Author version: *Nat. Hazards, vol.64; 2012; 853-872*

Coastal vulnerability assessment for Chennai, east coast of India using geospatial techniques

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Abstract

The study area is 56 km coastal zone of Chennai districts of the Tamil Nadu state, southeast coast of India. The coastline, which includes tourist resorts, ports, hotels, fishing villages, and towns, has experienced threat from many disasters such as storm, cyclone, flood, tsunami and erosion. This was one of the worst affected area during 2004 Indian Ocean tsunami and during 2008 Nisha cyclone. The present study aims to develop a Coastal Vulnerability Index (CVI) for the Chennai coast using eight relative risk variables to know the high and low vulnerable areas, area of inundation due to future SLR, and land loss due to coastal erosion. Both conventional and remotely sensed data were used and analyzed through the modeling technique and with the aid of the Remote Sensing and Geographic Information System (GIS) tools. Zones of vulnerability to coastal natural hazards of different magnitude (high, medium, and low) are identified and shown on a map. Coastal regional elevation, near shore bathymetry, and socio-economic condition has been considered as an additional important variables. This study revealed that 11.01 km of the coastline is low vulnerable, 16.66 km is medium vulnerable and 27.79 km is high vulnerable in the study area, showing the majority of coastline is prone to erosion. The map prepared for the Chennai coast can be used by the state and district administration involved in the disaster mitigation and management plan and also as a tool in planning a new facility and for insurance purpose.

Keywords: Coastal vulnerability index, SRTM data, geographic information systems, natural hazards, Chennai.

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1 Introduction

In addition to all anthropological stresses that coastal cities have been facing now, implications of exacerbated pressures from the prospects of climate change and associated sea level rise will be of serious concern in future. Despite the magnitude and urgency of the issue, scientific understandings of climate change and potential risks to coastal cities have not been fulfilled – though, since very long it has been recognized that these perspectives are required for a range of purposes. Due to diverse human pressures, many coastal areas are already experiencing acute environmental problems, such as coastal erosion, pollution, degradation of dunes, and saline intrusion of coastal aquifers and rivers. Indices have been developed in the past in order to study disturbances related to factors such as sea-level rise, wave erosion (Gornitz et al. 1997); human impacts (McLaughlin et al. 2002), and oil-spill impacts. The objective of coastal indices is to classify the shorelines into uniform entities having similar features. This classification can then help in the development of sound coastal management policies. To prepare a comprehensive coastal index that is a true representation of the ground realities, useful, sound, and reliable data are a prerequisite.

Tremendous population and developmental pressures have been building in the coastal areas for the last four decades. According to the estimates of the United Nations in 1992, more than half of the world's population lives within 60 km of a shoreline. Also, urbanization and the rapid growth of coastal cities have been dominant population trends over the last few decades, leading to the development of numerous mega cities in all coastal regions around the world. According to the United Nations Environment Programme (UNEP) report, the average population density in the coastal zone was 77 people/km^2 in 1990 and 87 people/km^2 in 2000, and a projected 99 people/km^2 in 2010 (UNEP, 2007). At least 200 million people were estimated to live in the coastal floodplain in 1990 (in the area inundated by a 1 in 1000 year flood), and it is likely that their number will increase to 600 million by the year 2100 (Mimura and Nicholls, 1998). Furthermore, global climate change and the threat of accelerated sea-level rise exacerbate the already existing high risks of storm surges, severe waves, and tsunamis. It has been estimated that a 1-m rise in sea-level would expose nearly 56 million people from 84 developing countries. (Dasgupta et al 2007: 9-10).

Vulnerability can be defined as the degree to which a person, community or a system is likely to experience harm due to an exposure to an external stress. Generically, vulnerability is a set of conditions and processes resulting from physical, social, economic and environmental factors that increase the susceptibility of a community to the impact of hazards (Mahendra et al. 2011). Vulnerability assessment is an estimate of the degree of loss or damage that could result from a hazardous event of given severity, including damage to structures, personal injuries, and interruption of economic activities and the normal functions of settlements.

Thieler and Hammer-Klose (1999) used coastal slope, geomorphology, relative sea-level rise rate, shoreline change rate, mean tidal range, and mean wave height for assessment of coastal vulnerability of the U.S. Atlantic coast. Pendleton, et al. (2005) assessed the coastal vulnerability of Golden Gate National Recreation area to sea level rise by calculating a coastal vulnerability index (CVI) using both geologic (shoreline-change rate, coastal geomorphology, coastal slope) and physical process variables (sea-level change rate, mean significant wave height, mean tidal range). Using sea level rise, erosion, inundation study, potential vulnerability implications of sea level rise for the coastal zone of Cochin, SW coast of India have been studied (Dinesh kumar 2006) to provide inputs to develop appropriate policies focusing on climate change issues for the region. Coastal vulnerability index (CVI) for the estimation of vulnerability of the coastal region of Mangalore coast, India, from Talapady to Surathkal has been developed (Hegde and Raju 2007) to understand relative vulnerability of the various segments of the Mangalore coast to coastal erosion hazards. Dwarakish et al. (2009) calculated CVI for Udupi coastal zone of Karnataka from shore-line change rate, sea-level change rate, coastal slope, mean tidal range, coastal geomorphology. Srinivasa Kumar et al. (2010) assessed the CVI for the Orissa, India coast using shore-line change rate, sea-level change rate, coastal slope, significant wave height, tidal range, coastal regional elevation, and coastal geomorphology and tsunami run-up. Mahendra et al. (2011) assessed coastal multi-hazard vulnerability along the Cuddalore-Villupuram, east coast of India with geospatial techniques by incorporating shore-line change rate, sea-level change rate, coastal slope, tidal range, coastal regional elevation, storm surge etc.

Scientific study of the natural hazards and coastal processes of the Indian coast has acquired greater significance after the December 2004 tsunami as the country understood the impact of natural hazards in terms of high damage potential for life, property, and the environment. The rapidly growing population of coastal residents and their demand for reliable information regarding the vulnerability of coastal regions have a necessitate need for classifying coastal lands and evaluating the hazard vulnerability. The main objectives of the geographic information system (GIS) and remote sensing based study is to develop a coastal vulnerability index map for coastal erosion and then use it to assess the impact along the Chennai coast, with a view to identify and quantify the spatial extent of the inundation caused by composite hazards along coastal areas of Chennai.

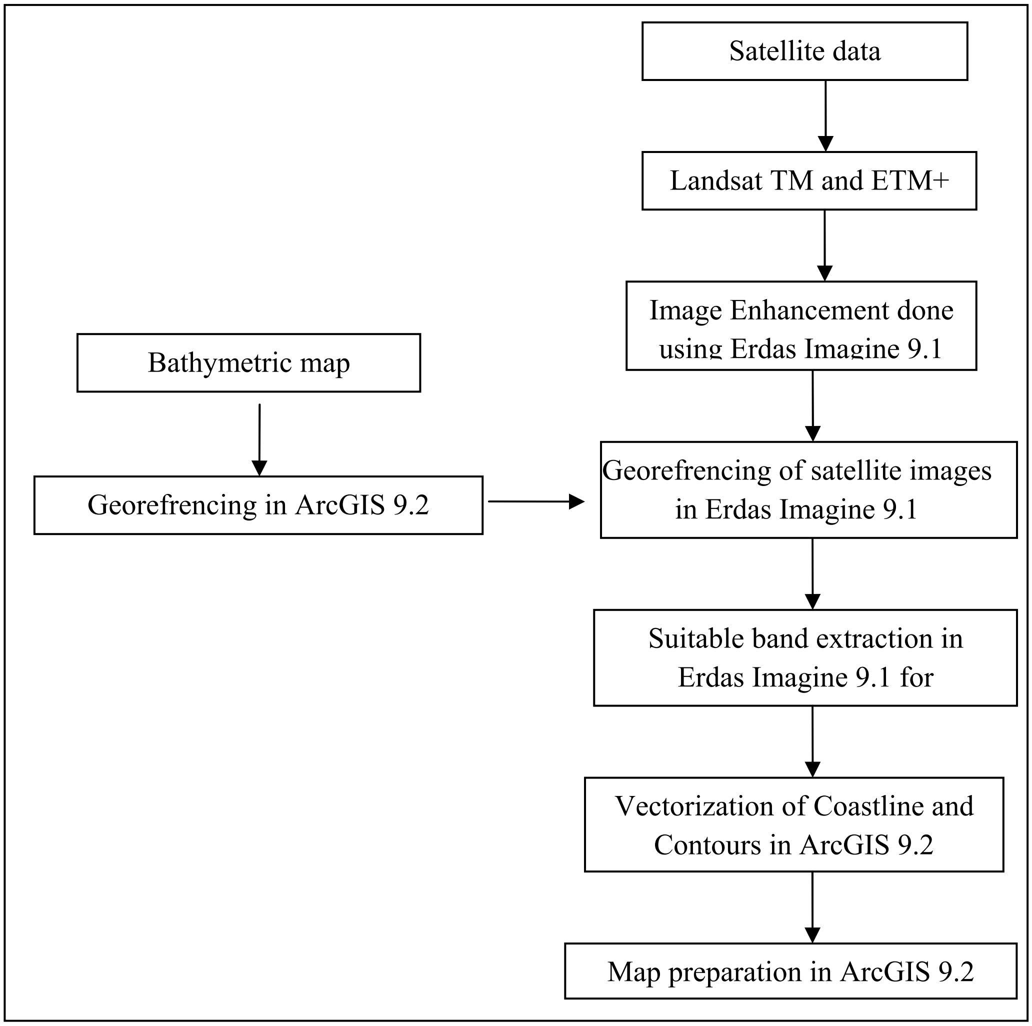
2 Study Area

The current study area is 56 km coastal zone covering Chennai districts of the Tamil Nadu state along the southeast coast of India (Fig. 1). Chennai is the capital city of the Tamil Nadu state. The study area lies between $12^{o}54'0''$ and $13^{o}18'0''$ of the northern latitude and $80^{o}12'$ and $80^{o}19'$ of the southern longitude on a `sandy shelving breaker swept beach'. It is bounded on the east by the Bay of Bengal and on the remaining three sides by land mass (http://www.chennai.tn.nic.in). Chennai is the fourth most populous metropolitan area and the fifth most populous city in India. Chennai city had a population of 4.34 million in the 2001 census within the area administered by the Corporation of Chennai and an extended Metropolitan Population of 6.5 million. The urban agglomeration of metropolitan Chennai has an estimated population over 8.2 million people. (http://en.wikipedia.org/wiki/Chennai# Geography).

The average elevation along Chennai coast is around 6.7 meters (22 ft), and its highest point is 60 m (200 ft). The Marina Beach runs for 12 km along the shoreline of the city. Two rivers meander through Chennai, the Cooum River (or Koovam) through the centre and the Adyar River to the south. A third river, the Kortalaiyar, flows through the northern fringes of the city before draining into the sea at Ennore.

3 Materials and Methods

The CVI allows the eight variables to be related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to future sea level rise. This method yields numerical data that cannot be equated directly with particular physical effects. It does, however, highlight areas where the various effects of sea level rise may be the greatest and methodology is the same as that used by Gornitz (1990) and Thieler and Hammer-Klose (1999). Shoreline Change Rate, Sea Level Change Rate, Regional Elevation, Bathymetry, mean Tidal Range, Significant Wave Height, geomorphology and socio-economy are eight variables considered in this study. Each section of the coastline is assigned a risk rate for each specific data variable. The CVI is calculated as the square root of the product of the ranked variables divided by the total number of variables.



Most of these parameters are dynamic in nature and require a large amount of data from different sources to be acquired, analyzed, and processed. The parameters are derived from conventional as well as using numerical model utilizing remote sensing and GIS as tools. Landsat Thematic Mapper, TM, of year 1990 and Enhanced Thematic Mapper data, ETM+, of 2000 (http://glcfapp.glcf.umd.edu:8080/esdi/index.jsp), and other data sets, their source and period used in the present study is presented in Table 1. The importance of each parameter and the procedure to generate the same are explained in the succeeding paragraphs and general steps to prepare shoreline maps using satellite data, image processing system and geographic information system are presented in flow chart 1.

Flow Chart 1: Steps to prepare shoreline maps using satellite data, image pressing system and geographic information system are presented.

3.1 Shore line Change Rate

Coastal shorelines are always subjected to changes due to coastal processes, which are controlled by wave characteristics and the resultant near-shore circulation, sediment characteristics, beach form, etc. From the coastal vulnerability point of view, coasts subjected to accretion will be considered as less vulnerable areas as coast move toward the ocean and result in the addition of land areas, whereas, areas of coastal erosion are considered as vulnerable because of the resultant loss of private and public property and important natural habitats such as beaches, dunes, and marshes. Ortho-rectified Landsat TM and ETM+ images covering the Chennai coastline for the years 1990 and 2000 were downloaded from Global Land Cover Facility (GLCF). The data have been projected to the Universal Transverse Mercator (UTM) projection system with WGS-84 datum. The shoreline along the Chennai coastline for years 1990 and 2000 was digitized using ArcMap 9.2. and ERDAS Imagine software using on-screen point mode digitization technique. Near infrared band has been used to demarcation of the land-water boundary while extracting both shorelines. The digitized shoreline for the years 1990 and 2000 in the vector format were used as the input to calculate the rate of shoreline change using the Digital Shoreline Analysis System downloaded from USGS site (USGS, 2005). The rate of shoreline change is calculated for the entire study area, and risk ratings are assigned. For better visualization, the entire study area is shown in eight sections in Fig. 2 a,b,c,d,e,f,g,h.

3.2 Sea-Level Change Rate

Sea-level rise is an important consequence of climate change, both for societies and for the environment. Mean sea level at the coast is defined as the height of the sea with respect to a local land benchmark, averaged over a period, such as a month or a year long enough that fluctuations caused by waves and tides are largely removed. Changes in mean sea level as measured by coastal tide gauges are called relative sea-level changes (Church and Gregory 2001). From the coastal vulnerability point of view, coast subjected to a high rate of sea-level rise is considered as a high vulnerable area and vice versa. For the present study, mean relative sea-level data for India is deduced from very long term (20 to 100 years), consistent annual mean relative sea-level data from all Indian Ocean tide gauges station surrounding Indian Ocean, is utilised (Unnikrishnan and Shankar, 2007). The rate of mean sea-level change is considered for the entire study area, and hence mean risk rating is assigned to study area.

3.3 Significant Wave Height

Heights of the waves depend on characteristics of the wind responsible for generating those (Ashok Kumar et al. 2005). Significant wave height is the average height (trough to crest) of the one-third highest waves valid for the indicated 12-hour period. Mean significant wave height is used here as a proxy for wave energy, which drives coastal sediment transport (Usgs, 2005). Wave energy increases as the square of the wave height; thus the ability to mobilize and transport beach/coastal materials is a function of wave height (Usgs, 2001). Using directional wave rider buoy, wave height data recorded by scientists of National Institute of Oceanography (NIO), was utilized to estimate significant wave height. In general, wave heights are measured to demarcate the vulnerability line all along the coast. Wave energy increases as the square of the wave height; thus the ability to mobilize and transport beach/coastal materials is a function of wave height (USGS, 2001). Those coastal areas of high wave height are considered as more vulnerable coasts and areas of low wave height as less vulnerable coasts.

3.4 Tidal Range

Forced by the gravitational attraction of the moon and the sun, tides are periodic and highly predictable. Tidal range is the vertical difference between the highest high tide and the lowest low tide. Tidal range is linked to both permanent and episodic inundation hazards. The tidal range is increased substantially by local effects such as shelving, funneling, reflection and resonance. From the vulnerability point of view, it is an obvious tendency to designate coastal areas of high tidal range as highly vulnerable. This decision was based on the concept that large tidal range is associated with strong tidal currents that influence coastal behavior. For the current study, coastal areas with high tidal range are considered as high vulnerable and low tidal range as low vulnerable. In the current study, predicted tide data (Fig. 3) from WXTide software for the year 1995 is taken as the base data, and the maximum amplitudes of the tide in a year for the Indian coastal locations are calculated, and risk rates are assigned.

3.5 Coastal Regional Elevation

Regional elevation is referred to as the average elevation of a particular area above mean sea level. It is important to study the coastal regional elevation contour for the study area to identify and estimate the extent of land area threatened by future sea-level rise. From the coastal vulnerability point of view, coastal regions having high elevation will be considered as less vulnerable areas because they provide more resistance for inundation against the rising sea level, tsunami run-up, and storm surge. Those coastal regions having low elevation are considered as highly vulnerable areas. In the present study, Shuttle Radar Topography Mission (SRTM) data were used to derive the coastal regional elevation. From the data, 1 meter contours were generated using GIS software (Fig. 4) and the risk classes are assigned.

3.6 Bathymetry

The bathymetry shows the depth from the coast towards the open ocean, it is the underwater equivalent of contour lines on the land. Bathymetry is the essential baseline for all forms of hydrodynamic, wave and inundation modeling. The bathymetry of the coast can visualize the predominant coastal process that operated in the region (Accretion or Erosion). Degree of near shore slope can be estimated using bathymetry of region. Near shore slope characteristic is an important parameter in deciding the degree to which coastal land is at risk of flooding from storm surges and during a tsunami. Locations having gentle land slope values have great penetration of seawater compared with locations with fewer slopes, and resulting land loss from inundation is simply a function of slope: the lower the slope, the greater the land loss (Klein, Reese, and Sterr, 2000). Thus coastal and near shore areas having gentle slope are considered as highly vulnerable areas and areas of steep slope as areas of low vulnerability. For the present study the naval hydrographic charts for the Chennai region for 1976 and 2002 were collected and the depth contour were vectorized and Triangulated Irregular Network (TIN) model was developed using ArcGIS 9.2 after geo-referencing with Universal Transverse Mercator (UTM) projection system with WGS-84 datum (Fig. 5a, 5b). The region, where there is active accretion is classified as low vulnerable area, since the deposit reduces the wave energy, whereas the area where the erosion is pronounced is marked as highly vulnerable area and thus risk rating was assigned.

3.7 Geomorphology

The geomorphology variable expresses the relative erodibility of different landform types. The term ‘‘coastal vulnerability’’ as used in this study refers to the (geomorphic) vulnerability of coastal landforms to hazards such as wave erosion, tsunami, and storm surge flooding, etc. Most erodible feature represents highest risk and is most vulnerable, whereas, least erodible feature (like rocky cliff) represents lowest risk and is least vulnerable. The northern coastal stretch of Chennai city is dominated by more vulnerable and fragile geomorphic features like flood plain, deltaic plain, salt flat, water bodies, sand beaches and mud flats etc. Whereas, in the central and southern coastal stretch, geomorphic features are covered by residential and industrial area beach sands, sand dunes, and beach ridges along coastal zone. For the present study, geomorphologic map has been prepared by using enlarged satellite images of 1:25,000 scales.

3.8. Extreme storm surges and return periods

The massive destruction and loss of human life associated with a tropical cyclone can be attributed mainly to the sudden inundation and flooding of the coastal areas produced by storm surges (Sindu and Unnikrishnan, 2011). The risks associated with extreme events can be assessed from the estimates of return periods and return levels. Probability and statistics were used Unnikrishnan et al. (2004) to predict the future frequencies of extreme surge heights based on the historic surge records. A set of 136 low-pressure systems (LPS)in Bay of Bengal, which initiates cyclones, storm surges, were identified during the period 1974–2000, were used to estimate extreme storm surge heights (Unnikrishnan and Shankar,2007). Based on historical storm surge, a value of 2.06 m was deduced as maximum surge height recorded. Using this as base data, the extreme storm level was estimated using Gringorten method for the Chennai tide gauge station was 2.31 m in a return period 100 years (Mahendra et al. 2011). The estimated return levels can be used as preliminary estimates for the design of marine structures for the protection of coastal areas. Estimates of return periods of extreme sea level events along the coast are useful for impact assessment.

3.9 Calculation of CVI

The CVI is determined by combining the relative risk variables to create a single indicator. For the purpose of the current study, the entire coastline is divided into six grids. Each of the eight input relative risk variables are then assigned appropriate risk classes 1, 2, and 3 based on its ability to cause low, medium and high damage, respectively, for a particular area of the coastline. After this process, each coastal grid will have risk ratings for all six variables under consideration. The risk rating assigned for each variable is given in Table 2. Once each section of coastline is assigned a risk value for each variable, the CVI is calculated as the square root of the product of the ranked variables divided by the total number of variables (Pendleton, et al. 2005). The CVI is represented by the Equation (1),

CVI = (a*b*c*d*e*f*g*h)/8 ---------------------1

$$CVI = \sqrt{(a*b*c*d*e*f)}/6 \text{ ----------------------------------- } 1$$

Where

Risk rating assigned to a) Shoreline Change Rate (m/yr); b) Mean Sea Level Change Rate (mm/yr); c) Significant Wave Height (m); d) Mean Tidal Range (m); e) Coastal Regional Elevation; f) Near-shore Bathymetry; g) Geomorphic units; h) Strom Surges (m).

The CVI is calculated based on the risk values assigned to input parameters using the simple vector algebraic technique using ESRI ArcMap software. The CVI values thus generated for different segments of the coastline are categorized into three CVI classes, viz., low, medium and high vulnerable corresponding to 25th percentile, 25th–50th percentile, and 50th percentile, respectively. Three districts covering the study area is separated into 6 equal grids into which the variables are fed. The grids are shown in the Fig. 1

4 Result and Discussion

4.1 Shoreline Change Rate

The present study revealed that about 9.92 km of coastline has a high risk rating (Fig. 7), recording erosion rates of more than 1.0 to 2.0 m/y. About 11.17 km of coastline has a medium risk rating with erosion rates between 0.1 and 1.0 m/y. About 34.65 km of coastline recorded deposition along the coastal stretches and has a low risk rating. Shoreline change rate assessed along the open coast, the river/creek mouths were excluded in this study. Because the changes at the river/creek mouth depict dynamic changes especially in the morphology of the river spits, hence the trend will be off the norms.

4.2 Sea Level Change Rate

The present study revealed that the annual sea level will be not being changing for a small region, and hence the entire coastline faces same level of vulnerability throughout. It is found that the sea level changes will not remain constant and it always fluctuates between sea level rise and fall. Statistically significant trends obtained from records longer than 40 years yielded sea level-rise estimates between 1.06–1.75 mm/yr, with a regional average of 1.29 mm yr^{-1}, when corrected for global isostatic adjustment (GIA) using model data. These estimates are consistent with the 1–2 mm/yr global sea-level-rise estimates reported by the Intergovernmental Panel on Climate Change. The entire coastline of 56 km is classified as medium risk class.

4.3 Significant Wave Height

Significant wave height is the average height (trough to crest) of the one-third highest waves valid for the indicated 12-hour period. The significant wave height will not be varying much for a small region. The mean significant wave height for the Chennai coast during 2005 is 0.39 to 1.66 (m). The entire coastline of 56 km is in the medium vulnerability class

4.4 Tidal Range

It is revealed that the tidal range for a smaller region won't be varying much in a year. The tide range is calculated for the year 1995 and the entire coastline is classified into a same vulnerability class since the tidal value for the entire Chennai coast is more or less equal to 1.2 m with lowest value as 0.1 and highest is 1.4 recorded for that year. The entire coastline of 56 km coastline is classified under medium risk class.

4.5 Coastal Regional Elevation

The present study revealed that (Fig. 8) about 22.04 km of coastline has a high risk rating, recording coastal regional elevation between 0 and 3 m. About 28.29 km of coastline has a medium risk rating with coastal regional elevation between 3.0 and 6.0 m. About 2.64 km of coastline that has recorded coastal regional elevation of more than 6.0 m, has a low risk rating.

4.6 Bathymetry

Based on the bathymetry the coastal region can be classified for vulnerability, the presence of sand deposit prevents the further erosion and the eroding environments like river mouth and estuaries will keep on eroding. The present study revealed (Fig. 9) that about 29.11 km of coastline has a high risk rating. About 18.85 km of coastline has a medium risk rating. About 10.54 km of coastline that has recorded has a low risk rating.

4.7 Geomorphology

This variable expresses relative erodibility of different landform types. The river systems in the study region are corridors for the inundation allowing the flood water to be carried upstream for long distances. This results in flooding along the proximal areas of the rivers. The northern study region, where geomorphic features like flood plain, deltaic plain, salt flat, water bodies, sand beaches and mud flats are in ample, deserves high risk rating. In the central and southern coastal stretch, geomorphic features are covered by residential and industrial area, beach sands, sand dunes, and beach ridges along coastal zone carry low risk rating.

4.8. Estimation of extreme storm surges and return periods

Based on historical storm surge, a value of 2.06 m was deduced as maximum surge height. Using this as base data, the extreme storm level was estimated using Gringorten method for the Chennai tide gauge station was 2.31 m in a return period 100 years (Mahendra et al. 2011). The estimated return levels can be used as preliminary estimates for the design of marine structures for the protection. Estimates of return periods of extreme sea level events along the coast are useful for impact assessment. The storm surge level for a smaller region won't be varying much in a year. The entire coastline is classified into a same vulnerability class with medium risk class.

4.9 Coastal Vulnerability Index (CVI)

The coastal stretches of Chennai are classified as low, medium, and high risk based on their vulnerability to the eight relative risk variables under study (Table 2). The CVI value along the Chennai coastline varied from 2.8 to 10.4. The 25th and 50th percentiles of CVI value are 3.0 and 3.45 respectively. Those parts of the coastline (Fig.. 10) having CVI values ranging from 2.8 to 3.0 are considered to be less vulnerable, those ranging from 3.00 to 3.45 are considered to be medium vulnerable, and the remaining parts having CVI values of more than 3.45 are highly vulnerable. The calculated Coastal Vulnerability Index values calculated for each grid considering all the eight parameters including Shoreline Change Rate, Mean Sea Level Change, Significant Wave Height, Mean Tidal Range, Coastal Regional Elevation, Bathymetry, geomorphology, and extreme storm surges is tabulated in the Table 3. Based on the vulnerability assessment study, it is clear that four issues are of great concern to the authorities and decision makers: coastal land loss, ecosystem disturbance and erosion and degradation of shoreline, and human and property loss.

The CVI presented in this study is similar to that used in Pendleton, Thieler, and Jeffress (2005); Thieler (2000); Thieler and Hammar-Klose (1999), Hegde and Raju (2007), Kumar et al.(2008), Dwarakish (2009), Dinesh Kumar (2006). This method is very effective in that it highlights coastal areas where the various effects of sea-level rise may be the greatest. In addition to the six variables used by earlier researchers, the recent study (Kumar, 2010) uses two additional variables to represent vulnerability more precisely; coastal slope and tsunami run-up. The imperative for using these additional variables is discussed. The present study considered extreme storm surges and return period instead of tsunami run-up as tsunami occurrences are rare and tsunami events can also be covered under extreme storm surges. Similarly earlier studies used coastal slope as one of the parameters to calculate CVI. However, in present study near-shore bathymetry rating is considered for CVI calculations as near-shore bathymetry decides fate of waves approaching coast. The integration of these parameters makes the present study much more comprehensive.

Most previously developed coastal vulnerability/sensitivity indices acknowledge that the addition of socioeconomic variables would assist in defining vulnerable areas (McLaughlin et al. 2002). One of the major socioeconomic variables is population. The population influences the vulnerability of a coast. Coastal population can be seen as an economic variable as people would invest to protect their homes, property, possessions and infrastructures that built up over many years. They incur economic costs if they lose their possessions. Areas where less people live may not suffer the same pressure on the environment or have the same resources for protection. However, population can also be interpreted as a direct "erosion-inducing" variable because large population near the coast may produce damaging impacts on the coastal area in general (www.**chennai**.tn.nic.in/chndistprof.htm). Several problems were encountered in assessing socio-economic vulnerability indicators due to inherent difficulties involved in ranking socio-economic data on an interval scale. Study (McLaughlin et al. 2002) suggest an under representation of the socio-economic index and hence excluded from CVI calculations.

Flooding causes damage to agricultural land affecting the crops, thus the livelihood and the economy of the country. The encroachment of sea water into soil alters the pH value, decreasing the soil quality and affecting the produce. Also in terms of ecological factors, sea water encroachment alters the floral habitats and their environment. All wet-land elements like coral reefs, mangroves and sea-grass are disturbed due to flooding. The options available for the protection of the Chennai coast from future coastal hazards could be dune afforestation, mangrove restoration and management, periodic beach nourishment and building seawalls and groins. The construction of seawalls is to be restricted only for some settlements that are at high risk of inundation. The integrated coastal zone management plan, though active in India, is still not fully functional. It must emphasize more on building regulation, urban growth planning, development of institutional capacity, involvement of local community, increasing public awareness and should be based on long-term sustainable developmental programmes.

5 Conclusion

The CVI method is very effective way to highlight coastal areas where the various effects of sea-level rise may be the greatest. In addition to the variables used by earlier researchers, the present study uses bathymetry to represent vulnerability more precisely; an additional geologic process variable, this study revealed that 11.01 km of the coastline is low vulnerable, 16.66 km is medium vulnerable and 27.79 km is high vulnerable in the study area. Evolving technologies in remote sensing, GIS, and numerical modeling are making accurate data available at better spatial and temporal scales for all the considered variables. Use of such data sets might throw better light on coastal vulnerability aspects at a much more local level. Use of additional parameters such as socio-economic aspects and associated parameters will provide an additional dimension to the current study. The coastal vulnerability index (CVI) provides insight into the relative potential of coastal damage due to coastal hazards. The map presented here can be viewed in at least two ways: (i) to identify areas where physical changes are most likely to occur; and (ii) as a planning tool for managing and protecting resources in the study area. The most severely affected sectors are expected to be the residential and recreational areas, port and fishery facilities and the natural ecosystem. These are to be protected through strict enforcement of the Coastal Regulation Zone (CRZ) Act and any further coastal developmental activities and protection work along the Chennai coast should be based upon an integrated coastal zone management (ICZM) approach for long-term sustainable development.

Acknowledgments

We express our gratitude to Director, National Institute of Oceanography for the encouragement. The authors would like to thank the Global Land Cover Facility, , http://www.landcover.org for the Landsat TM, ETM+ data, and USGS for the making available the Digital Shoreline Analysis Software (DSAS) on their website. This is NIO contribution No. ---------.

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Table 1: Source and period of different CVI parameters

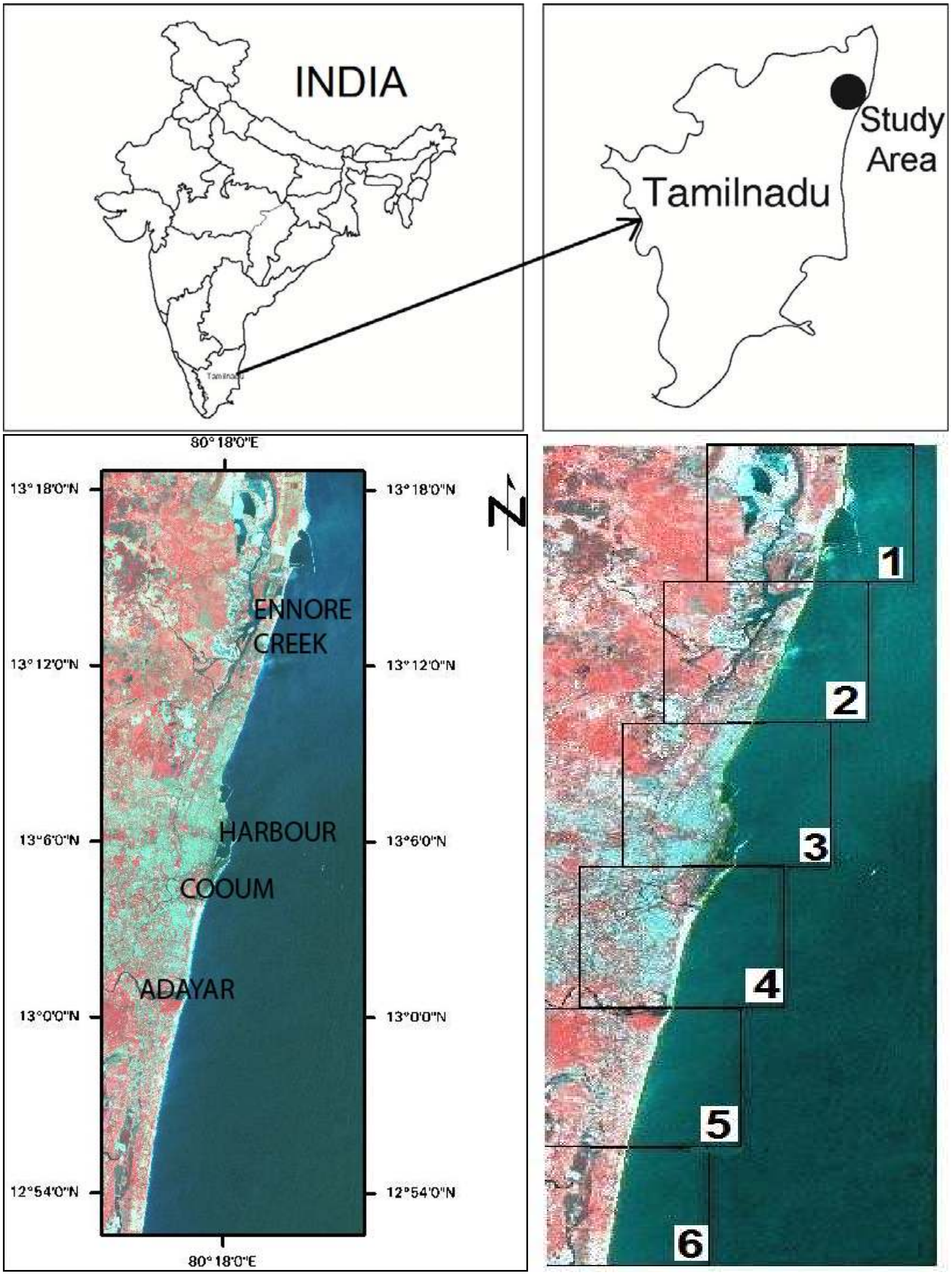
Parameter	Source	Period
Shore line change	Satellite Images of TM, ETM and using ArcMap 9.2, ERDAS, DSAS	1990 and 2000.
Bathymetry	Naval Hydrographic Chart of Madras. Scale 1:300,000. and Etopo5 data	Compiled map published in 1976, 2002
Mean Sea Level Change rate	Annual mean relative sea-level data from all Indian Ocean tide gauges station surrounding Indian Ocean	Data 20 to 100 years old
Significant Wave Height	National Institute of Oceanography Using directional wave rider buoy	From data collected
Mean Tidal Range	WX Tides Software	Year 1995.
Regional Elevation	SRTM data and GIS software	Year 2000
Geomorphology	Landsat TM & ETM	1990, 2000
Strom surges	Statistically calculated from 136 low pressure system data	1974-2000

Table 2: Risk rating assigned for different parameters

Parameters	Risk Rating		
	Low	Medium	High
Shoreline Change Rate m/y)	Accretion	0.1 to 1.0	1.0 to 2.0
Bathymetry (m)	>1	0.5 to 1.0	< 0.5
Sea Level Change Rate (mm/y)	------	> 1.0 and < 2.0	----
Significant Wave Height (m)	-----	0.39 to 1.66	----
Tidal Range (m)	-----	1.2	-----
Coastal Regional Elevation (m)	> 6	> 3 and < 6	> 0 and < 3
Geomorphology	Rocky cliffs	Beaches, dunes, ridges, beach vegetation, beach protection etc	Flood plains, estuary mouths, salt pans, mud flats etc.
Extreme storm surges	--	2.31 m	----

Table 3: Coastal vulnerability index values

GRID Numbers (in Fig. 1)	CVI
1	3.45
2	10.4
3	2.8
4	4.9
5	3.4
6	3.0



Satellite Image of the Chennai	Study Area with the Coastal Grids

Fig. 1 Satellite image showing location of study area and coastal grids**.**

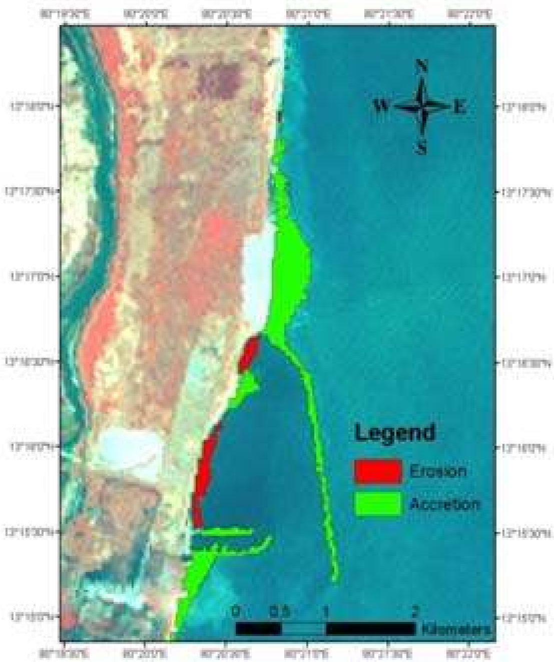


Fig. 2a Chennai – Section 1
showing Accretion and Erosion

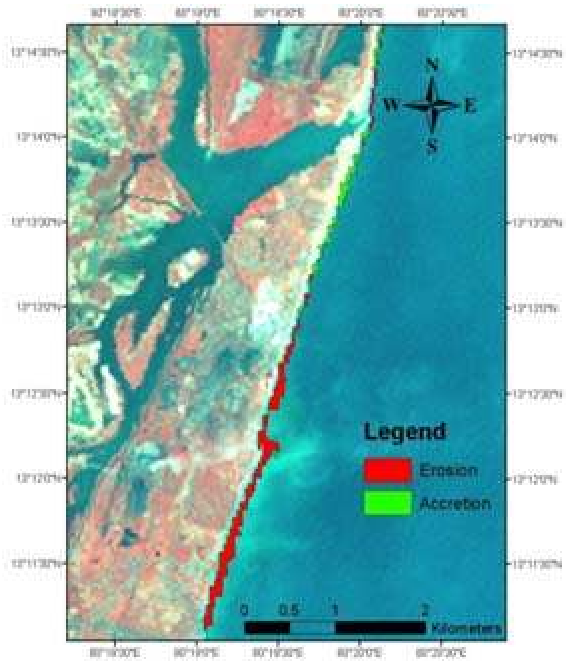


Fig. 2b Chennai – Section 2
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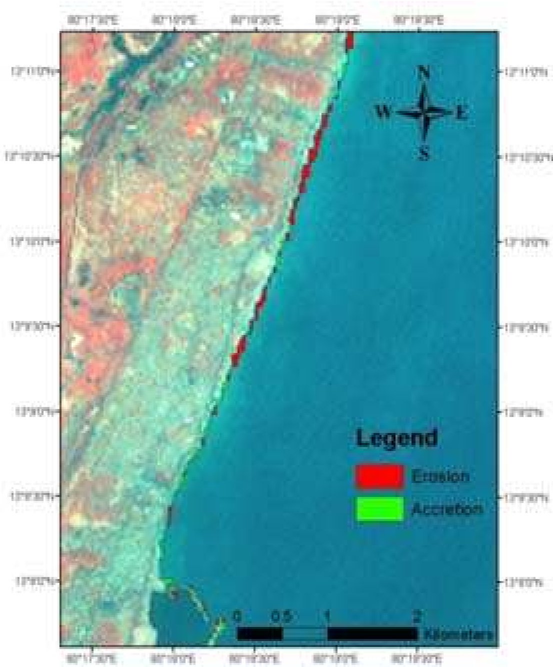

Fig. 2c Chennai – Section 3
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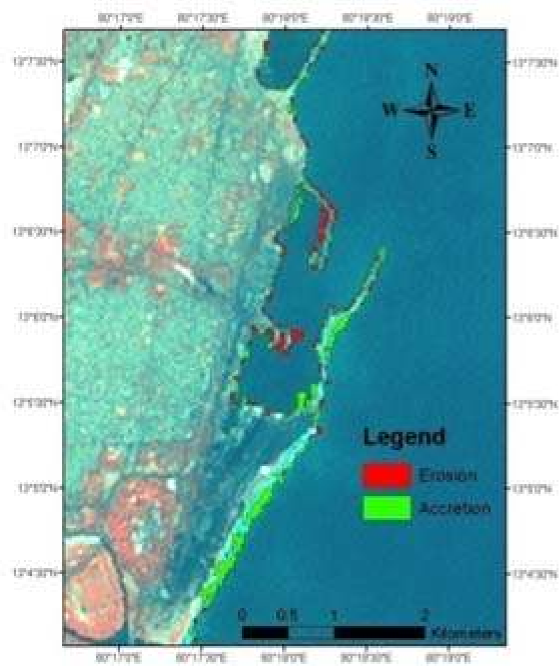


Fig. 2d Chennai – Section 4
showing Accretion and Erosion

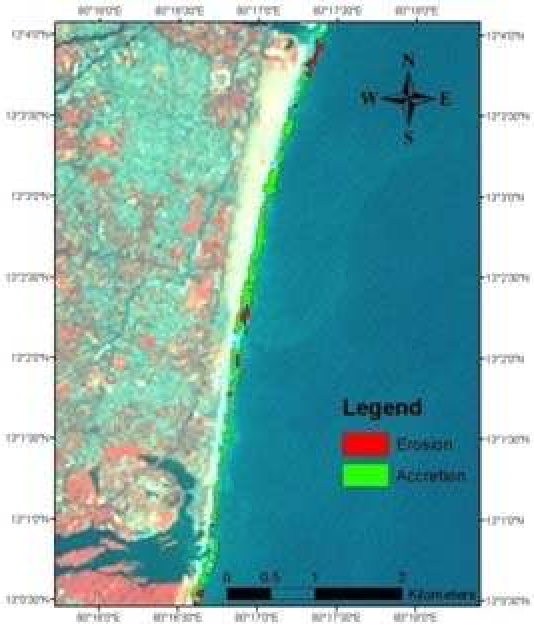


Fig. 2e Chennai – Section 5 showing Accretion and Erosion

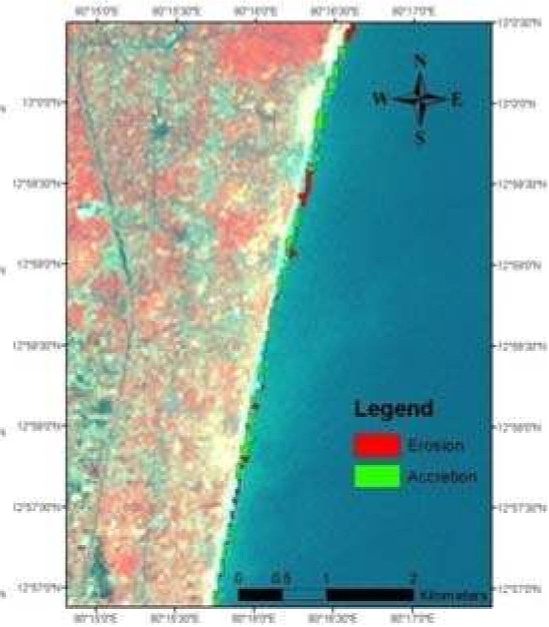


Fig. 2f Chennai – Section 6 showing Accretion and Erosion

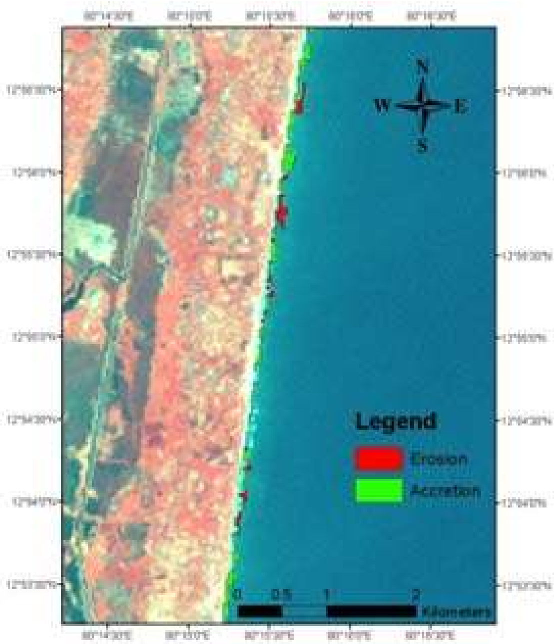


Fig. 2g Chennai – Section 7 showing Accretion and Erosion

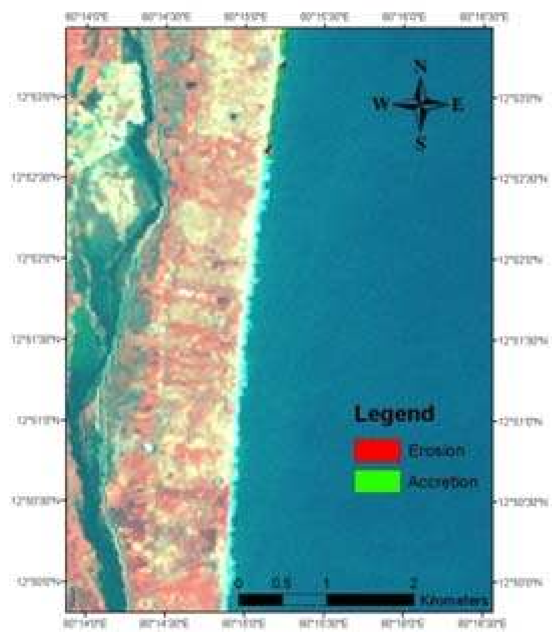
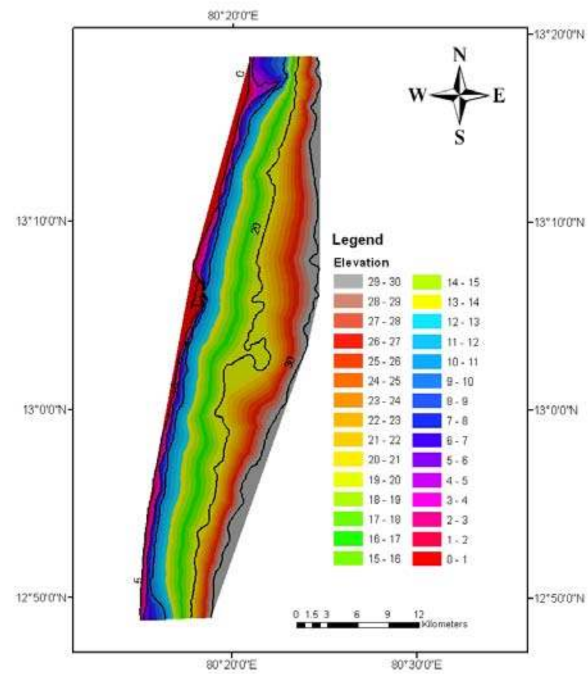


Fig. 2h Chennai – Section 8 showing Accretion and Erosion



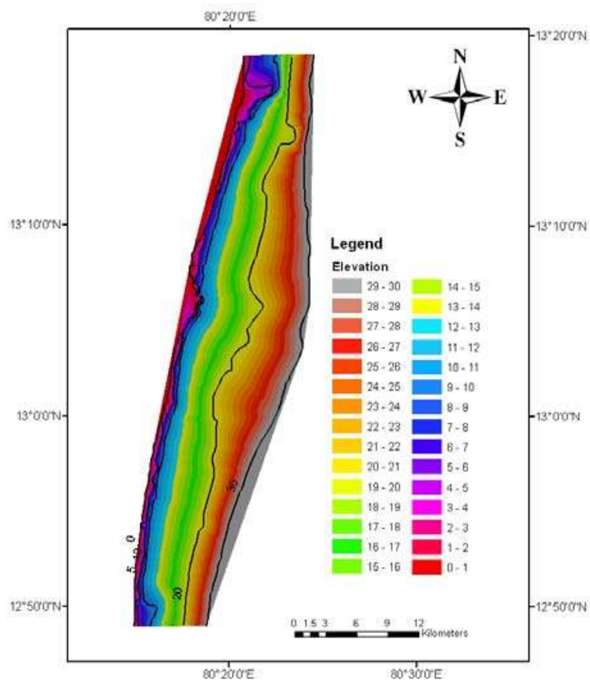


Fig: 3a TIN Model of 1976 Depth Contours **Fig: 3b TIN Model of 2002 Depth Contours**

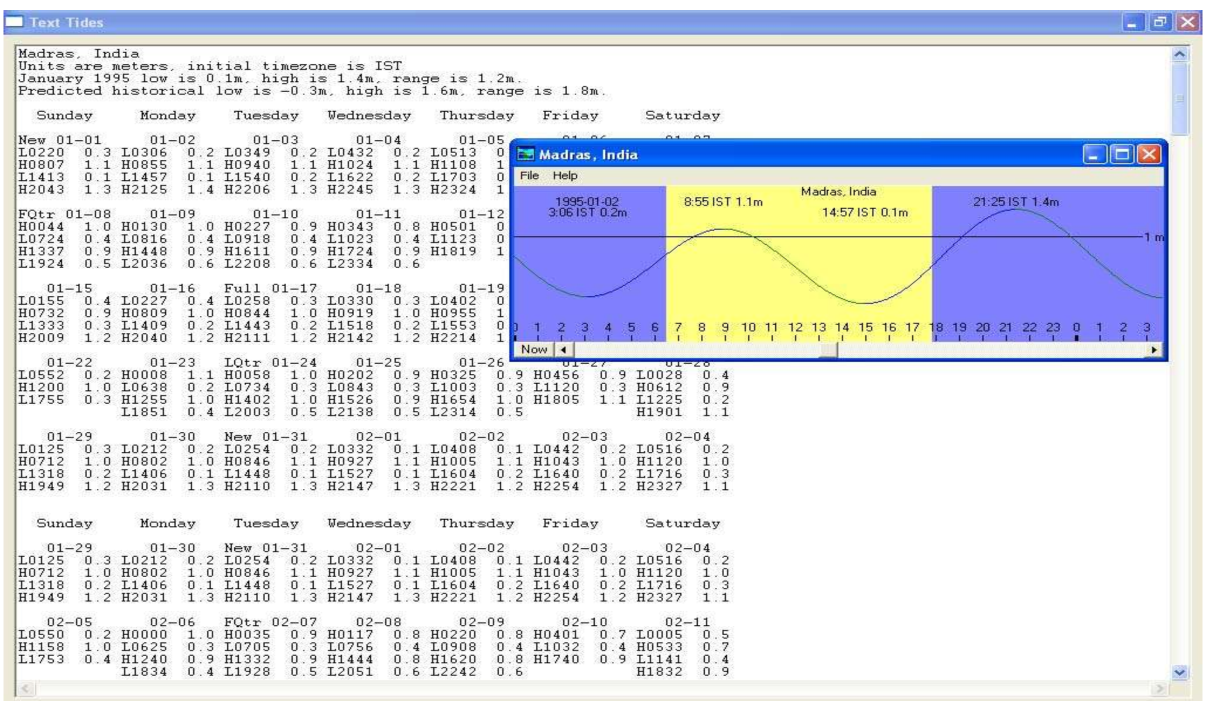


Fig. 4 Tide Data for Chennai Coast (WX Tide) for January 1995

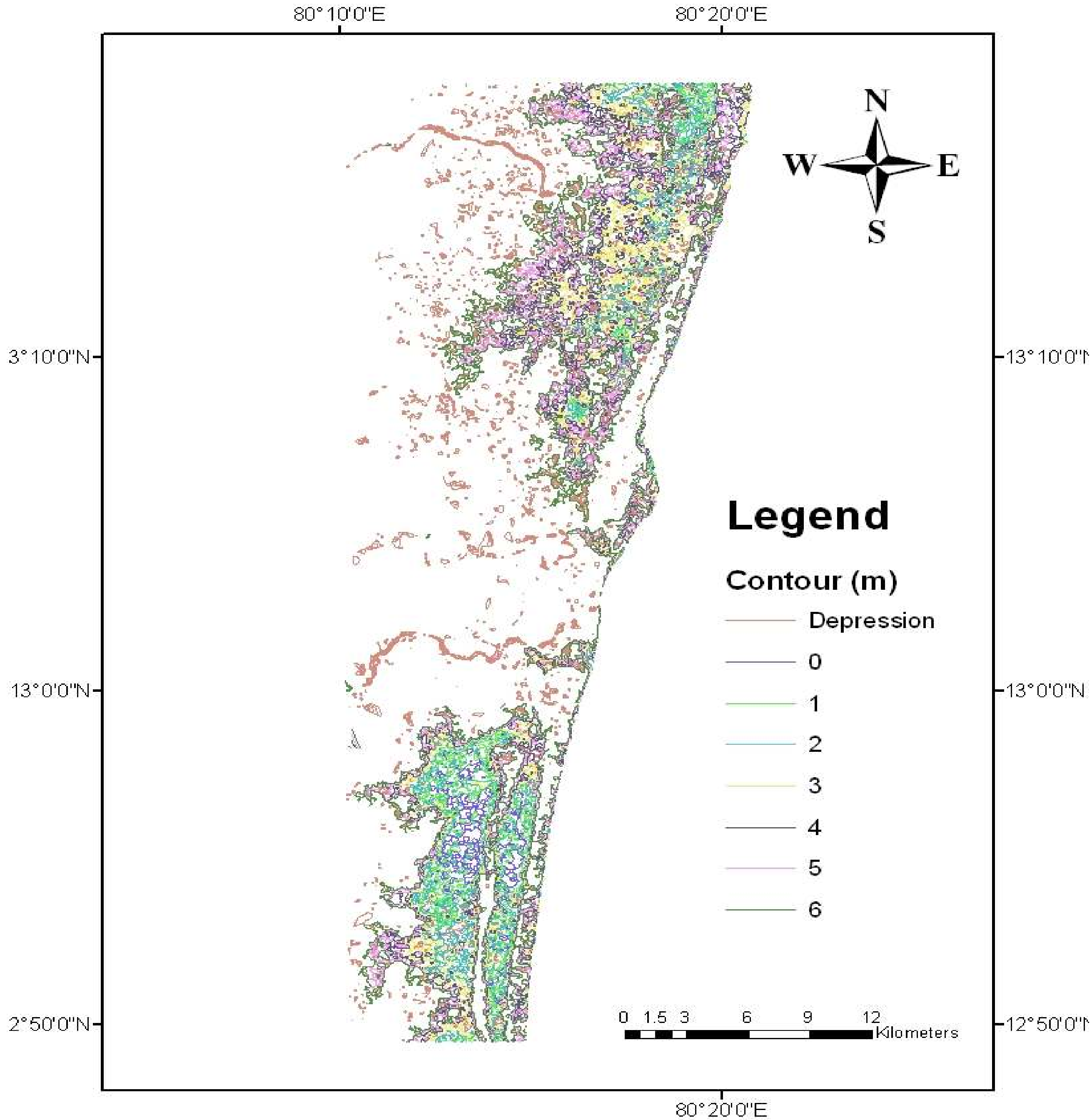


Fig. 5 Contour Map developed from SRTM Data Showing Coastline and Rivers

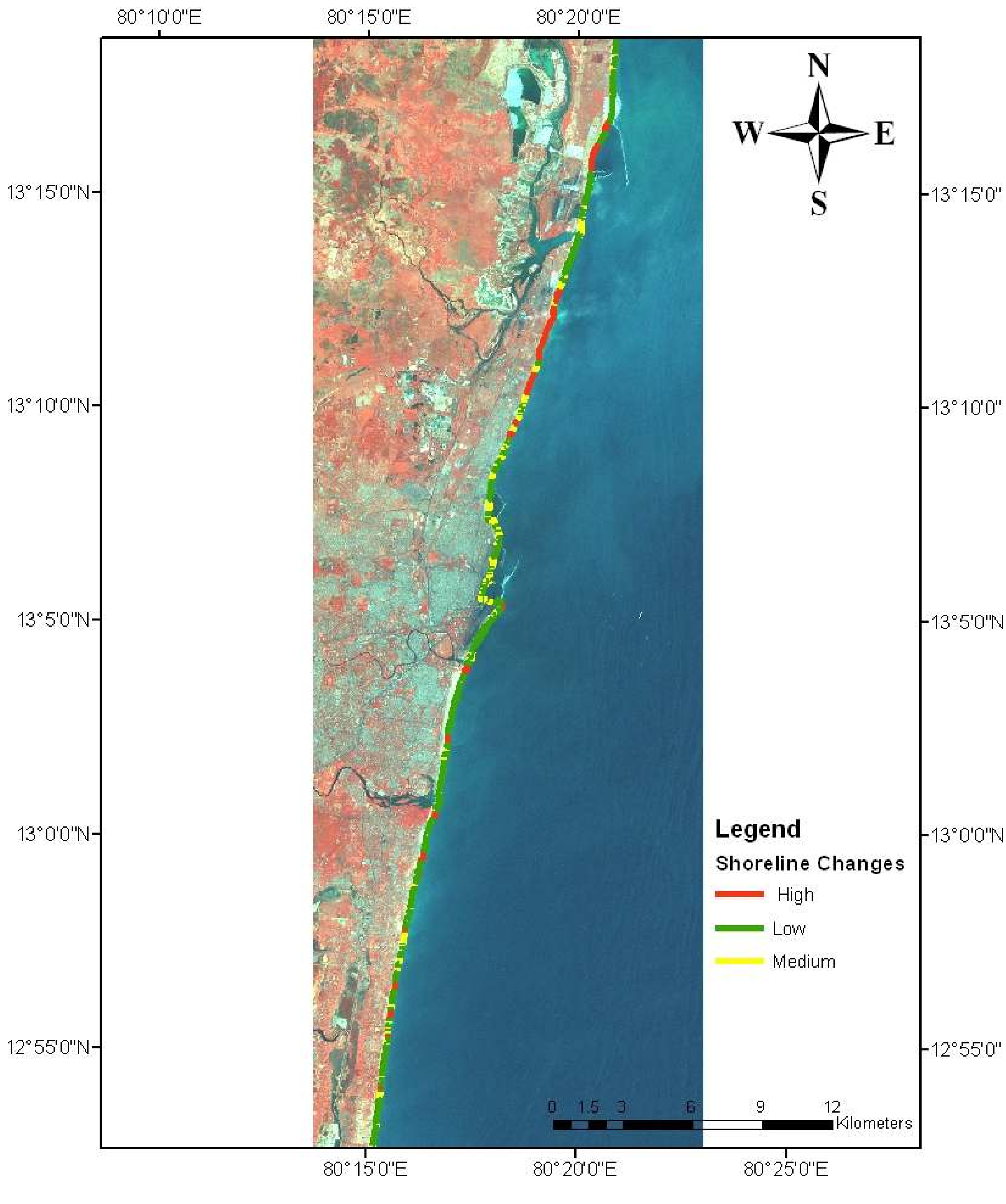


Fig. 6 Risk Class for Shoreline Changes

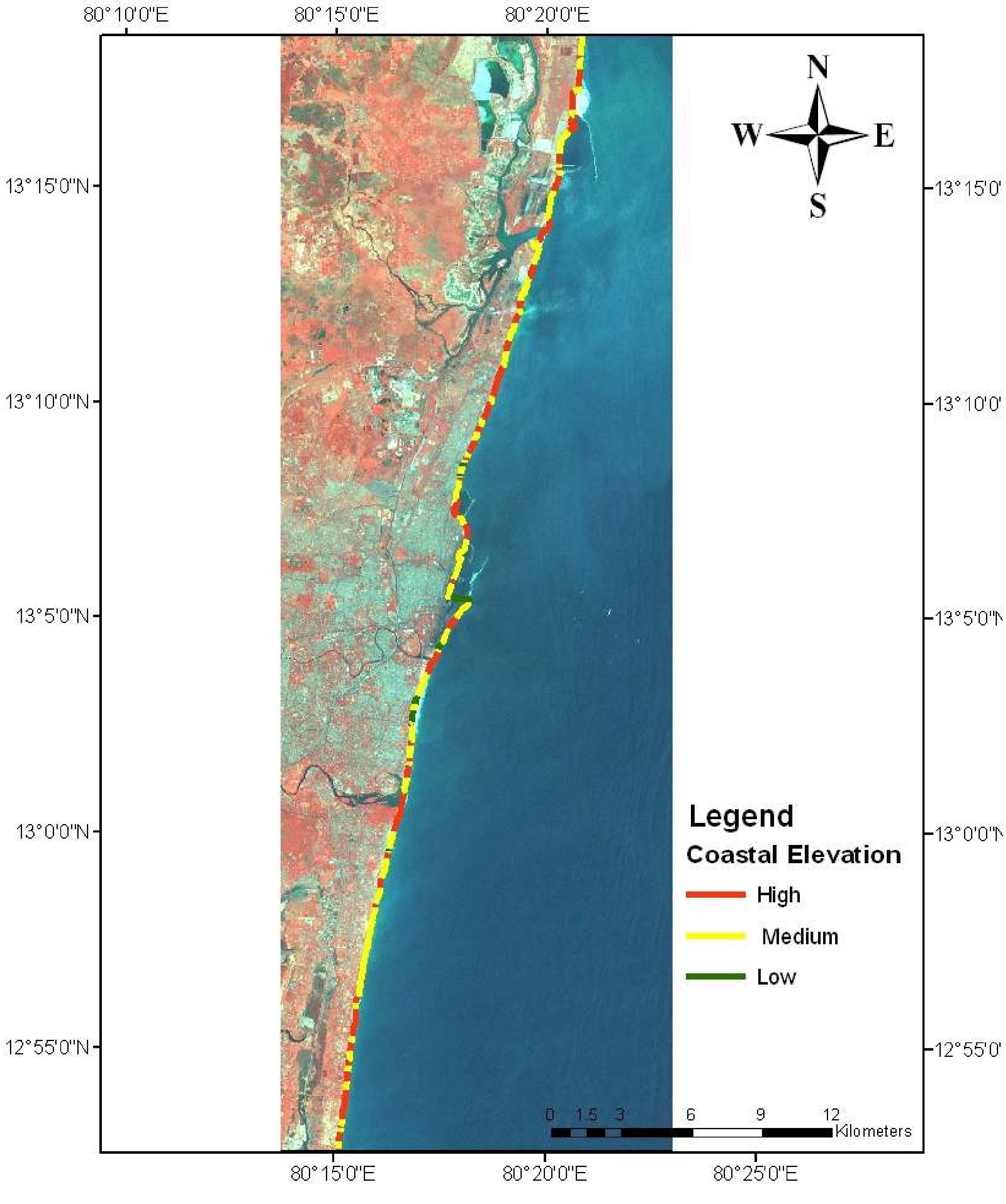


Fig. 7 Risk Classes for Coastal Elevation

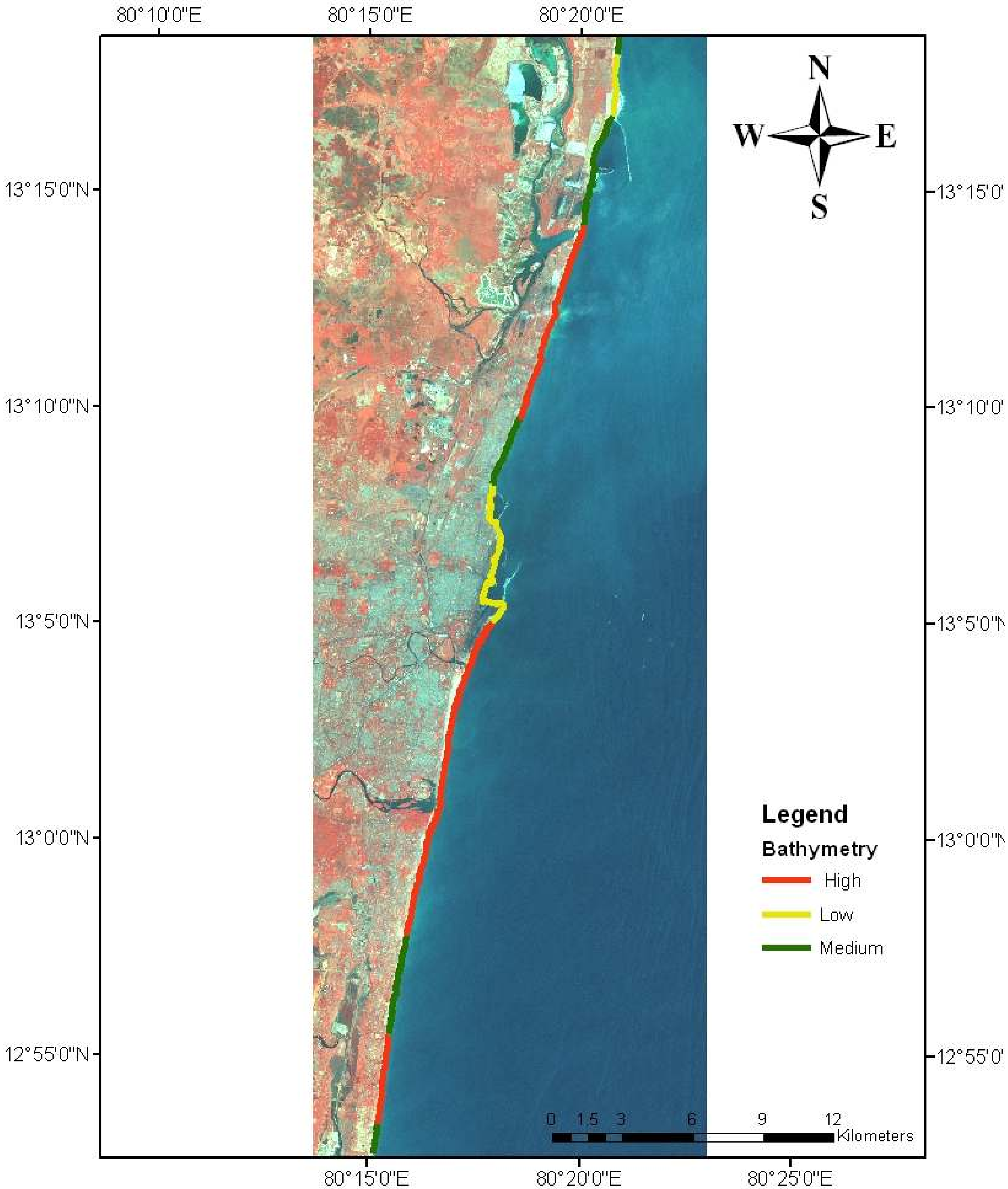


Fig. 8 Risk Classes for Bathymetry

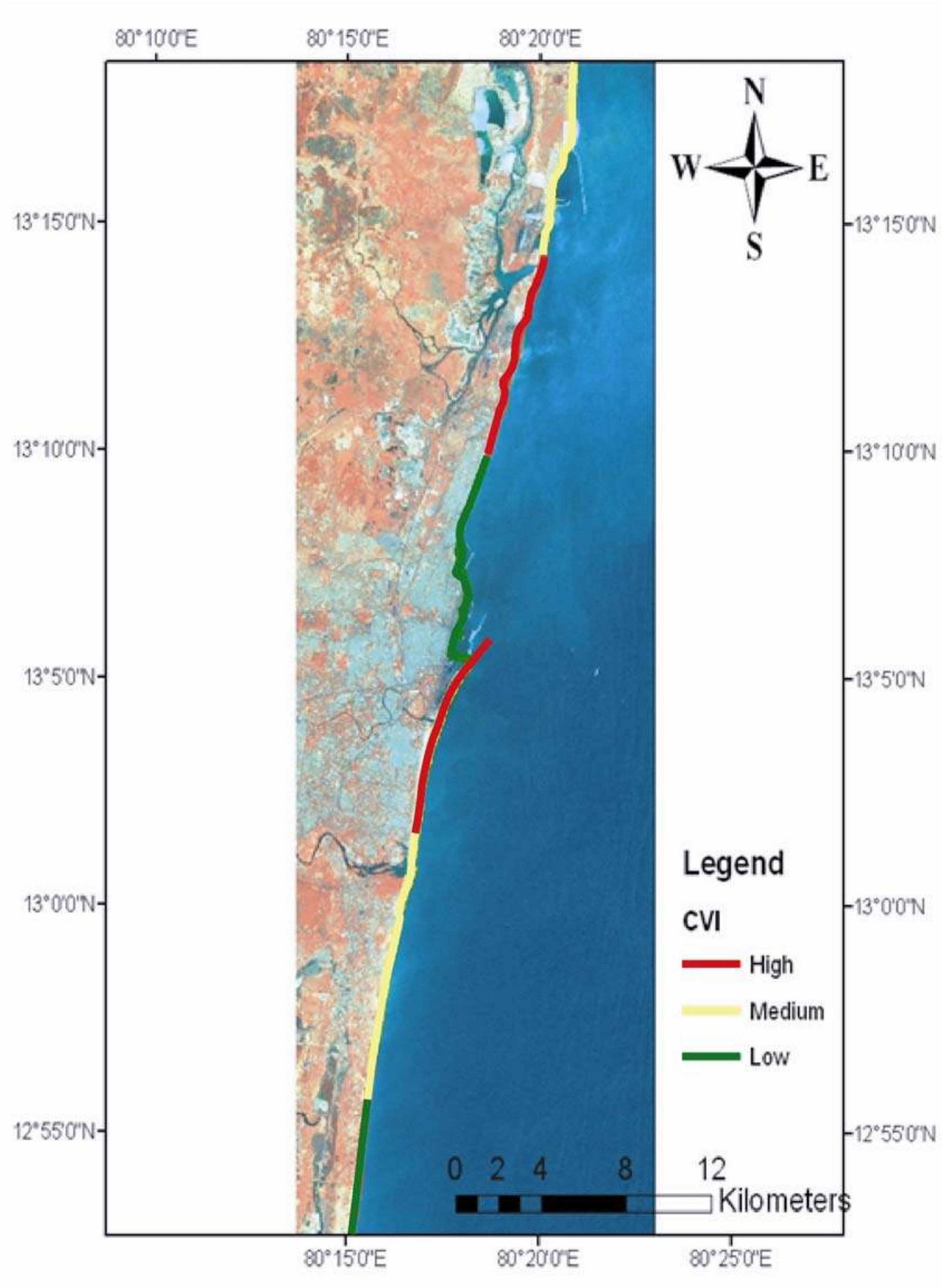


Fig. 9 Classes for Coastal Vulnerability Index