

Coastal sensitivity assessment for Thiruvananthapuram, west coast of India

J. Shaji

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Abstract The densely populated coastline of Thiruvananthapuram district of Kerala, along the southwest coast of India, is sensitive to sea surge and severe coastal erosion. The December 2004 Indian Ocean Tsunami had inundated several parts of this coastal zone, indicating nature of sensitivity. The present study is an attempt to develop a coastal sensitivity index (CSI) for Thiruvananthapuram coast within the framework of coastal sediment cells. Seven variables, namely (a) coastal slope, (b) geomorphology, (c) shoreline change, (d) mean sea-level rise, (e) nearshore slope, (f) significant wave height and (g) mean tide range, were adopted in calculation of CSI (the square root of the product of the ranked variables divided by the number of variables). Remote sensing data, topographic maps supported by field work and data from numerical models are used in geographic information system environment to generate CS index for each kilometer segment of this 76-km coastline. This study reveals that 72 % of the Thiruvananthapuram coastline falls in the high sensitive category. This exercise, first of its kind for Kerala coast will be useful for disaster mitigation and management.

Keywords Coastal sensitivity index · Sediment cell · Geographic information system · Thiruvananthapuram

1 Introduction

Coastal zone, an interface between terrestrial and marine environments, is an important geographic entity both in terms of resources and human inhabitation. It is also the most intensively used under multiple stakeholders. The United Nations Atlas on Oceans in 2010 reported that about 44 % of the world's population lives within 150 km of the sea. Being a

J. Shaji (✉)
Research Scholar, Resources Analysis Division, Centre for Earth Sciences Studies,
Thiruvananthapuram, Kerala, India
e-mail: shaji.jjohnson@gmail.com

highly dynamic part of the earth's surface, coastal areas are subjected to various types of hazards like coastal erosion, storm surges, tsunami and cyclones. Furthermore, global climate change and the threat of accelerated sea-level rise exacerbate the already existing high risks of the coastal zone. Recent global projections suggest sea levels could rise by as much as 1.9 m by 2100 (Schaefer et al. 2012; Vermeer and Ramstorfs 2009) which would exacerbate storm surge impacts and wave damage in many regions (Lin et al. 2012; IPCC 2012) all the more if tropical storm intensities also increase (Bender et al. 2010; Knutson et al. 2010).

The coastal vulnerability index is a concept proposed by Gornitz (1990) to assess the risk of rising sea levels on the east coast of the USA. Gornitz created a database for analysis of coastal disasters. There are other attempts to workout CVI/CSI by incorporating the variables of coastal slope, geomorphology, relative sea-level rise rate, shoreline change rate, mean tidal range and mean wave height (Nunn and Ravuvu 1994; Thieler and Hammer-Klose 1999; Belperio et al. 2001; Domniny-Howes and Papatoma 2003; Boruff et al. 2005; Pendleton et al. 2005; Hong et al. 2006; Giorgio Anfuso et al. 2009; Ozyurt and Ergin 2010; Abuodha and Woodroffe 2010; Pendleton et al. 2010; Duriyapong et al. 2011; Gaki-Papanastassiou et al. 2011; Boateng 2012; Karymbalis et al. 2012; Yin et al. 2012; Nuno Martins et al. 2012; Di Paola et al. 2013; Addo 2013; Jeremy et al. 2013; Sahin and Mohamed 2014). This study uses the term "sensitivity" in preference to "vulnerability," the term that was used by Gornitz (1990) on the US coasts and which continues to be adopted by the United States Geological Survey (USGS 2001). The distinction is made because the approach assesses only the physical aspects of the coast and not socio-economic variables such as population. Vulnerability is generally perceived in terms of people being vulnerable to particular hazards and therefore requires a consideration of socio-economic factors. The later, if added, as by Boruff et al. (2005) in their synthesis of physical and socio-economic variables, might extend "sensitivity" as a measure of susceptibility to enable it to address vulnerability. This paper uses a coastal sensitivity index (CSI) to characterize susceptibility, as applied on the Canadian coast and Australian coast (Shaw et al. 1998; Pamela et al. 2010) rather than calling the index a CVI as applied to USA, India, Greece (Nageswara Roa et al. 2008; Gaki-Papanastassiou et al., 2011). However, all the previous studies considered coastal grids to calculate CV/CS index. Of late, there were debates on using grid cell approach in coastal sensitivity analysis and sediment cells are being proposed as units of study (John Pethick 2008). The present study uses the frame work of coastal sediment cells for CS analysis and thus distinguishes itself from all the previous works on coastal sensitivity.

In India, there had been several attempts both in east and west coast to study coastal vulnerability/sensitivity (Rajawat et al. 2006; Dinesh Kumar, 2006; Hegde and Raju 2007; Pradeep Kumar and Thakur 2007; Roa 2007; Nageswara Roa et al. 2008; Dwarakish et al. 2009; Srinivasa Kumar et al. 2010; Mahendra et al. 2011 and Arun Kumar and Pravin Kunte 2012; Sheik Mujabar and Chandrasekhar 2013; Murali Mani et al. 2013). Further, all available studies in India use coarse grid and highly generalized data, thus limiting their applicability. Moreover, no such study ever attempted in Kerala. Assessment of coastal sensitivity within the framework of coastal sediment cell is a need for present day coastal zone management activities since it provides the natural boundary or units for various integrated coastal zone management (ICZM) programmes. Sediment cells are coastal compartments containing the complete cycle of erosion, deposition, sediment sources and sinks and the transport paths involved. Each cell should have sufficient sediment reservoirs (sources of sediment) in the form of buffer zones between the land and the sea and sediment stocks in the nearshore and offshore coastal zones to compensate by natural or

artificial processes (nourishment) for sea-level rise effects and human-induced erosional effects leading to an overall favorable sediment status (The EUROSION Study 2004). The management interventions within a defined coastal cell that result in interruptions to sediment movement within the cell itself will have minimal impact on adjacent or far-field cells so limiting any collateral damage. The Fourth Assessment Report of IPCC 2007 recommended that research is required at all scales, improved understanding at the physiographic unit scales (e.g., coastal cells, deltas or estuaries) would have particular benefits and support adaptation to climate change and wider coastal management. The main objective of the present study is to assess coastal sensitivity of 76-km-long coastline of Thiruvananthapuram district of Kerala, India, within the framework of coastal sediment cells using seven geographic—geologic and oceanographic—variables.

2 Study area

The current study area spreads over 76-km-long coastal zone of Thiruvananthapuram district, Kerala, on the southwest coast of India. It is located between $8^{\circ}17'27''$ – $8^{\circ}46'57''$ north latitudes and $76^{\circ}40'25''$ – $77^{\circ}05'56''$ east longitudes, bounded on the west by Lakshadweep Sea and the remaining three sides by land mass. It supports people from eleven panchayats and two urban centers, Varkala Municipality and Thiruvananthapuram City Corporation (Fig. 1). The average population density of this area is more than 1,508 persons per sq.km (2011, Census) which is much higher than the state's average population density of 860 persons per sq.km.

The beaches at Kovalam and Varkala and religious centers like Vettukad and Beemapalli are famous destinations for tourists and pilgrims. Topographically, the area is not uniform and is characterized by variations in elevation, rock types, stability and resource potential. The geomorphic features range from an assemblage of coastal plain, rocky coast to undulated lateritic terrain with occasional structural or residual hills. Northern and southern parts of the coastal stretch are characterized with coastal cliffs intermitted by the presence of pocket beaches. Two promontories, at Vizhinjam and Kovalam are of different type. Vizhinjam promontory is of sedimentary rock composition, while Kovalam promontory is crystalline rocks. The cliff faced coastline along Varkala is also of sedimentary rocks. The central part and southern part show development of sandy beaches, sand bars, channel bars and estuaries. The major water bodies in the coastal zone of Thiruvananthapuram are Akkulam lagoon with closed estuary at Veli, Kadinamkulam lagoon with open estuary at Perumathura, Panathura estuary at the mouth of Karamana River and Poovar estuary at the mouth of Neyyar River. Its climate is monsoon controlled and has a steep bathymetry. Mixed tree crops with settlements dominate the land-use pattern in this area as a whole. Vizhinjam, Poovar, Valiathura, Punthura, Adimalathura and Anchuthengu are the fishing villages of the area. The proposed site for Vizhinjam port and Trivandrum International Airport are located within the coastal zone of Thiruvananthapuram district. Being erosion prone densely populated coastal area and threatened by 2004 Indian Ocean Tsunami, identification of sensitive areas and effective risk mapping and assessment assumes importance.

3 Materials and methods

Sensitivity has been defined in this study in terms of a number of semi-quantifiable variables, comprising four structural and three process variables. The four structural

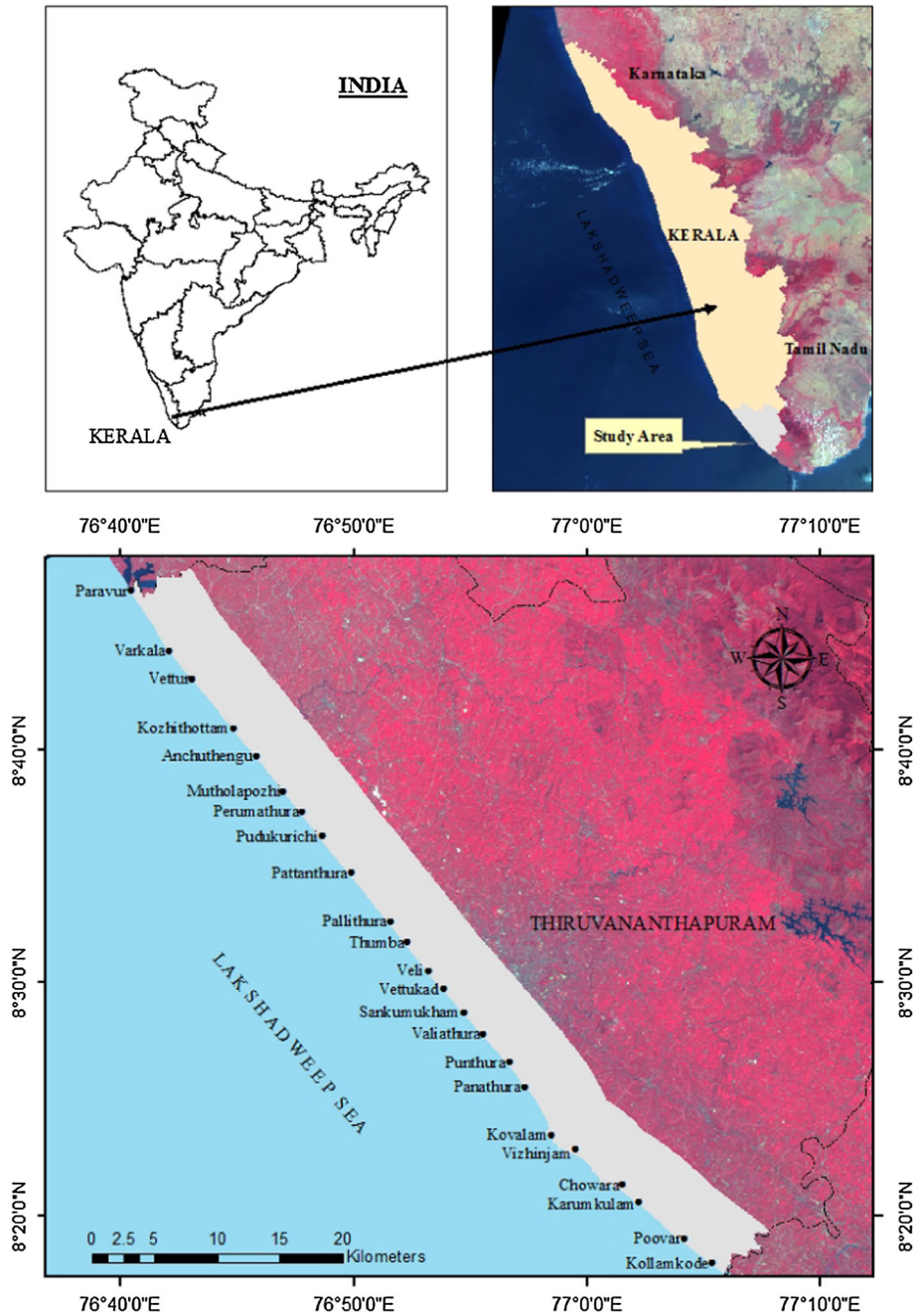


Fig. 1 Study area and location

variables are as follows: (a) coastal slope, (b) geomorphology, (c) shoreline change and (e) nearshore slope. The three process variables are as follows: (f) mean sea-level rise, (g) significant wave height and (h) mean tide range. The CS index allows the seven

variables to be related in a quantifiable manner that expresses the relative sensitivity of the coast to physical changes due to future sea-level rise. The methodology used is the same as that advocated by Gornitz (1990) and Thieler and Hammar-Klose (1999). The 76-km-long coastline of Thiruvananthapuram has been divided into six sediment cells on the basis of position of coastal promontories, estuaries, coastal slope and bathymetry. The coastline within the sediment cell is again divided into 1 km segments each by setting transect lines perpendicular to shoreline from a baseline placed parallel to the shoreline. Each of these 1 km segments is assigned a sensitivity value with respect to each of the seven variables. Sensitivity value for each specific variable is graded with a three point scale, namely low, medium and high sensitivity. Finally, the CSI has been worked out using a formulae discussed in the following sections.

Most of the parameters considered for calculating CSI are for dynamic in nature and data for which need to be acquired from different sources. Data are derived from conventional as well as using numerical model utilizing remote sensing and GIS. Nature of data, their sources and time period are presented in Table 1. Image enhancement, georeferencing, band extraction of satellite were carried out using ERDAS Imagine 9.2, and ArcGIS 9.3 was used for vectorization of coastline and contour map preparation. Each of the parameters is briefly described here.

3.1 Shoreline change rate

Coastal shorelines are always subjected to changes due to coastal processes, which are controlled by wave characteristics and the resultant nearshore circulation, sediment characteristics, beach form and bathymetry. In sensitivity scale, the accreted coasts will be considered as less sensitive areas, whereas areas of coastal erosion are considered as sensitive because of the resultant loss of private and public property and important natural habitats such as beaches, dunes and marshes. LANDSAT Thematic Mapper (TM) data of the year 1990 and Enhanced Thematic Mapper (ETM+) data for the year 2000 with a resolution of 30 m were used for enumerating rate of shoreline change. The data have been projected to the Universal Transverse Mercator (UTM) projection system with WGS –84 datum. The shoreline along the Thiruvananthapuram coastline for the year 1990 and 2000 was digitized using ArcMap 9.3 and ERDAS Imagine software using on-screen point mode digitization technique. The near infrared band that is most suitable for the demarcation of land–water boundary has been used to extract the shoreline. The vector layers were overlaid. The rate of shoreline change is calculated for the entire study area and the risk ratings are assigned. Three classes have been identified. The accreted coast is considered under the low-risk class (Fig. 2). The shoreline experienced change of <-3 m/year is categorized under medium-risk class and the shoreline recording change of >-3 m/year has been enumerated under high-risk category.

3.2 Significant wave height

Significant wave height is defined as the average height (trough to crest) of the one-third highest waves valid for the indicated 12-h period. Mean significant wave height is used here as a proxy for wave energy, which controls coastal sediment transport. The sensitivity study based on wave height is an important step in setting up an all-hazards warning and management system (USGS 2005). The wave energy increases with increases in the wave height, which results in loss of land area due to increased erosion and inundation along shore. Sensitivity of coast is directly proportional to wave height. For the present study, the

Table 1 Data source and period of different CSI parameters

Parameter	Data source	Year
Coastal geomorphology	Survey of India toposheet (1:50,000 scale)	1967
Coastal slope (%)	Contours from survey of India toposheet (contour interval 20 m)	1967
Shoreline change rate (m/year)	LANDSAT thematic mapper (TM) and enhanced thematic mapper (ETM +) (resolution 30 m)	1990 and 2000
Mean tidal range (m)	Indian Tide Table, for Cochin Port	2010 and 2011
Significant wave height (m)	Field data collected for Valiathura by (CESS)	1980–1984
Mean sea-level rise	Report of Indian Network for Climate Change Assessment (INCCA)	Data for 54 years
Nearshore slope (%)	Isobaths from Survey of India toposheet (isobaths interval, 9 m)	1967

monthly maximum wave height at Valiathura, Trivandrum, for the period 1981–1984 (Thomas 1990) is used. The significant wave height will not be varying much for a small region. The significant wave height range for Thiruvananthapuram coast during 1980–1984 is 1.78–2.24 m. The entire coastline of 76 km is in the medium sensitivity class (Fig. 3).

3.3 Mean tidal range

Tides are periodic and highly predictable. Tidal range is the vertical difference between the highest high tide and the lowest low tide. It is linked to both permanent and episodic inundation hazards. In the previous and related studies (Gornitz 1990; Shaw et al. 1998, Arun kumar et al. 2012; Srinivasa Kumar et al. 2010; Addo 2013), large tidal range was assigned a high-risk classification and low tidal range coast received a low-risk rating. This decision was based on the concept that a large tidal range is associated with strong tidal currents that influence coastal behavior. At the same time, there are studies based on the invert ranking, low tidal range means high-risk rating and vice versa (USGS 2001; Dwarakish et al. 2009). The reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tidal range. However, the present study is based on the earlier that high tidal range means high risk since the entire coastal area under study falls in the micro-tidal region, and the frequency of storm events is negligible here. For the present study, the difference between mean high high water and mean low low water for 2010 and 2011 for the Kochi, Kerala, are used (Indian Tide Tables 2010, 2011) (Fig. 4).

3.4 Geomorphology

Geomorphology of an area manifests the nature of landforms and the underlying process that operated incoming out of their landform. The term “coastal sensitivity” as used in this study refers to the geomorphic sensitivity of coastal landforms to hazards such as wave erosion, tsunami and storm surge flooding. Most erodible feature is subjected to the highest risk and therefore is the most sensitive, whereas the least erodible feature (like rocky cliff) faces lowest risk and hence least sensitive. Landforms identified in the study area include sandy beach, estuary, spits, sand bars, channel bars, sandy plains, pocket beaches,

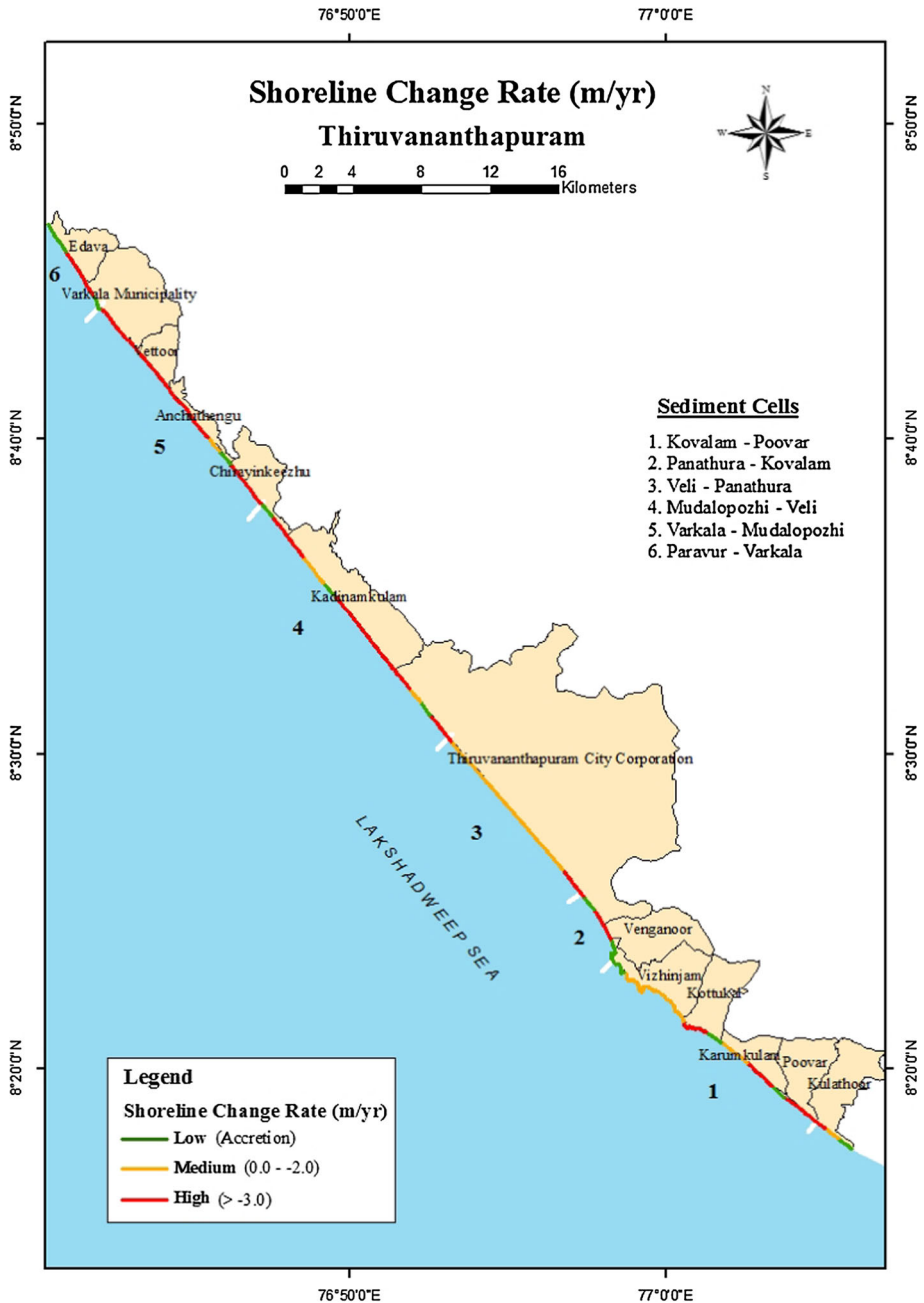


Fig. 2 Shoreline change rate (m/year)

crystalline and sedimentary coastal cliffs and laterite sloping terrain (Fig. 5). Northern and southern parts of the coastal stretch are characterized with coastal cliffs intermitted by the presence of pocket beaches. The central part and southern part show development of sandy

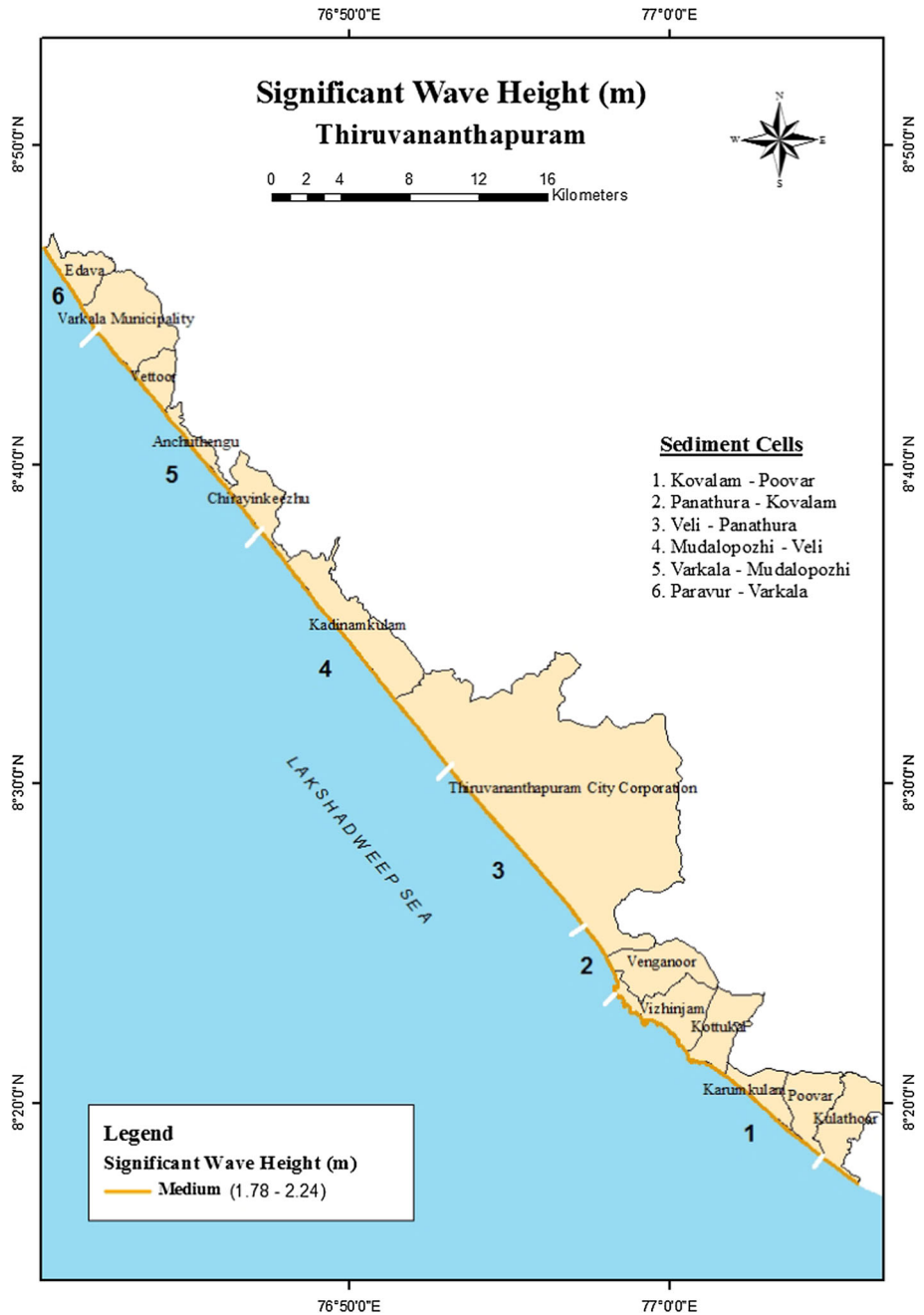


Fig. 3 Significant wave height (m)

beaches, sand bars, channel bars and estuaries. For the present study, geomorphology map has been prepared for the coastal zone of the area based on the Survey of India toposheets of 1:50,000 scale. Further, these geomorphic features were assigned the risk rating (Fig. 6)

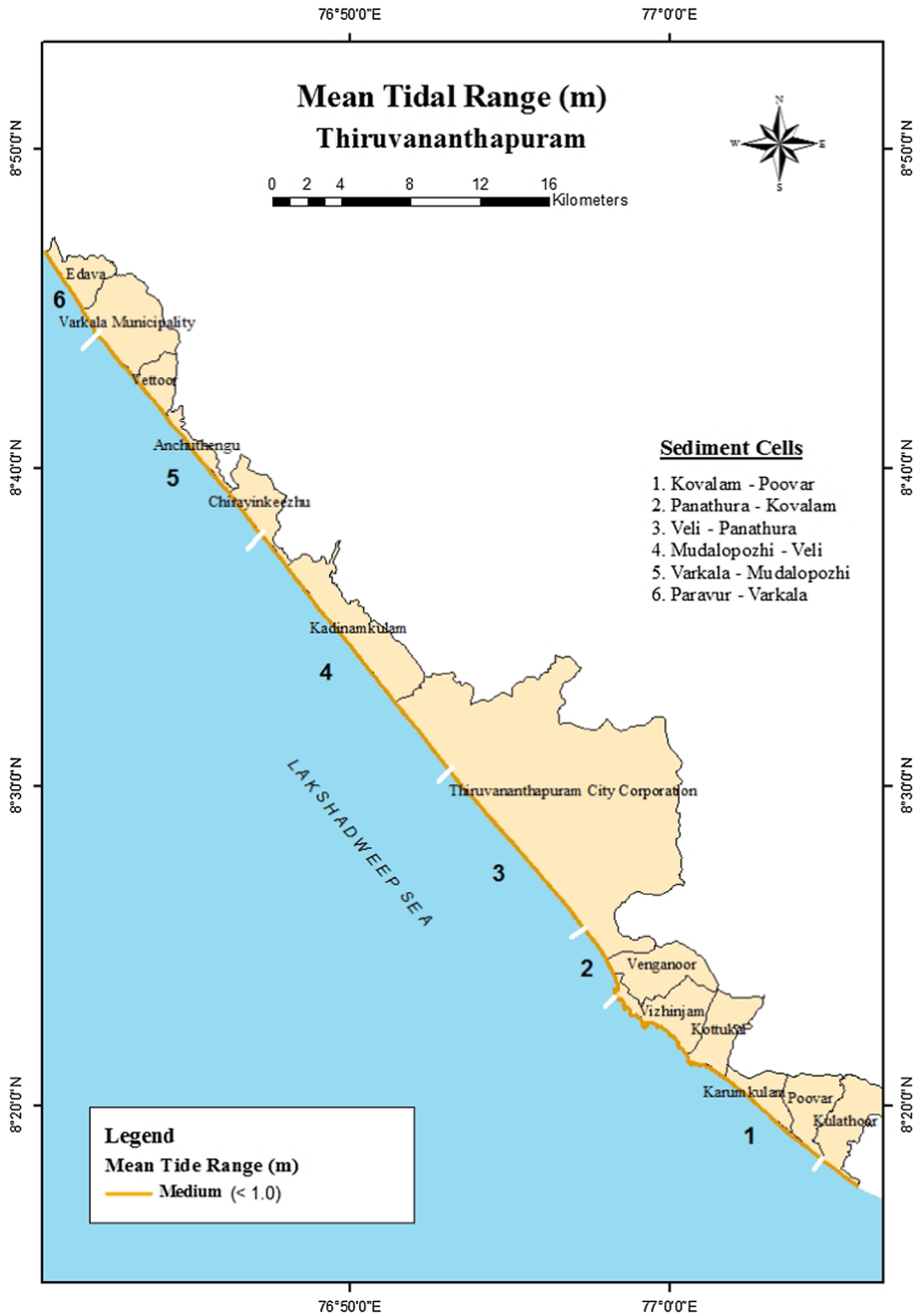


Fig. 4 Mean tidal range (m)

of high sensitive (sandy beaches, spits, sand bars, channel bars and estuary), medium sensitive (sandy plains, flood plains and sedimentary cliff) and low sensitive (crystalline cliffs and laterite sloping terrain).

3.5 Coastal slope

Coastal slope is another parameter that helps determination of relative sensitivity of inundation and the potential rapidity of shoreline retreat because low sloping coastal regions are thought to retreat faster than steeper regions. Locations having gentle land slope experiences great penetration of seawater compared to the locations with steep slopes. Therefore, land loss from inundation is simply a function of slope, lower the slope, the greater is the land loss (Klein et al. 2000). Coastal and nearshore areas having gentle slope are considered as highly sensitive areas and areas of steep slope as areas of low sensitive. For the present study, contours (contour interval 20 m) from Survey of India toposheets have been used. Coastal slope has been calculated for every 1 km by measuring the distance between the shoreline and the twenty-meter contour line. The elevation difference (20 m) between them has been divided by the distance. The slope in percentage is calculated here. Areas recording slope of greater than 3 % is assigned low sensitivity and that with 1–3 % slope is assigned as medium sensitivity and areas with <1 % slope is rated as of high sensitivity (Fig. 7).

3.6 Mean sea-level change rate

Sea-level rise is an important consequence of the climate change. Mean sea level is defined as the height of the sea with respect to a local bench mark, averaged over a period, such as a month or a year long enough so that the fluctuations caused by the waves and tides are largely assessed. Changes in the mean sea level as measured by coastal tide gauges are called relative sea-level changes (Church and Gregory 2001). The coast sharing high rate of sea-level rise is considered as highly sensitive area and vice versa. For the present study, the sea-level estimate for Kochi is used. The tide data for 54 years have used and the estimates show a sea-level trend of 1.31 mm/year having the glacial isostatic adjustment correction of -0.44 mm/year and the net sea-level rise of 1.75 mm/year (INCCA 2010). The annual sea level will not be changing for a small region, and hence, same risk rating is assigned to the entire study area (Fig. 8).

3.7 Nearshore slope

Nearshore coastal bathymetry decides fate of wave approaching the coast. Degree of nearshore slope can be estimated using bathymetry of the region. For the present study, depth contours with an interval of 9 m shown in the Survey of India toposheets have been vectorized and triangulated irregular network model was developed using ArcGIS 9.3 after georeferencing with Universal Traverse Mercator (UTM) projection with WGS-84 datum. The nearshore slope in percentage has been calculated using ArcGIS Spatial Analyst extension. The nearshore areas having gentle slope are considered as high sensitive areas and areas of steep slopes are considered as areas of low sensitive (Fig. 9). Areas recording nearshore slope of greater than 4 % is assigned low sensitivity and that with 2–4 % slope is assigned as medium sensitivity and areas with <2 % slope is rated as of high sensitivity (Fig. 9).

3.8 Calculation of CSI

The CSI is determined by combining the relative risk variables to create a single indicator. Each of the 7 input relative risk variables are then assigned appropriate risk classes 1, 2 and

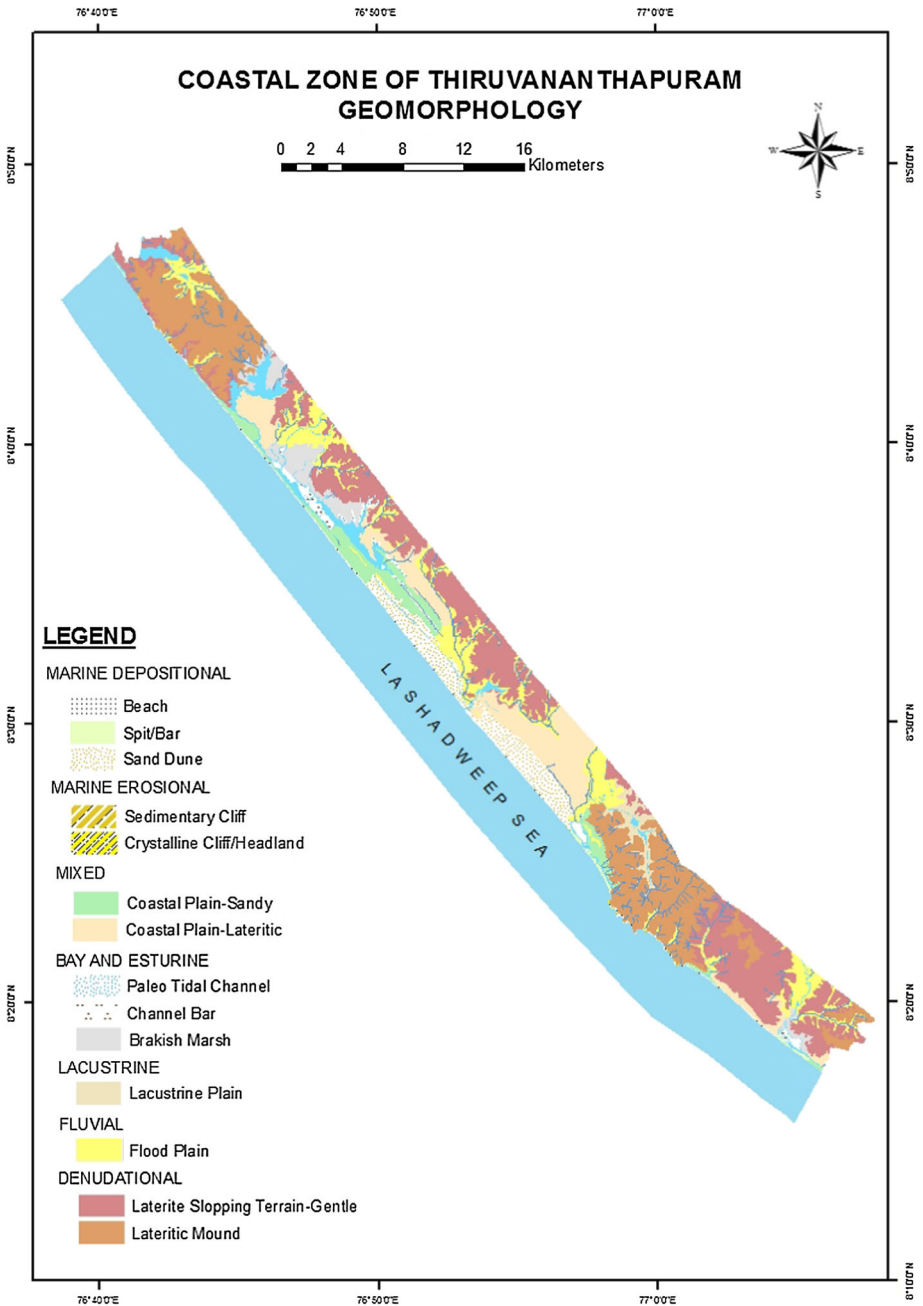


Fig. 5 Geomorphology

3 based on its ability to cause low, medium and high damage, respectively, for the coastline. The risk rating assigned for each variable is given in Table 2. The CSI is calculated based on the formula given here.

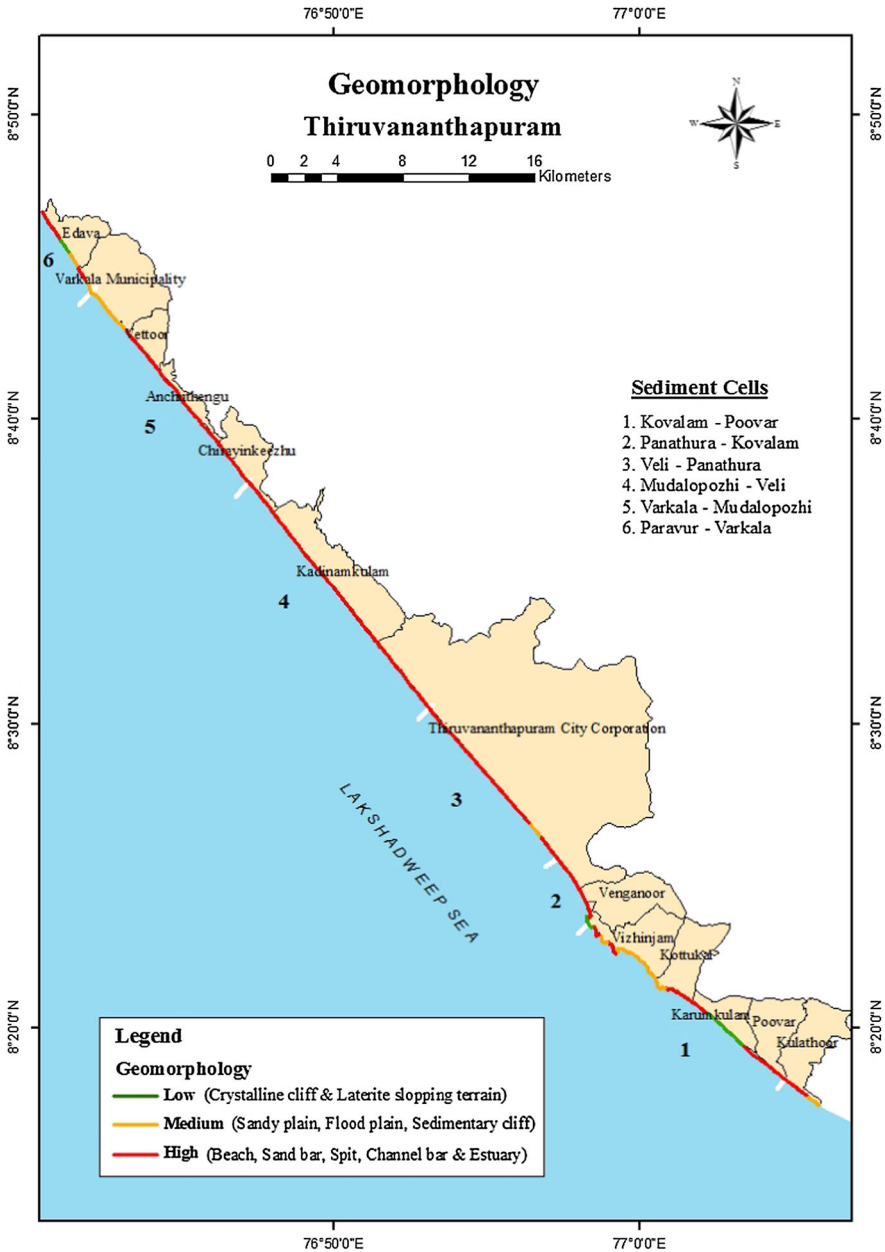


Fig. 6 Geomorphology—risk rating

$$CSI = \sqrt{(a \times b \times c \times d \times e \times f \times g) / 7},$$

where *a* = shoreline change rate (m/year); *b* = significant wave height (m); *c* = mean tidal range (m); *d* = coastal slope (%); *e* = coastal geomorphology; *f* = nearshore slope (%); *g* = mean sea-level rise (mm)



Fig. 7 Coastal slope (%)

4 Results

The six sediment cells identified from the coastline of Thiruvananthapuram are Kovalam–Poovar, Panathura–Kovalam, Veli–Panathura, Muthalopozhi–Veli, Varkala–Muthalopozhi

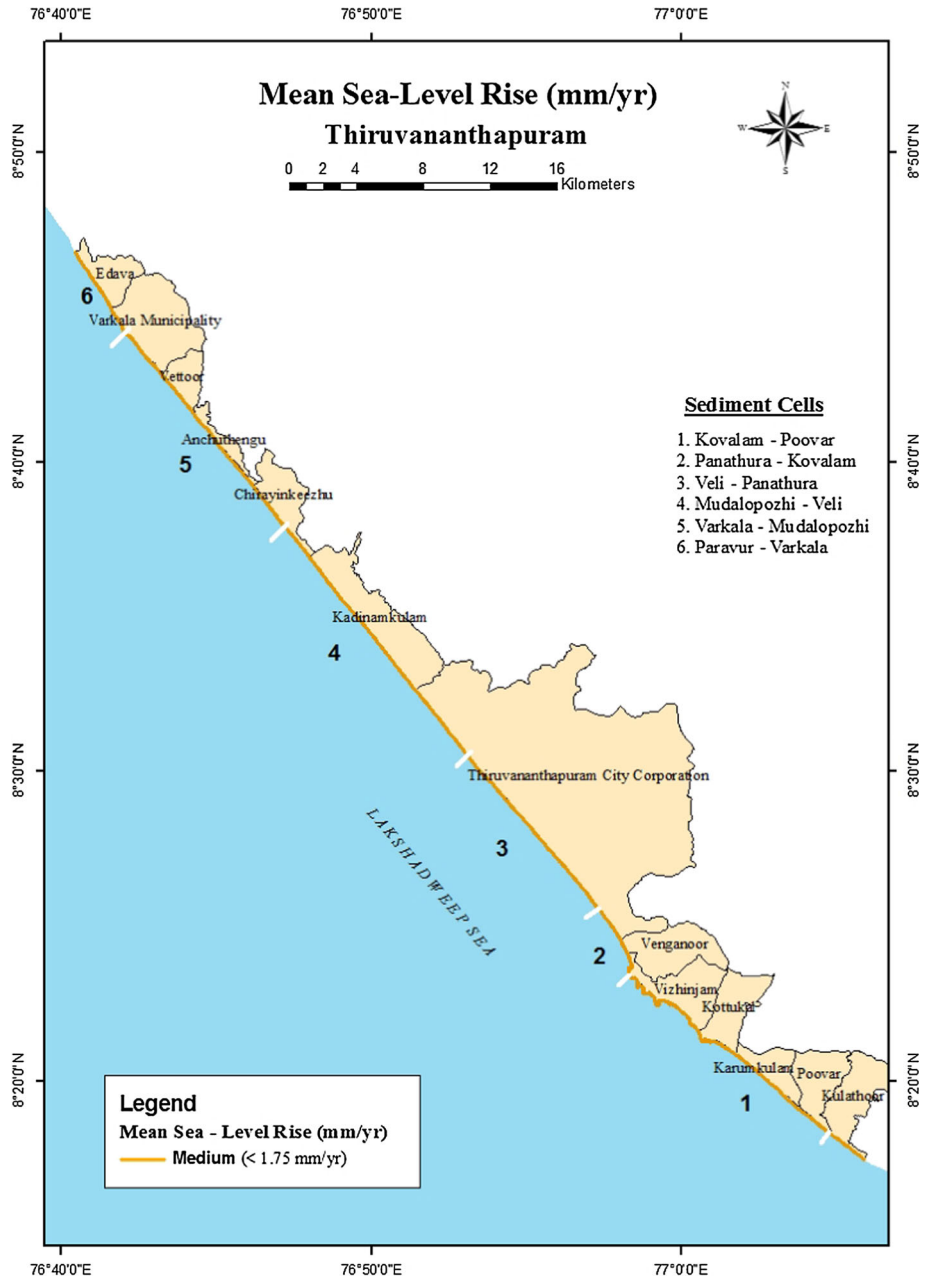


Fig. 8 Mean sea-level rise (mm/year)

and Paravur–Varkala on the basis of position of coastal promontories, estuaries, coastal slope and bathymetry. The risk rating to the seven variables for each kilometer segments in each sediment cell have input (Table 3). The present study reveals that about 39 km of coastline has a high-risk rating recording erosion rate of more than -3 m/year. About

23 km of coastline has a medium-risk rating with erosion rates between 0.1 and -3 m/year and 14 km recorded accretion along the coastal stretches with low-risk rating.

The coastal zone of Thiruvananthapuram is classified as low, medium and high sensitivity risk (Fig. 10). The CSI value along the Thiruvananthapuram coastline varied from 1.11 to 9.62. The percentile values have been used to identify three classes of sensitivity (Pendleton et.al 2005). The 25th and 50th percentiles of CSI value are 2.62 and 3.70, respectively. Those parts of the coastline having CSI values ranging from 1.51 to 2.62 are considered to be in low sensitive category and those ranging from 2.62 to 3.70 are considered to be medium sensitive, and the remaining parts having CSI values of more than 3.70 are high sensitive (Table 4). This study reveals that 55 km (72 %) of the Thiruvananthapuram coastline is in high sensitive category. Veli–Panathura, Muthalopozhi–Veli, Varkala–Muthalopozhi and Paravur–Varkala sediment cells have most of their areas belonging to high sensitivity category. The detailed sediment cell wise distribution of coastal sensitivity is provided below.

4.1 Kovalam–Poovar

The southernmost sediment cell with a length of 21 km along the coastline in NW to SE direction between Kovalam Headland on the north and Poovar estuary on the south, covers Kulathoor, Poovar, Karumkulam, Kottukal and Vizhinjam Grama Panchayat and is significant both for economic and tourism development. The calculated CSI values in this sediment cell range between 1.51 and 7.86 (Table 4). The high sensitive area spreading over 4 km is observed along the coastline to the south of Poovar and Vizhinjam Grama Panchayats. These segments require immediate attention as this is an estuarine coastal stretch, densely populated and significant for fishing and tourism. The part of coastline (9 km) in northern part of Kottukal and sedimentary cliff area of Vizhinjam Grama Panchayats fall under medium sensitive category (Fig. 10). The proposed Vizhinjam International Port site within this sediment cell recorded a medium sensitivity. The low sensitive area (8 km) includes Kovalam headland of Vizhinjam, Karumkulam and southern part of Kulathoor Grama Panchayat. The proposed Vizhinjam International port site within this sediment cell recorded a medium sensitivity.

4.2 Panathura–Kovalam

This sediment cell spreads over 4-km coastal stretch of Thiruvananthapuram city between Panathura estuary formed by river Karamana on the north and Kovalam Headland in the south.

The CSI values of this sediment cell vary between 3.21 and 7.86 (Table 4). The 3-km coastline covering Panathura and Vazhamuttam of Thiruvananthapuram Corporation and Venganore Grama Panchayat comes in the high sensitive area and 1-km coastline along Vizhinjam Grama Panchayat belongs to medium sensitive grade. Since the coastline of this sediment cell is significant for tourism development in Kerala, it needs special attention while preparing ICZM.

4.3 Veli–Panathura

The 12-km-long sediment cell lies between Veli and Panathura estuaries covers Veli, Karikakam, Vettukad, Kadakampalli, Sankhumukam, Valiathura, Muttatura, Beemapalli,

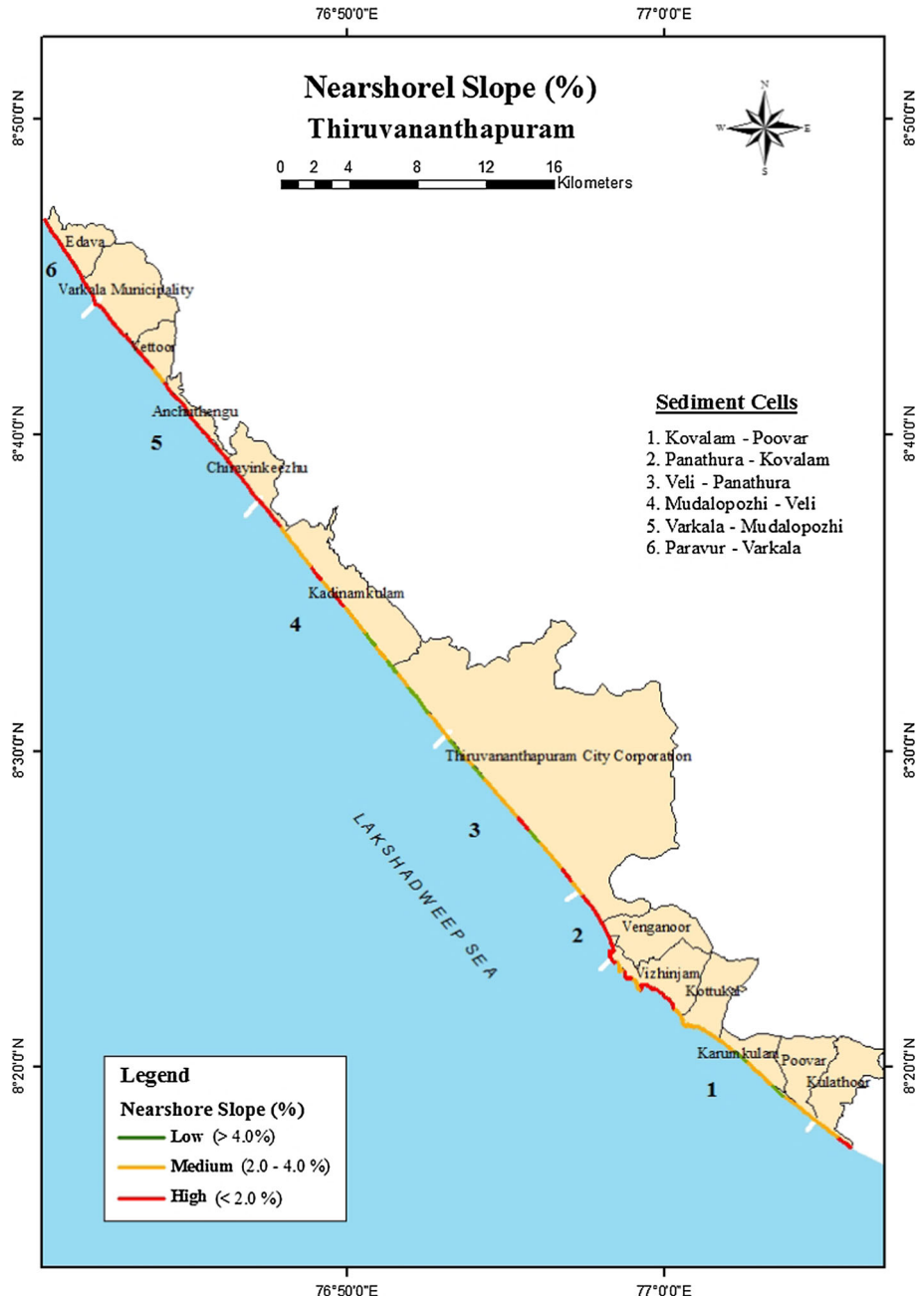


Fig. 9 Nearshore slope (%)

and northern part of Punthura areas of Thiruvananthapuram city corporation. Narrow sandy beach is visible all along this coastal stretch and beaches at Veli and Sankhumukam are famous tourist destinations attracting people from all over the world. The CSI values of

Table 2 Rating of parameters according to risk level

Parameters	Risk level		
	Low	Medium	High
Geomorphology	Crystalline cliff, laterite sloping terrain	Sandy plains, flood plains and sedimentary cliff	Beach, sand bar, spit, channel bars and estuary
Coastal slope (%)	More than 3.0	1.0–2.0	<1.0
Shoreline change rate (m/Y)	Accretion	0.1 to –3.0	More than –3
Mean tide range (m)	–	<1.0	–
Significant wave height (m)	–	1.78–2.24	–
Nearshore slope (%)	More than 4.0	2.0–4.0	<2.0
Mean sea-level rise (mm/y)	–	1.75	–

this sediment cell vary between 3.70 and 9.62 (Table 4). Most part of this sediment cell (11 km) covering Punthura, Beemapalli, Valiathura, Muttatura, Sankumugham and Vettukad fall in the high sensitive category. These areas are important both for tourism and socio-economic development of Kerala. Beach tourism at Sankumugham and Veli, religious centers at Beemapalli and Vettukad, Trivandrum International Airport and fishing villages at Valiathura and Punthura are important activities that require proper protection.

4.4 Muthalopozhi–Veli

The sediment cell stretches from Muthalopozhi estuary of Vamanapuram River in the north and Veli estuary in the south for 19 km is very significant on strategic point of view as it borders the TERLS (Thumba Equatorial Rocket Launching Station). Coastline of Chirayinkeezhu, Kadinamkulam Grama Panchayats and northern part of Thiruvananthapuram City Corporation became the part of this sediment cell. The CSI values of this sediment cell range between 3.21 and 9.62 (Table 4). Similar to Veli–Panathura sediment cell, this sediment cell has 18 km in high and 1 km in medium sensitive area. The high sensitive area includes Kadathutra and Pallithura of Thiruvananthapuram City Corporation; Punthura, Mundanchira and Pudukuruchi areas of Kadinamkulam Grama Panchayat; and Perumathura, and Muthalopozhi of Chirayinkeezhu Grama Panchayat. The 1-km coastline at Thumba falls in the low sensitivity category.

4.5 Varkala–Muthalopozhi

This sediment cell is 14-km-long bordering Varkala cliff on the north and Muthalopozhi estuary in the south borders the coastal zone of Varkala Municipality and Vettoor, Anchuthengu and Chirayinkeezhu Grama Panchayats. The CSI values of this sediment cell vary between 4.54 and 9.62 (Table 4). The entire 14.00-km coastline of this sediment cell fall in the high sensitive grade and cover southern part of Varkala Municipality, Vettoor, Anchuthengu and northern part of Chirayinkeezhu Grama Panchayats. The main activities in this cell are tourism, coir industry and fishing.

Table 3 Sediment cell wise distribution of coastline under risk level for each parameter

Parameters	Sediment cell/extent of sensitivity (length of coastline in km)							
	Risk rating	Kovalam–Poovar	Panathura–Kovalam	Veli–Panathura	Muthalopozhi–Veli	Varkala–Veli	Paravur–Varkala	
Geomorphology	Low	4.00	–	–	–	–	–	1.00
	Medium	7.00	4.00	1	–	–	3.00	2.00
	High	10.00	–	11.00	19.00	–	11.00	3.00
Shoreline change rate (m/year)	Low	5.00	2.00	–	3.00	1.00	–	3.00
	Medium	9.00	–	10.00	3.00	1.00	–	–
	High	7.00	2.00	2.00	13.00	12.00	–	3.00
Coastal slope (%)	Low	19.00	2.00	–	–	6.00	–	3.00
	Medium	1.00	2.00	1.00	1.00	–	–	2.00
	High	1.00	–	11.00	18.00	8.00	–	1.00
Mean sea-level rise (m/year)	Low	–	–	–	–	–	–	–
	Medium	21.00	4.00	12.00	19.00	14.00	–	6.00
	High	–	–	–	–	–	–	–
Mean tidal range (m)	Low	–	–	–	–	–	–	–
	Medium	21.00	4.00	12.00	19.00	14.00	–	6.00
	High	–	–	–	–	–	–	–
Significant wave height (m)	Low	–	–	–	–	–	–	–
	Medium	21.00	4.00	12.00	19.00	14.00	–	6.00
	High	–	–	–	–	–	–	–
Nearshore slope (%)	Low	2.00	–	3.00	4.00	–	–	–
	Medium	13.00	–	7.00	10.00	1.00	–	–
	High	6.00	4.00	2.00	5.00	13.00	–	6.00

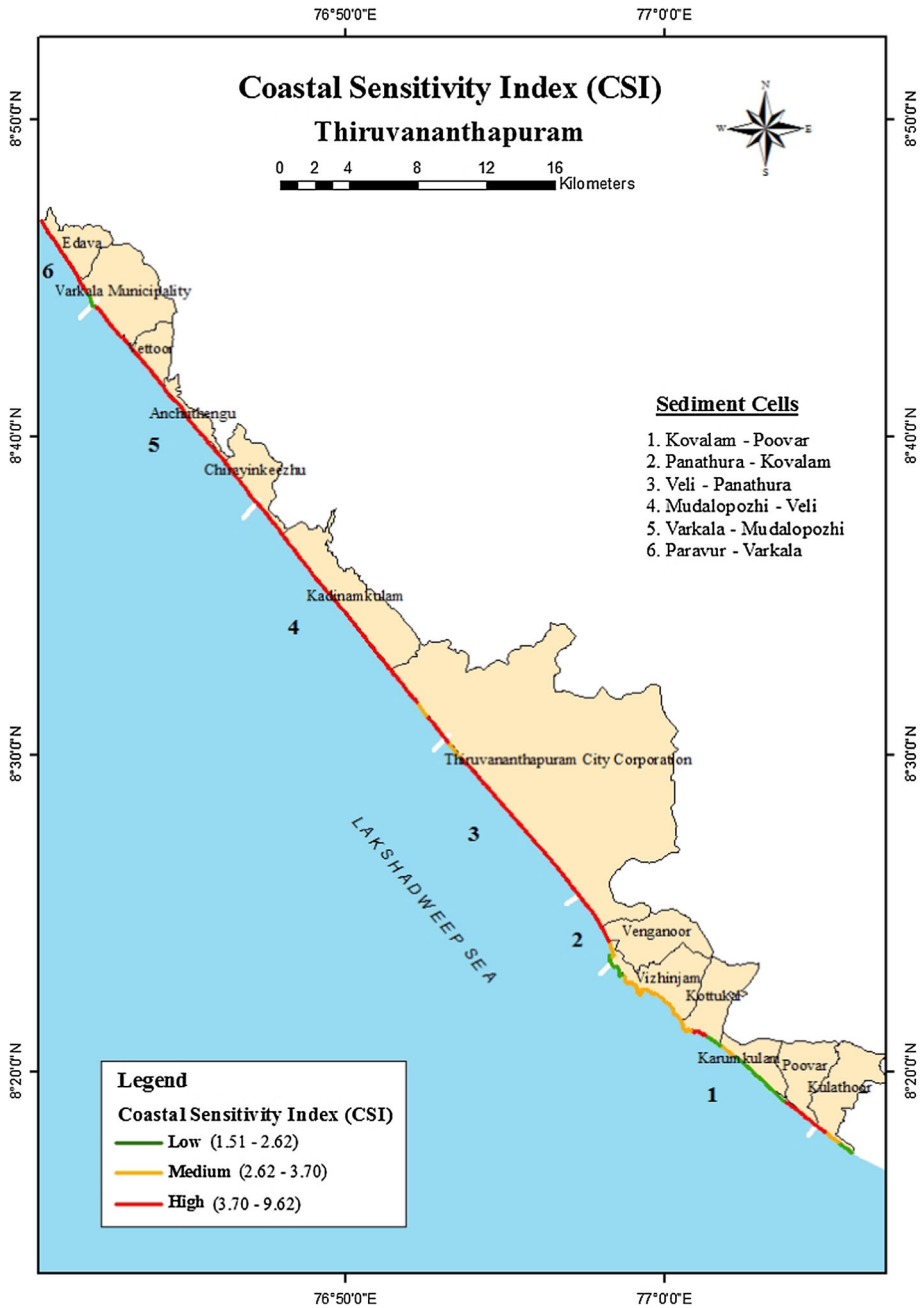


Fig. 10 Coastal sensitivity index (CSI)

Table 4 Coastal sensitivity index values

Sediment cell	Coastal segment	CSI values	Average CSI values
Kovalam–Poovar	1–21	1.51–7.86	3.66
Panathura–Kovalam	22–25	3.21–7.86	5.29
Veli–Panathura	26–37	3.70–9.62	6.28
Muthalopozhi–Veli	38–56	3.21–9.62	7.01
Varkala–Muthalopozhi	57–70	4.54–9.62	7.12
Paravur–Varkala	71–76	2.62–5.55	4.56

4.6 Paravur–Varkala

The northern most sediment cell of Thiruvananthapuram coast for 6 km from Paravur estuary in the north and Varkala cliff in the south covers Edava Grama Panchayat and part of Varkala Municipality. The CSI values of this sediment cell range between 2.62 and 5.55. The high sensitive area for 5 km of coastline comprises of northern part of Varkala Municipality and whole coastal stretch of Edava Grama Panchayat. The 1-km coastline belonging to low sensitive area includes Varkala cliff and adjacent area of Varkala Municipality.

This study reveals that 56 km (74 %) of the Thiruvananthapuram coastline is in high sensitive category. Veli–Panathura, Muthalopozhi–Veli, Varkala–Muthalopozhi and Paravur–Varkala sediment cells have most of their areas belonging to high sensitivity category.

5 Discussion

The variables used to derive CSI/CVI in this study is similar to that used in Thieler and Hammer-Klose (1999), Pamela et al. (2010), Pendleton et al. (2005), Pendleton et al. (2010), Duriyapong et al. (2011), Karymbalis et al. (2012) and Addo (2013). This method is very effective in highlights coastal areas where the various effects of sea-level rise may be the greatest. The study reveals that both the geologic and physical variables have involved in the modification of the coast in the study area. The physical variables such as significant wave height, mean tidal range and mean sea-level rise have less influence over the study area. The geologic variables show the maximum variability and thus have the most influence on the CSI value. The most influential variables in the CSI are geomorphology and shoreline change; therefore, they may be considered the dominant factors controlling how the Thiruvananthapuram coast will evolve as sea level rises.

The high sensitivity areas within Veli–Panathura, Muthalopozhi–Veli, Varkala–Muthalopozhi and Paravur–Varkala sediment cells are due to the dominance of sensitive geomorphic features like beach, estuary, channel bars and spit/bar, high shoreline change rate (>–3 m/year), gentle nearshore slope (<2 %) and gentle coastal slope (<1 %). Most part of this area is densely populated and possesses residential, recreational and agricultural lands. A magnitude of 8.9 earthquake of December 26, 2004, with epicenter in the Sumatra has generated the devastative tsunami waves which have also affected these sediment cells with a run up height of more than 2 m (Kurian and Praveen 2010). The medium sensitivity for 12 km revealed from parts of Kovalam–Poovar and Paravur–Varkala sediment cells are

eroding, dominance of medium sensitive landform: sedimentary cliffs at Vizhinjam and Varkala and extensive sandy plains with a shoreline change rate (0.1 to -3 m/year) in the Panathura–Kovalam, Veli–Panathura, Muthalopozhi–Veli and Varkala–Muthalopozhi sediment cells. The coastal and nearshore slopes are also belonging to medium-risk category.

The sediment cell lies between Kovalam and Poovar encompasses low sensitive areas particularly because of the presence of crystalline sea cliffs and laterite sloping terrain with steep nearshore and coastal slopes. The coastlines north of Karumkulam and Kulathoor Grama Panchayats are accretional which made this stretch low sensitive. The CVI/CSI studies conducted along the Indian coast (Rajawat et al. 2006; Dinesh Kumar 2006; Hegde and Raju 2007; Pradeep Kumar and Thakur 2007; Nageswara Roa et al. 2008; Dwarakish et al. 2009; Srinivasa Kumar et al. 2010; Mahendra et al. 2011 and Arun Kumar and Pravin Kunte 2012 Sheik Mujabar and Chandrasekhar 2013; Murali Mani et al. 2013) following the same methodology adopted in the present study is succeed in highlighting the sensitive sectors in respective east and west coasts. However, all these studies considered coarse coastal grids of larger size which is highly generalized and the 1 km transect applied here is more realistic to address the situation. The assessment of coastal sensitivity within the framework of coastal sediment cells distinguished the present study from all the earlier studies which have based coastal grids as the base for the apply of different CSI variables. Since sediment cells provide natural boundary to the coastal management activities without exerting negative effects on the distant cells, the sensitivity assessment within the framework of sediment cells may enable coastal planners and managers to appreciate the contrast between the most sensitive and the least sensitive areas within the study area. This can assist in prioritizing efforts to enhance the natural resilience of the coast, or invest in adoption measures such as vegetating dunes and geotextiles. The six sediment cells identified from the study area reflects the complex dynamic nature of various coastal processes operating on them. The CSI is based only on physical variables; integration with further social, cultural and economic factors may enable a broader assessment of the vulnerability of the coast and the communities who live there.

Adaptation measures in the context of climate change and sea-level rise are relevant in integrated coastal zone management. ICZM plan, though active in India, is still not fully functional. It must emphasize more on building regulations, urban planning, development of institutional capacity, involvement of local community, increasing public awareness and should be based on coastal sediment cells in order to achieve long-term sustainable development.

6 Conclusions

The present study was carried out with a view to identify vulnerable areas due to future sea-level rise along the Thiruvananthapuram coast within the framework of coastal sediment cells through the analysis of conventional and remotely sensed data and the conclusions of the same are as follows.

Coastal sensitivity index (CSI) provides insight into the relative potential of coastal damage due to future sea-level rise. The maps presented here can be viewed in at least two ways: (1) to identify areas where physical changes are most likely to occur as sea level rises; and (2) as a planning tool for managing and protecting resources in the study area. This study revealed that 55 km (72 %) of the coastline belongs to high sensitive category in the study area. The high sensitive parts are mainly distributed in Veli–Panathura,

Muthalopozhi–Veli, Varkala–Muthalopozhi and Paravur–Varkala sediment cells. Although construction of sea walls and groins are available to protect the coast in certain areas, the inappropriate construction of these structures without considering the sediment source, pathways, movement and sinks has accelerated the coastal erosion in the distant areas posing new threat to people and coastal ecosystem. Hence, the present study will be useful for disaster mitigation and management in Thiruvananthapuram coast. Sensitivity of the coast if considered in conjunction with other social factors may be an input into broader assessments of the overall vulnerability of coasts and their communities.

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