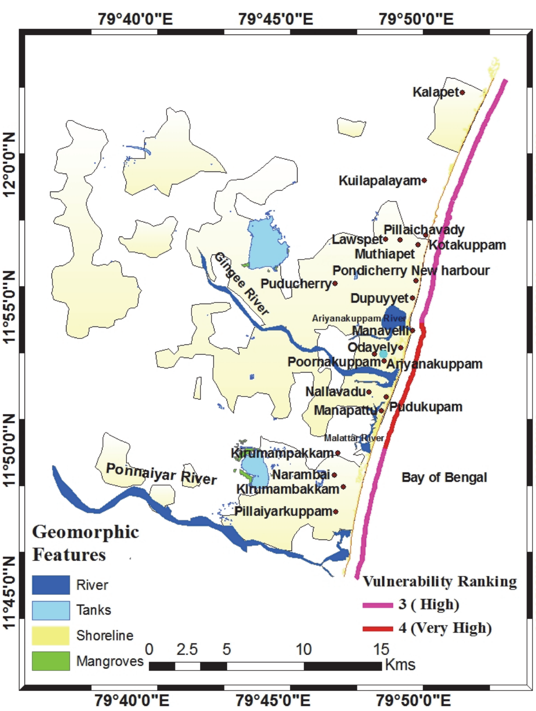

Fig. 3. Vulnerability ranking map of geomorphology.

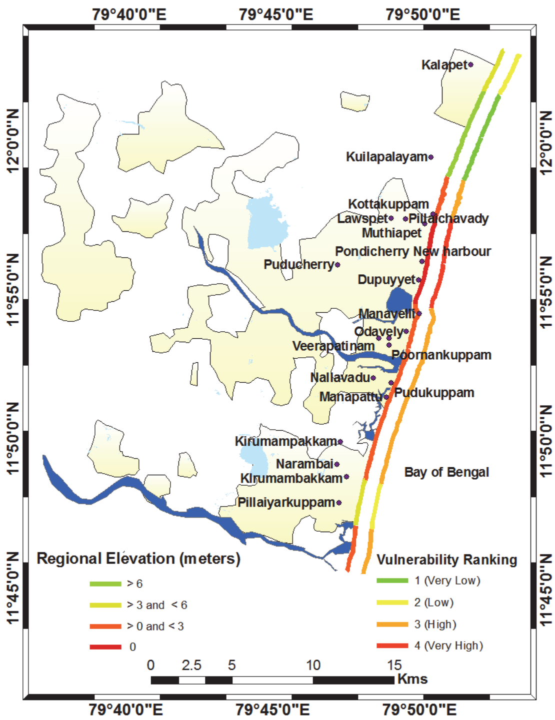

Fig. 4. Vulnerability ranking map of regional elevation.

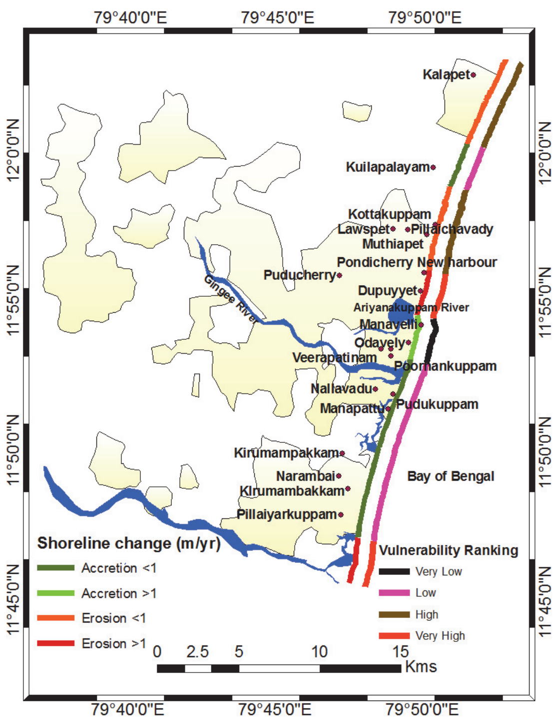

Fig. 5. Vulnerability ranking map of shoreline change rate.

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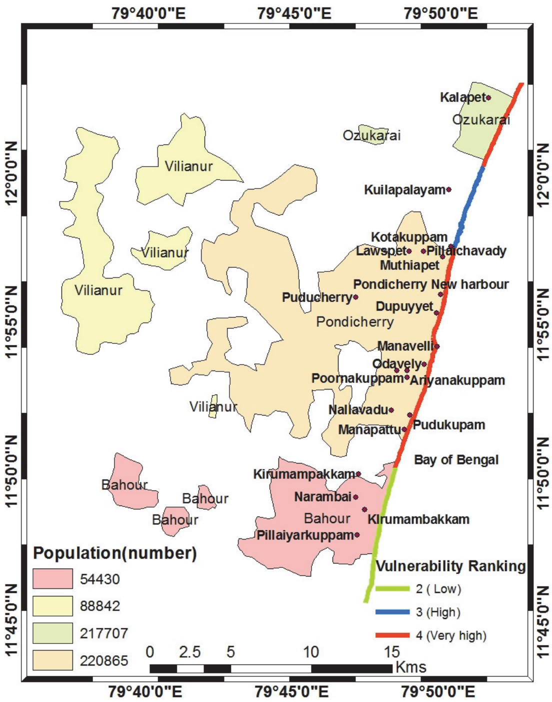

Fig. 6. Vulnerability ranking map of population.

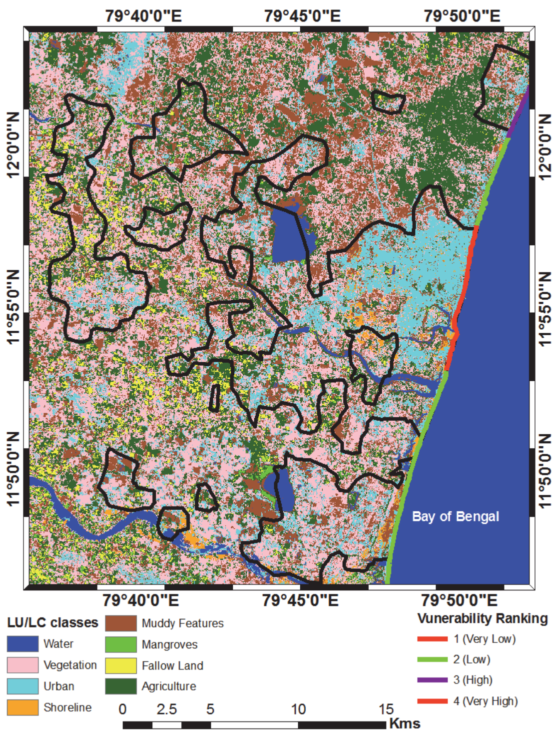

Fig. 7. Vulnerability ranking map of land-use/land-cover.

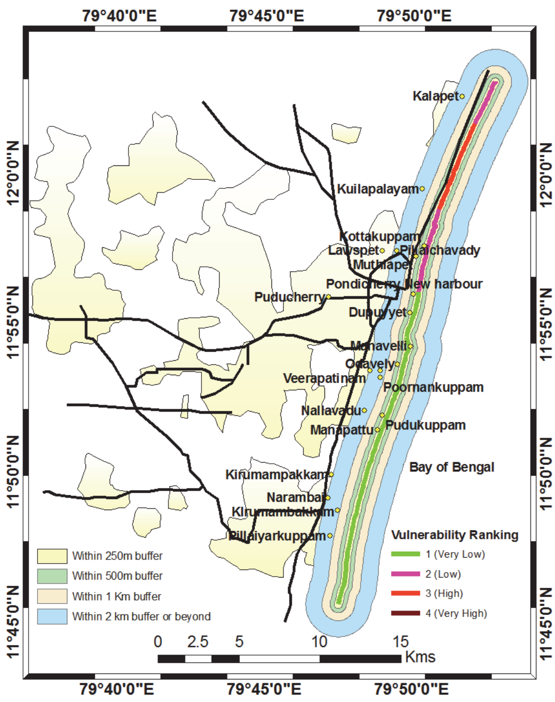

Fig. 8. Vulnerability ranking map of road network.

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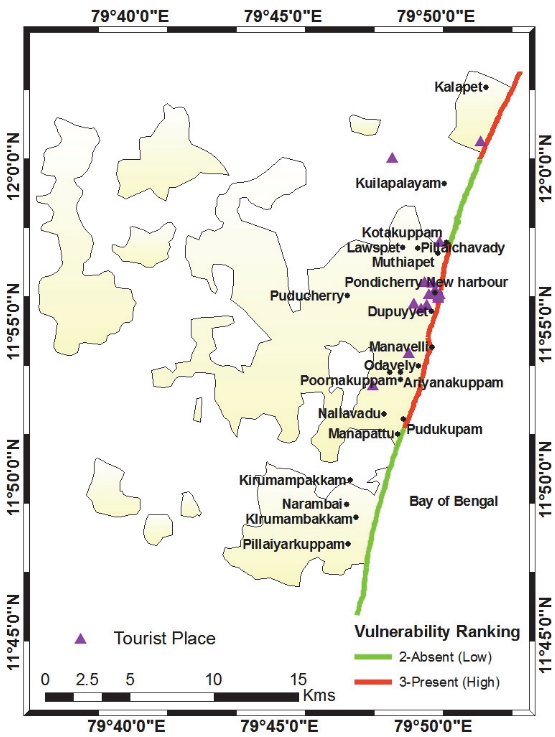

Fig. 9. Vulnerability ranking map of distributionof tourist places.

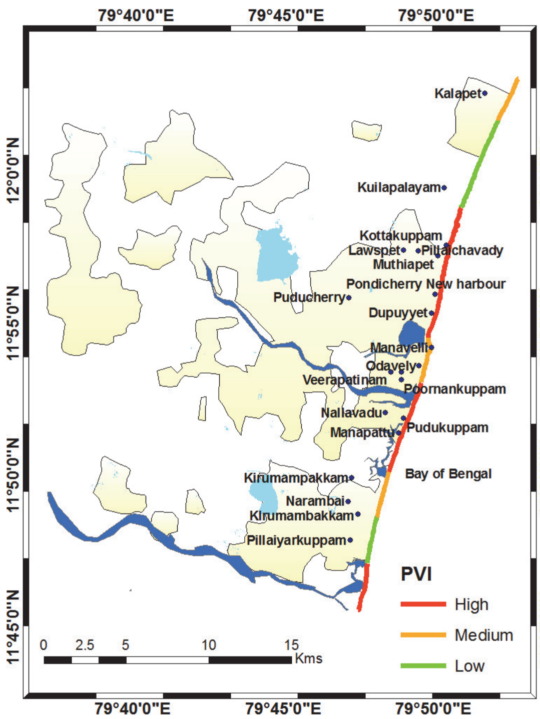

Fig. 10. Physical vulnerability index map.

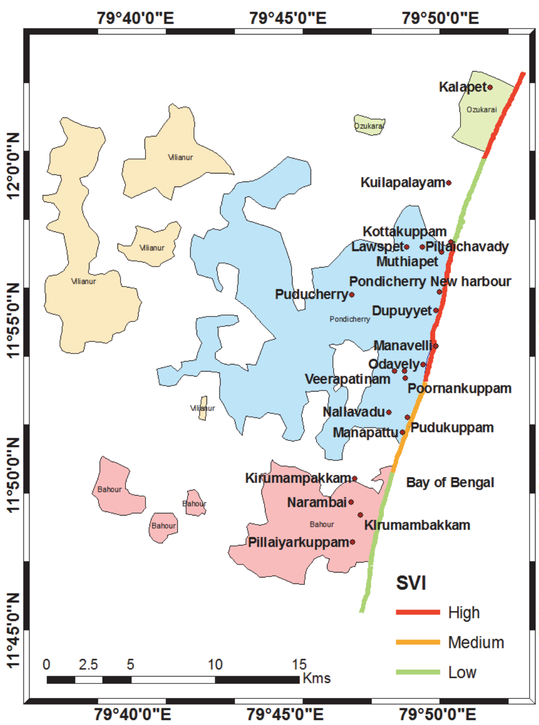

Fig. 11. Socio-economic vulnerability index map.

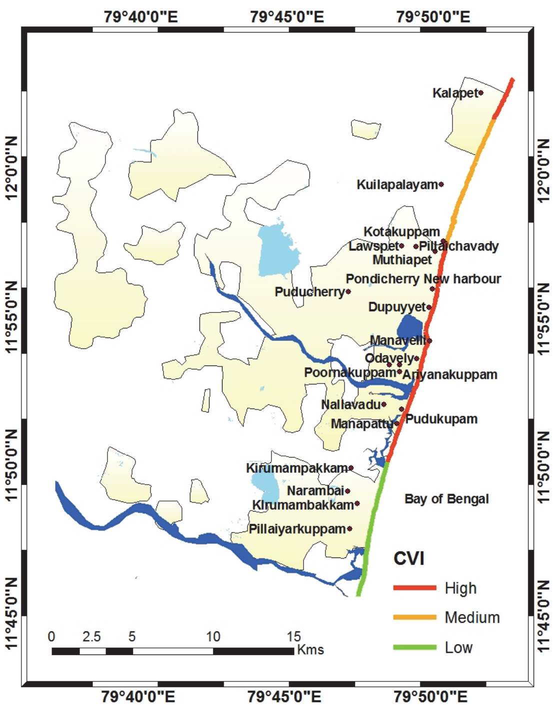

Fig. 12. Final coastal vulnerability index map.