Journal of Coastal Research	26	3	523–534	West Palm Beach, Florida	May 2010

Coastal Vulnerability Assessment for Orissa State, East Coast of India

T. Srinivasa Kumar[†], R.S. Mahendra[†], Shailesh Nayak[†], K. Radhakrishnan[‡], and K.C. Sahu[§]

[†]Indian National Centre for Ocean Information Services (INCOIS)
Hyderabad—500 055 India
srinivas@incois.gov.in

[‡]Vikram Sarabhai Space Centre (VSSC)
Thiruvananthapuram—695022 India

[§]Department of Marine Sciences
Berhampur University
Berhampur—760 007 India

ABSTRACT

KUMAR, T.S.; MAHENDRA, R.S.; NAYAK, S.; RADHAKRISHNAN, K., and SAHU, K.C., 2010. Coastal vulnerability assessment for Orissa State, east coast of India. *Journal of Coastal Research*, 26(3), 523–534. West Palm Beach (Florida), ISSN 0749-0208.

Coastal areas of Orissa State in the northeastern part of the Indian peninsula are potentially vulnerable to accelerated erosion hazard. Along the 480-km coastline, most of the coastal areas, including tourist resorts, hotels, fishing villages, and towns, are already threatened by recurring storm flood events and severe coastal erosion. The coastal habitats, namely the largest rookeries in the world for olive Ridley sea turtles (the extensive sandy beaches of Gahirmatha and Rushikulya), Asia's largest brackish water lagoon (the "Chilika"), extensive mangrove cover of Bhitarkanika (the wildlife sanctuary), the estuarine systems, and deltaic plains are no exception. .The present study therefore is an attempt to develop a coastal vulnerability index (CVI) for the maritime state of Orissa using eight relative risk variables. Most of these parameters are dynamic in nature and require a large amount of data from different sources. In some cases, the base data is from remote sensing satellites; for others it is either from long-term *in situ* measurements or from numerical models. Zones of vulnerability to coastal natural hazards of different magnitude (high, medium, and low) are identified and shown on a map. In earlier studies, tidal range was assumed to include both permanent and episodic inundation hazards. However, the mean of the long-term tidal records tends to dampen the effect of episodic inundation hazards such as tsunamis. For this reason, in the present study, tsunami run-up has been considered as an additional physical process parameter to calculate the CVI. Coastal regional elevation has also been considered as an additional important variable. This is the first such study that has been undertaken for a part of the Indian coastline. The map prepared for the Orissa coast under this study can be used by the state and district administration involved in the disaster mitigation and management plan.

ADDITIONAL INDEX WORDS: *Coastal vulnerability index, Tunami N2 Model, MIKE-21, GLOSS/SRTM data, geographic information systems, Orissa, erosion hazard area.*

INTRODUCTION

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. There were only 2 mega cities in 1950 (New York and London), whereas there were 20 mega cities in 1990. It has been projected that there will be 30 mega cities by 2010, having a population of 320 million people (Nicholls, 1995). The ratio of people living in coastal zones compared with available coastal lands further indicates that there is a greater tendency for people to live in coastal areas than inland. 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).

Collectively, this is placing both growing demands on coastal resources as well as increasing people's exposure to coastal hazards. 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. Over the last 100 years, global sea level rose by 1.0–2.5 mm/y. Present estimates of future sea-level rise induced by climate change range from 20 to 86 cm for the year 2100, with a best estimate of 49 cm. It has been estimated that a 1-m rise in sea-level could displace nearly 7 million people from their homes in India (Ipcc, 2001).

Scientific study of the natural hazards and coastal processes of the Indian coast has assumed greater significance after the December 2004 tsunami because the country learned lessons on the impact of natural hazards in terms of high damage potential for life, property, and the environment. The nation's rapidly growing population of coastal residents and their demand for reliable information regarding the vulnerability of coastal regions have created a need for classifying coastal lands and evaluating the hazard vulnerability. Government officials and resource managers responsible for dealing with

DOI: 10.2112/09-1186.1 received 14 January 2010; accepted in revision 10 February 2010.

natural hazards also need accurate assessments of coastal hazards to make informed decisions before, during, and after such hazard events.

Disciplines such as geography, physical, urban, or territorial planning, economics, and environmental management helped to strengthen what can be called an applied science approach to disasters. Maps became more and more common because of the ever greater participation of geologists, geotechnical engineers, hydrologists, and other experts. They were able to provide required data for the adequate identification of the danger or hazard zones, according to the area of influence of the natural phenomena. Computer science tools such as geographic information systems (GIS) have facilitated this type of identification and analysis. This type of study or analysis of risk has increasingly been presented with the intention of contributing data on threats or risk to physical and territorial planning specialists as an ingredient of the decision making process (Bankoff, Frerks, and Hilhorst, 2003).

PREVIOUS WORK

Hegde and Reju (2007) developed a coastal vulnerability index for the Mangalore coast using geomorphology, regional coastal slope, shoreline change rates, and population. However, they opined that additional physical parameters like wave height, tidal range, probability of storm, *etc.*, can enhance the quality of the CVI.

Gornitz (1990) assessed the vulnerability of the east coast of the United States with emphasis on future sea level rise.

Dominey-Howes and Papathoma (2003) applied a new tsunami vulnerability assessment method to classify building vulnerability (BV) by taking the worse case of the tsunami scenario of 7 February 1963, for two coastal villages in the Gulf of Corinth, Greece. The result showed 46.5% of all buildings are classified as highly vulnerable (BV) and 85% of all businesses are located within buildings with a high BV classification and 13.7% of the population is located within buildings with a high BV class.

Rajawat *et al.* (2006) delineated the hazard line along the Indian coast using data on coastline displacement, tide, waves, and elevation.

Pradeep Kumar and Thakur (2007) assessed the role of bathymetry in modifying the propagation of the tsunami wave of 26 December 2004 and concluded that undersea configuration has an important role in enhancing the wave height because some coastal stations on the eastern margin of India have suffered maximum damage wherein bathymetry has shown an anomalous pattern.

Dinesh Kumar (2006) used sea-level rise scenario for calculating the potential vulnerability for coastal zones of Cochin, southwest coast of India, and concluded that climate-induced sea-level rise will bring profound effects on coastal zones.

Belperio *et al*. (2001) considered elevation, exposure, aspect, and slope as the physical parameters for assessing the coastal vulnerability to sea-level rise and concluded that coastal vulnerability is strongly correlated with elevation and exposure, and that regional scale distributed coastal process modeling may be suitable as a "first cut" in assessing coastal vulnerability to sea-level rise in tide-dominated, sedimentary coastal regions.

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. The result showed that 28% of the U.S. Atlantic coast is of low vulnerability, 24% of the coast is of moderate vulnerability, 22% is of high vulnerability, and 26% is of very high vulnerability.

Pendleton, Thieler, and Jeffress (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). The CVI allows the six 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.

STUDY AREA

Orissa, located in the northeastern coast of India, is a maritime state with immense potential in natural resources. It is located between 17°49′ N and 22°34′ N latitudes and 81°27′ E and 87°29′ E longitudes. Orissa State covers an area of 156,000 km^2 and has a total population of 36.7 million (2001 census). The state has a population density of 236 persons/km^2 (2001 census) covering 30 districts including six coastal districts, *viz.*, Balasore, Bhadrak, Kendrapada, Jagatsinghpur, Puri, and Ganjam, spanning a coastline of 480 km (Figure 1). The total population of these six coastal districts is 8,975,581 and is distributed in an area of 21,887 km^2 with a population density 410 persons/km^2 (2001 census). The study area enjoys international importance and is one of the sites of world heritage attracting tourists and pilgrims. It is gifted with Asia's largest brackish water lagoon, the Chilika; a 672 km^2 extensive mangrove forest and wetland, the Bhitarkanika wildlife sanctuary; and the world's largest known nesting beaches of olive Ridley sea turtles, the Gahirmatha and the Rushikulya.

It is pitiable that Orissa is also vulnerable to multiple disasters such as tropical cyclones, storm surges, and tsunamis. The threat of the coastal vulnerability to such hazards has increased manyfold with the growing population. The economy of the state has received tremendous setbacks because several natural hazards occurred in succession. The coastal districts of Orissa have experienced major surges in the past. Severe flooding caused by storm surges during the 1999 super cyclone caused massive destruction to life and property. Extreme sea levels are major causes of concern for coastal flooding in this region. The loss of land to the sea has now become a more recurrent phenomenon. Identification of vulnerable areas and effective risk mapping and assessment is the need of the hour. Damage can certainly be minimized if extreme sea levels are forecast well in advance. The government of Orissa, after witnessing the alarming situation in the state, has decided to start with an "Integrated Coastal Zone Management Plan Development Project" financed by the World Bank to the tune of INR 100 crores. The present study is an attempt to develop

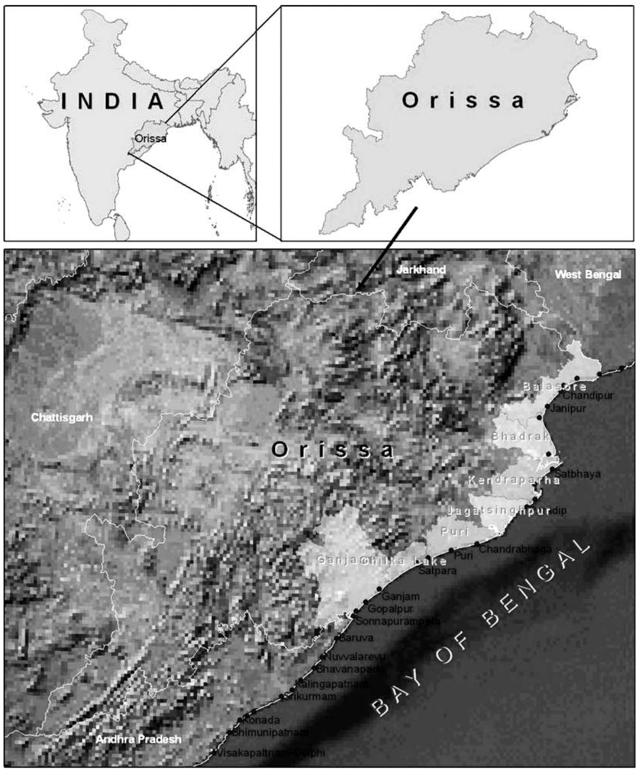

Figure 1. Study area.

Table 1. *Data used for the study on coastal hazard.*

Parameter	Data Used	Resolution	Period
Shore-line change rate	LANDSAT MSS	57 m	1972
	LANDSAT TM	30 m	1991, 2000
Sea-level change rate	GLOSS data	—	1900–2000
Coastal slope	GEBCO data	1 min	—
Significant wave height	Numerical model	0.25°	2005
Tidal range	Prediction tool	—	2006
Coastal regional elevation	SRTM data	90 m	—
Coastal geomorphology	IRS P6 LISS IV	5.8 m	2005
Tsunami run-up	Numerical model	1 min	—

— = not applicable.

coastal vulnerability indices for Orissa, which can facilitate the state and district administration involved in disaster mitigation and management.

METHODOLOGY

Vulnerability may be defined as an internal risk factor of the subject or system that is exposed to a hazard and corresponds to its intrinsic predisposition to be affected, or to be susceptible to damage. In general, the concept of "hazard" is now used to refer to a latent danger or an external risk factor of a system or exposed subject. This can be in mathematical form as the probability of occurrence of an event of certain intensity in a specific site and during a determined period of exposure. On the other hand, vulnerability may be understood, in general terms, as an internal risk factor that is mathematically expressed as the feasibility that the exposed subject or system may be affected by the phenomenon that characterizes the hazard. Thus, risk is the potential loss to the exposed subject or system resulting from the convolution of hazard and vulnerability. In this sense, risk may be expressed in a mathematical form as the probability of surpassing a determined level of economic, social, or environmental consequence at a certain site and during a certain period.

Although a viable, quantitative predictive approach is not available, the relative vulnerability of different coastal environments to sea-level rise may be quantified at a regional to national scale using basic information on coastal geomorphology, rate of sea-level change, past shoreline evolution, and other factors by following the method of estimating the CVI. This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions and yields a relative measure of the system's natural vulnerability to the effects of sea-level rise (Klein and Nicholls, 1999). All these parameters have been related in a quantifiable manner that expresses the relative vulnerability of the coast. This method uses a rating system that classifies the coastal area based on degree of vulnerability as low, medium, and high according to the CVI value of that area.

The method of computing the CVI in the present study is similar to that used in Pendleton, Thieler, and Jeffress (2005); Thieler (2000); and Thieler and Hammar-Klose (1999). In addition to the six parameters used by earlier researchers, the present study uses an additional geologic process variable, *i.e.*, coastal regional elevation, and an additional physical process variable, *i.e.*, tsunami run-up. The eight relative risk variables used are shoreline change rate, sea-level change rate, coastal slope, mean significant wave height, mean tidal range, coastal regional elevation, coastal geomorphology, and tsunami run-up. This is the first such study that has ever been undertaken for a part of the Indian coastline.

Most of these parameters are dynamic in nature and require a large amount of data from different sources to be acquired, analyzed, and processed. They are derived from remote sensing, GIS, and numerical model data. Data sets used for the present study in deriving each of these parameters is presented in Table 1.

The importance of each of the considered parameters and the procedure to generate the same for use in assessment of CVI are given in the following section.

Shoreline 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 they move toward the ocean and result in the addition of land areas, whereas areas of coastal erosion will be considered as more vulnerable because of the resultant loss of private and public property and important natural habitats such as beaches, dunes, and marshes. It also reduces the distance between coastal population and ocean, thereby increasing the risk of exposure of population to coastal hazards.

Ortho-rectified Landsat MSS and TM images covering the Orissa coastline for the years 1970, 1980, and 2000 were downloaded from Michigan State University (2008). The data have been projected to the Universal Transverse Mercator (UTM) projection system with WGS-84 datum. The shoreline along the Orissa coastline was digitized using ArcMap 9.2 and ERDAS Imagine software using the on-screen point mode digitization technique. The near infrared band that is most suitable for the demarcation of the land–water boundary has been used to extract the shoreline. The digitized shoreline for the years 1970, 1980, and 2000 in the vector format were used as the input to the Digital Shoreline Analysis System (DSAS) to calculate the rate of shoreline change. The inputs required for this tool are shoreline in the vector format, date of each vector layer, and transect distance. The rate of shoreline change is calculated for the entire study area, and risk ratings are assigned.

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). Sea-level rise can be a product of global warming through two main processes: thermal expansion of seawater and widespread melting of land ice. Global warming is predicted to cause significant rises in sea level over the course of the twenty-first century. Thus it becomes necessary to study the effect of sea-level rise on the coastal areas. 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*.

The tide gauge data set of the Global Sea-level Observing System (GLOSS) during the past century is used as the primary source of information for sea-level trend in the study area. Tide gauge data recorded in 15 stations around the Indian Ocean, including Paradip, Sagar, Visakhapatnam, Chennai, *etc.*, during the period from 1900 to 2005 is used to form the sea-level–rise rate contour. The rate of sea-level change is calculated for the entire study area, and risk ratings are assigned.

Coastal Slope

Slope is used to describe the measurement of the steepness, incline, gradient, or grade of a straight line. A higher slope value indicates a steeper slope and *vice versa*. The coastal slope is defined as the ratio of the altitude change to the horizontal distance between any two points on the coast. Coastal slope (steepness or flatness of the coastal region) is linked to the susceptibility of a coast to inundation by flooding (Thieler, 2000). The run-up of waves on a coast is the most important stage of a tsunami from the viewpoint of evaluation of the level of tsunami hazard for the coast (Dotsenko, 2005). Coastal 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 (Klein, Reese, and Sterr, 2000). Coastal 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 areas having gentle slope were considered as highly vulnerable areas and areas of steep slope as areas of low vulnerablity.

General Bathymetric Chart of the Oceans (GEBCO) data of one-minute grid resolution coastal topography and bathymetry have been used to get the regional slope of the coastal area. It also incorporates land elevations derived from the Global Land One-kilometer Base Elevation project data set. GEBCO data are useful in deriving the coastal slope values on both land and in the ocean. The slope values in degrees are calculated using the Environmental Information System software package. The slope is calculated for the entire study area, and risk ratings are assigned.

Significant Wave Height

Heights of the waves depend on characteristics of the wind responsible for generating them (Ashok Kumar, Raju, and Sanil Kumar, 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). In general, wave heights are considered to demarcate the vulnerability line all along the coast. The vulnerability study based on wave height is an important step in setting up an all-hazards warning and management system (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). The wave energy increases with increase in the wave height, which results in loss of land area due to increased erosion and inundation along shore, so those coastal areas of high wave height are considered as more vulnerable coasts and areas of low wave height as less vulnerable coasts.

In the present study, MIKE 21 SW software, a new third-generation spectral wind–wave model was used to estimate the significant wave height in the study area. MIKE 21 SW, which simulates the growth, decay, and transformation of wind-generated waves and swells in offshore and coastal areas, solves the spectral wave action balance equation formulated in either Cartesian or spherical coordinates. The model includes the following physical phenomena: wave growth by action of wind, nonlinear wave–wave interaction, dissipation by white capping, dissipation by wave breaking, dissipation due to bottom friction, refraction due to depth variations, and wave–current interaction. Daily significant wave height data were generated using this software forced with wind data from European Center for Medium-Range Weather Forecast (ECMWF) for the year 2005, and the mean values were calculated and risk ratings were assigned.

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. 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 from WXTide software for the year 2006 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.

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 detail for the study area to identify and estimate the extent of land area threatened by future sea-level rise. These coastal elevation data are also used to estimate the land potentially available for wetland migration in response to sea-level rise and the sea-level rise impacts to the human built environment (Anderson *et al.*, 2005). 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 are used to derive the coastal regional elevation. The 90-m resolution SRTM raster data are resampled to 1 km and risk rates are assigned to the entire coastline based on the elevation values.

Coastal Geomorphology

Geomorphology is defined as the study of landforms and landscapes, including the description, classification, origin, development, and history of planetary surfaces. Geomorphology seeks to identify the regularities among landforms and what processes lead to patterns. Geomorphology includes endogenic processes—volcanism, tectonics, flooding, cyclones, tsunami, faulting and wrapping—and exogenic processes—weathering, mass wasting, erosion, transportation, and deposition. The processes responsible for this are alluvial and fluvial, glacial, aeolian, and coastal.

Coastal geomorphology provides a basic understanding of the coastal environment. With the predicted rise in sea level as a result of global warming, there has been increasing speculation and concern as to the impact on coastal geomorphology. Sea-level rise and changes to wave conditions will likely bring changes in the dimension and function of the coastal habitats as well as increased risk to those living in the coastal areas (Ipcc, 2001). Rising sea level will bring about the redistribution of coastal landforms comprising subtidal bedforms, intertidal flats, salt marshes, shingle banks, sand dunes, cliffs, and coastal lowlands (Pethick and Crooks, 2000). This evolution in geomorphology will determine not only the quality and quantity of associated habitats and the nature of their ecosystem linkages but also the level of vulnerability of wildlife, people, and infrastructure in coastal areas.

Coastal geomorphology is a result of prevailing geomorphic processes that were forced to attain the present morphology. Hence the geomorphic units are the indicators of the coastal processes that act on it. 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.* The study on coastal vulnerability assessment described here identifies coastal areas that are in many cases already vulnerable to coastal hazards under present-day conditions but that are likely to become increasingly vulnerable in future as a result of climate change and sea-level rise.

Indian Remote Sensing Satellite (IRS) P6 Linear Imaging Self-scanning Sensor-IV (LISS-IV) data and the Digital Terrain Model (DTM) have been used to extract the coastal geomorphology. LISS-IV satellite data were imported into the ERDAS Imagine 9.1 image processing software package. The satellite data were geo-corrected using the reference image and projected to the UTM projection system. Then coastal geomorphic classes were extracted based on the visual interpretation keys using the on-screen digitization technique. The coastline geomorphology has been classified based on the dominant geomorphic class representing the section of coastal zone (500 m). Coastline representing the geomorphology has been overlaid on the DTM using ESRI 3D Analyst. Using the topographic information from the DTM, cliff areas were identified and classified. The classes recorded in the study area include sandy beach, delta, mangrove, cliff, estuary, mud flat, spits, aquaculture and salt pans, and inundated coasts. Further, these geomorphic classes were assigned the risk rating as high vulnerable (sandy beaches, deltas, mangroves, spits), medium vulnerable (estuaries), and low vulnerable (cliffs, aquaculture and salt pans, and inundated coasts).

Tsunami Arrival Height

Tsunamis result in generation of waves of different periods and height. These wave parameters depend on earthquake source parameters, bathymetry, beach profile, coastal land topography, and presence of coastal structures. These surges cause flooding of seawater into the land as much as 1 km or even more, resulting in loss of human life and damage to property.

The Indo–Burma–Sumatra subduction zone is known to trigger large undersea earthquakes that are capable of generating tsunamis in the Indian Ocean. Indicators suggest a high potential for giant earthquakes along the coast of Myanmar (Cummins, 2007) that could be especially dangerous for the east coast of India. In the current study, a magnitude 9.5-Moment Magnitude (Mw) earthquake with epicenter in the Andaman subduction zone has been considered to cause the

Table 2. *Risk rating assigned for different parameters.*

Variable	Risk Rating Low (1)	Medium (2)	High (3)
Shoreline change rate (m/y)	>0 (accretion)	≥−10 and <0 (erosion)	<−10 (severe erosion)
Sea-level change rate (mm/y)	<=0	>0 and ≤1.0	>1.0 and ≤2.0
Coastal slope (degrees)	>1.0	>0.2 and ≤1.0	≥0 and ≤0.2
Significant wave height (m)	—	1.25–1.40	—
Tidal range (m)	≤2.5	>2.5 and ≤3.5	>3.5
Regional elevation (m)	>6.0	>3.0 and ≤6.0	≥0 and ≤3.0
Geomorphology	Inundated coasts, cliffs	Estuaries, vegetated coasts (other than mangroves)	Sandy beaches, deltas, spits, mangroves, mud flat
Tsunami arrival height (m)	≥0 and ≤1.0	>1.0 and ≤2.0	>2.0

worst-case tsunami scenario for Orissa state. This translates to a source segment of 1200 km in length extending from Myanmar in the north to Car Nicobar in the south, 300 km in width, 15 m slip and strike angle parallel to the plate boundary of the subduction zone.

The TUNAMI N2 model has been used, which basically takes the seismic deformation and bathymetry as input to predict the run-up heights and travel times of a tsunami wave for different parts of the coastline for any given earthquake. GEBCO bathymetric data have been used as input in the model. The seismic deformation for an earthquake has been computed using the earthquake parameters like location, focal depth, strike, dip and rake angles, length, width, and slip of the fault plane (Mansinha and Smylie, 1971). Based on the run-up estimated along the entire study area, the risk ratings are assigned.

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 grids of 1 km × 1 km. 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 eight 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, Thieler, and Jeffress, 2005). The CVI is represented by the Equation (1).

$$\mathrm{CVI} = \sqrt{(a * b * c * d * e * f * g * h)/8}, \qquad (1)$$

where

a = risk rating assigned to shoreline-change rate
b = risk rating assigned to sea-level change rate
c = risk rating assigned to coastal slope
d = risk rating assigned to significant wave height
e = risk rating assigned to tidal range
f = risk rating assigned to coastal regional elevation
g = risk rating assigned to coastal geomorphology
h = risk rating assigned to tsunami run-up

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.

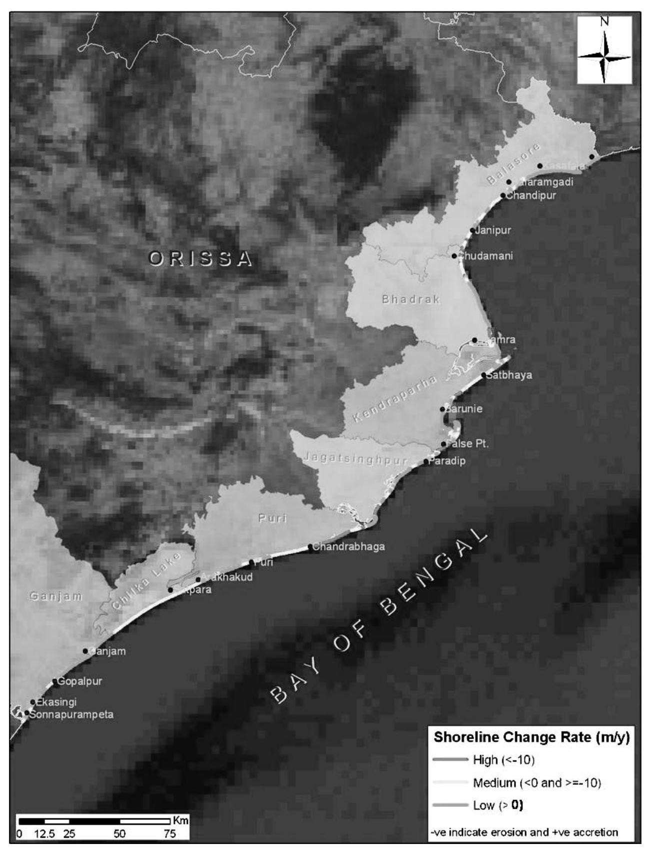

Figure 2. Risk classes for shoreline change rate.

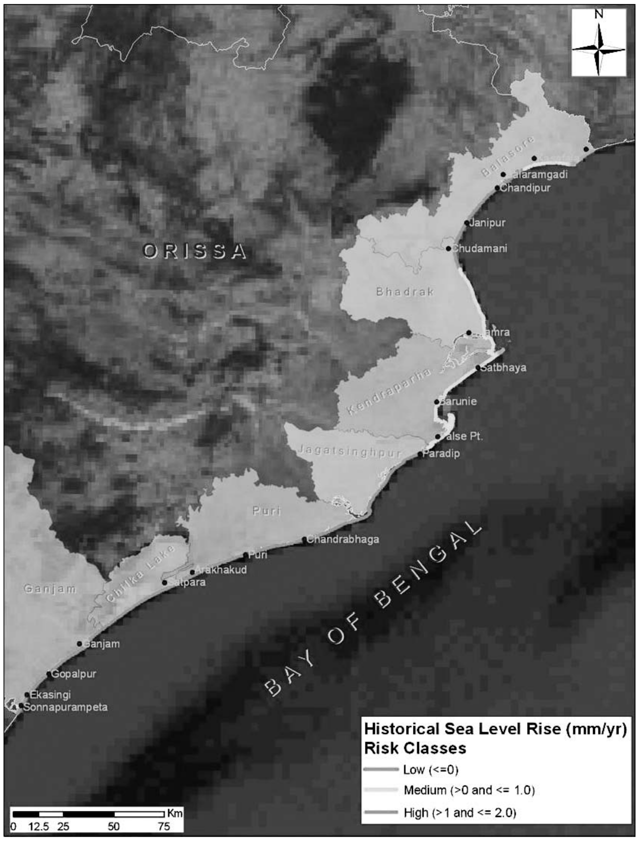

Figure 3. Risk classes for sea-level change rate.

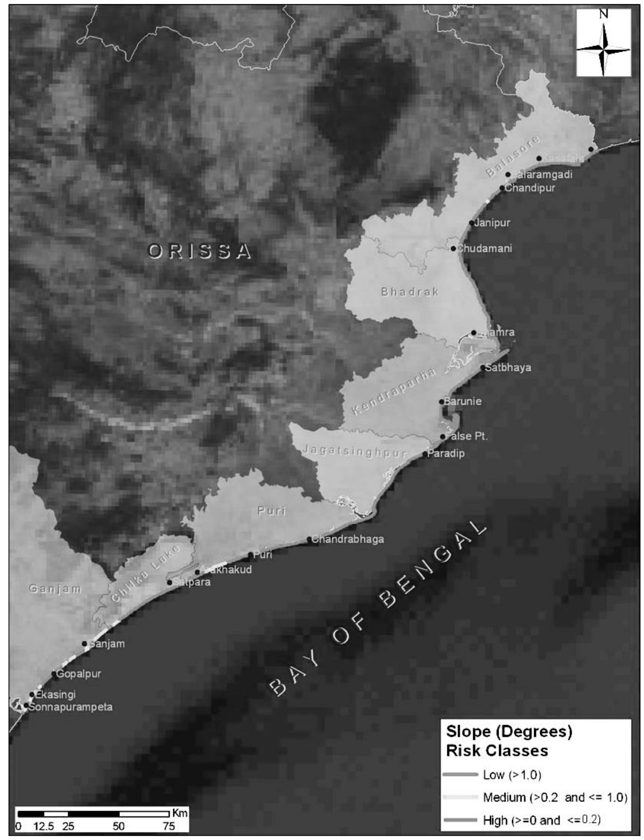

Figure 4. Risk classes for coastal slope.

The CVI is an indication of the relative vulnerability of the various segments of the Orissa coast to coastal inundation hazards. The map prepared for the Orissa coast under this study can be used by state and district administrations involved in the disaster mitigation and management to take advance action to mitigate the effects of impending disasters and to prioritize areas for evacuation.

RESULTS

Shoreline Change Rate

The present study revealed that about 55 km of coastline has a high risk rating, recording erosion rates of more than 10 m/y along the coastal stretches north of Puri, of central Kendrapara, and south of Bhadrak. About 194 km of coastline has a medium risk rating with erosion rates between 0 and 10.0 m/y along the coastal stretches near Chilika Lake, north of Kendrapara, and north of Bhadrak. About 231 km of coastline that recorded accretion along the coastal stretches of Ganjam, Jagatsinghpur, Bhadrak, Balasore, south of Puri and south of Kendrapara has a low risk rating (Figure 2).

Sea-Level Change Rate

The present study revealed that about 292 km of coastline fell has a high risk rating, recording historical sea-level change rates of more than 1.0 mm/y along the coastal stretches of Ganjam, Chilika, Puri, Jagatsinghpur, and southern Balasore districts. About 166 km of coastline has a medium risk rating with sea-level change rates between 0.1 and 1.0 mm/y along the coastal stretches of Kendrapara and Bhadrak districts. About 23 km of coastline that has not recorded change in sea level along the northern Balasore district has a low risk rating (Figure 3).

Coastal Slope

The present study revealed that most of the study area (429 km of coastline) has a high risk rating, recording coastal slopes of less than 0.2°. Only 41 km of coastal stretch covering parts of Ganjam and Puri districts are in the medium risk category, with a coastal slope between 0.2° and 1.0° (Figure 4).

Significant Wave Height

The present study revealed that the mean significant wave height ranges between 1.25 and 1.40 m. The entire coastline is in the medium vulnerability class (Figure 5).

Tidal Range

The present study revealed that about 37 km of coastline that has recorded tidal ranges more than 3.5 m along the

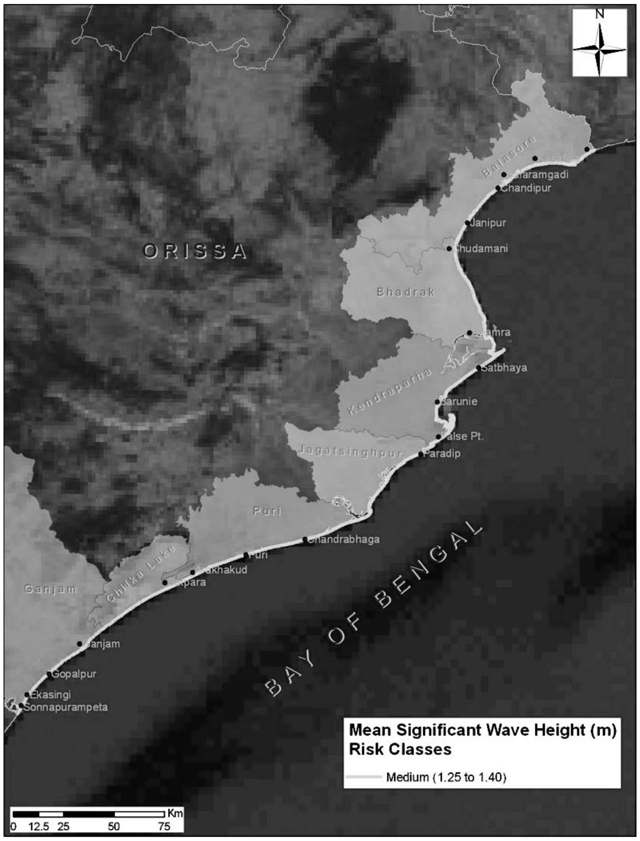

Figure 5. Risk classes for significant wave height.

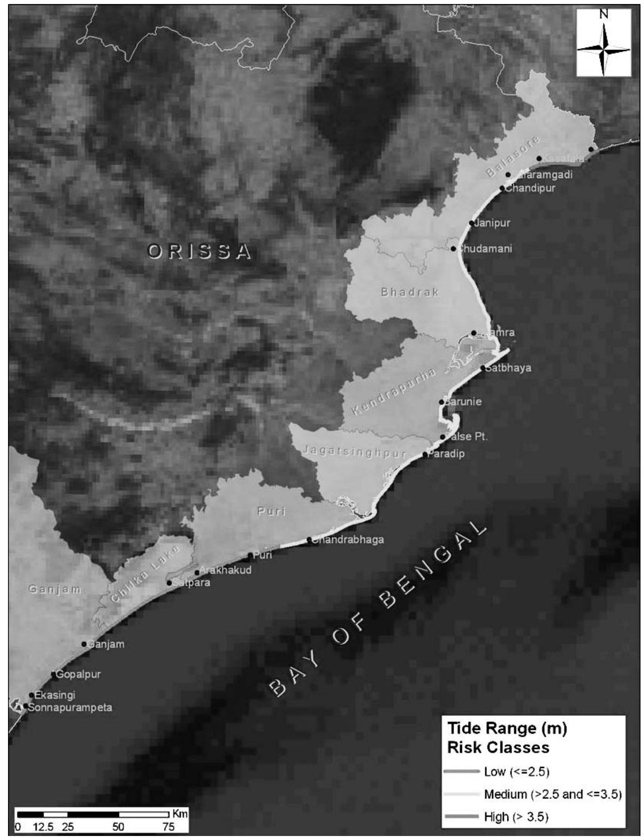

Figure 6. Risk classes for tidal range.

coastal stretches of northern Balasore district has a high risk rating. About 302 km of coastline has a medium risk rating with tidal range between 2.5 and 3.5 m along the coastal stretches of northern Puri, Jagatsingpur, Kendraparha, Bhadrak, and southern Balasore. About 141 km of coastline has a low risk rating, recording tidal ranges of less than 2.5 m in Ganjam, Chilika Lake, and southern Puri (Figure 6).

Coastal Regional Elevation

The present study revealed that about 207 km of coastline has a high risk rating, recording coastal regional elevation between 0 and 3 m along the coastal stretches of Jagatsinghpur, Bhadrak, and northern Balasore. About 182 km of coastline has a medium risk rating with coastal regional elevation between 3.0 and 6.0 m along the coastal stretches of Kendraparha and southern Balasore. About 91 km of coastline that has recorded coastal regional elevation of more than 6.0 m along Ganjam, Chilika Lake, Puri, and mid-Balasore has a low risk rating (Figure 7).

Coastal Geomorphology

The Orissa coast forms a very wide arc with an overall concavity toward the sea, maintaining a general trend of southwest to northeast. It is observed that at the river mouths, there are a number of intermittent extensions of sand spits northward and repeated destruction of the same. The majority of the geomorphic classes along the Orissa coastline (367 km) comprised sandy beaches, deltas, spits, mangroves, and mudflats that have a high risk rating. About 74 km length of coastline comprising estuaries and nonmangrove vegetated coasts have a medium risk rating. About 39 km of coastline comprising inundated coasts and cliffs along the Chilika region has a low risk rating (Figure 8).

Tsunami Run-up

The present study revealed that about 121 km of coastline has a high risk rating, recording tsunami run-up of more than 2.0 m along the coastal stretches of Ganjam, Chilika and southern Puri. About 327 km of coastline has a medium risk rating with tsunami run-up between 1.0 to 2.0 m along most of the coastal stretches of Jagatsinghpur, Kendraparha, Bhadrak, and Balasore districts. About 31 km of coastline that has recorded tsunami run-up between 0 and 1.0 m was accorded a low risk rating along the mid-Balasore coast (Figure 9).

Coastal Vulnerability Index (CVI)

The coastal stretches of Orissa are classified as low, medium, and high risk based on their vulnerability to the eight relative

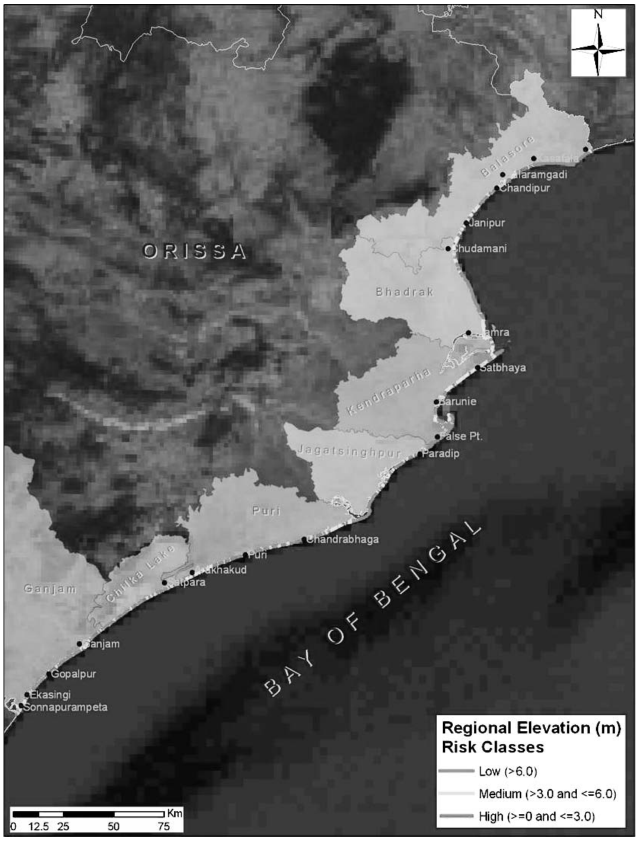

Figure 7. Risk classes for regional elevation.

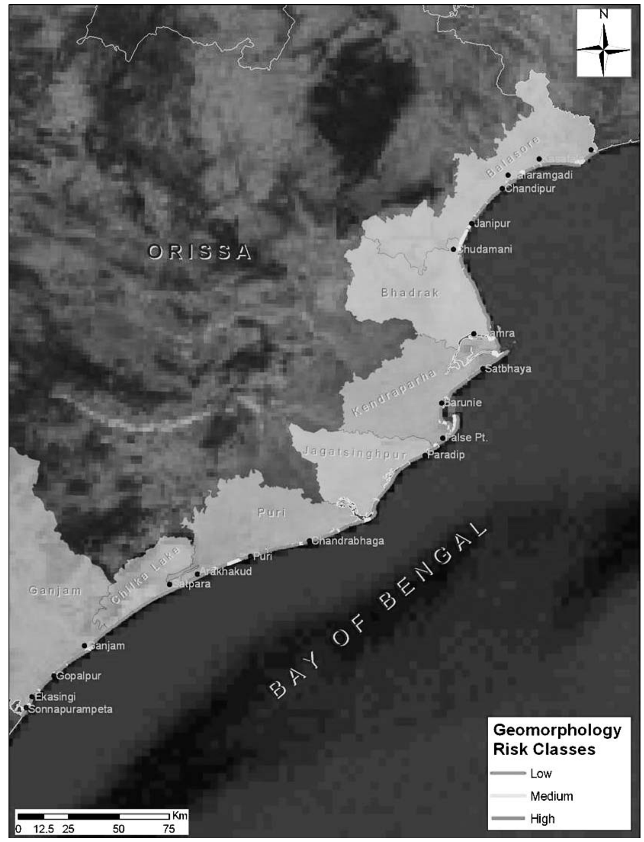

Figure 8. Risk classes for coastal geomorphology.

risk variables under study (Table 3). The resultant CVI is calculated and the vulnerability zones along the coastal shoreline are delineated on the map (Figure 10).

The CVI value along the study area of Orissa coastline varied from 2.1 to 19. The 25th and 50th percentiles of CVI value are 4.75 and 9.5, respectively. Those parts of the coastline having CVI values ranging from 2.1 to 4.75 are considered to be low vulnerable, those ranging from 4.75 to 9.5 are considered to be medium vulnerable, and the remaining parts having CVI values of more than 9.5 are high vulnerable. Accordingly, about 76 km of the coastal stretch of Orissa state, covering parts of Ganjam, Chilka, southern Puri, and Kendraparha, is low vulnerable. About 297 km of the coastal stretch of Orissa state, covering northern Ganjam, Chilika, central Puri, Jagatsinghpur, Kendraparha, southern Bhadrak, and northern Balasore, is medium vulnerable. About 107 km of the coastal stretch of Orissa state, covering northern Puri, parts of Jagatsinghpur, Kendraparha, northern and southern Bhadrak and southern Balasore, is high vulnerable (Figure 11).

DISCUSSION

The CVI presented in this study is similar to that used in Pendleton, Thieler, and Jeffress (2005); Thieler (2000); and Thieler and Hammar-Klose (1999). 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 present study uses two additional variables to represent vulnerability more precisely; an additional geologic process variable, *i.e.*, coastal regional elevation and an additional physical process variable, *i.e.*, tsunami run-up. The imperative for using these additional variables is discussed.

In the earlier studies, tidal range was assumed to include both permanent and episodic inundation hazards. However, the mean of the long-term tidal records tends to dampen the effect of episodic inundation hazards such as tsunamis. For this reason, in the present study, tsunami run-up has been considered as an additional physical process parameter to calculate the CVI. Similarly earlier studies used coastal slope as one of the parameters to calculate CVI with low coastal slope representing high risk and *vice versa*. Such an assumption does not always hold. For instance, areas with low coastal slope falling in areas of high coastal regional elevation are not as vulnerable as similar areas falling in low coastal regional elevation. Such inconsistencies could be effectively addressed if coastal regional elevation is also considered as an additional parameter that represents the vertical level of the terrain. The integration of these parameters makes the present study much more comprehensive.

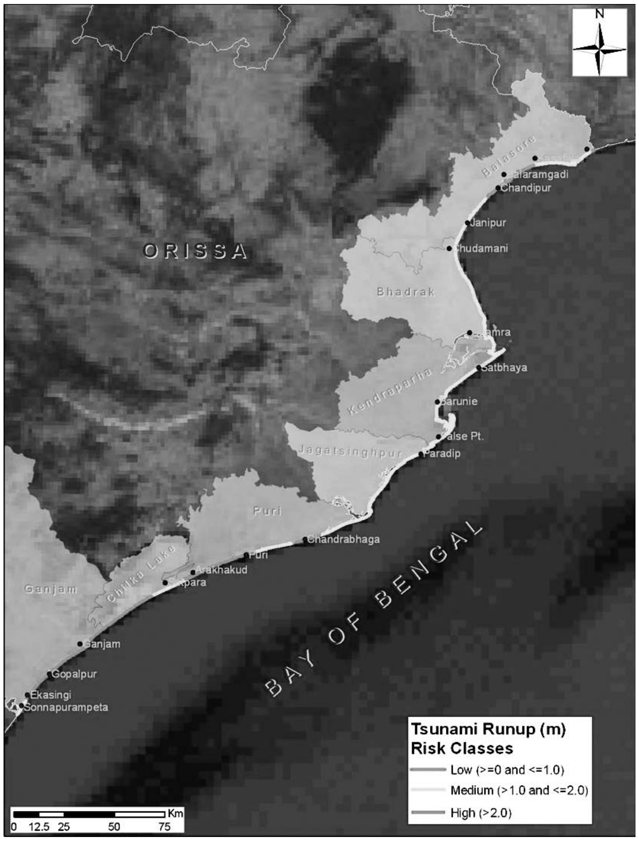

Figure 9. Risk classes for tsunami run-up.

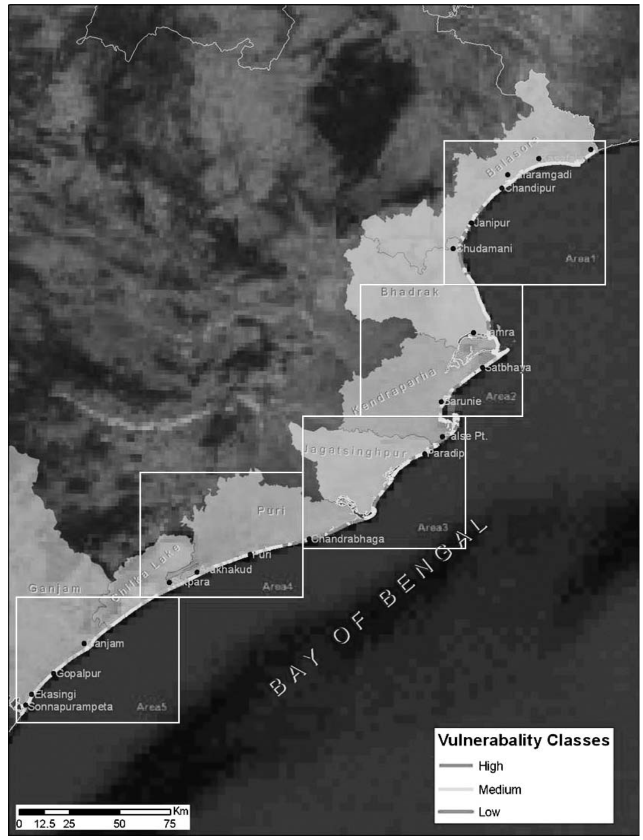

Figure 10. CVI classes along Orissa coast.

This study revealed that 22% of the Orissa coastline is in the high vulnerable category, 62% in the medium vulnerable category, and 16% in the low vulnerable category. Results showed that coastal areas in the districts of Puri and Jagatsinghpur are in the high vulnerable class. These areas are known to be historically vulnerable to coastal flooding especially from storm surges, thus validating the credibility of this study. Many coastal areas in Ganjam, Chilka, and southern Puri fall in the low vulnerable category.

The vulnerability maps derived from this study depict vulnerable areas as per the eight parameters considered. These maps are therefore not maps of total vulnerability but of essential aspects constituting overall vulnerability. They depict the problematic regions, and therefore further attention should be directed to these regions to analyze their vulnerability in the context of nested scales and on higher resolution than the 1000 m $\times$ 1000 m grid. 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 cyclone, storm surge, and coastal flooding will add an additional dimension to the current study.

CONCLUSIONS

The present study conclusively proves the usefulness of remote sensing data, *in situ* observations, numerical modeling, and GIS analysis tools for coastal vulnerability studies. The coastal vulnerability maps produced using this technique serve as a broad indicator of threats to people living in coastal zones.

This is a objective methodology to characterize the risk associated with coastal hazards and can be effectively used by coastal managers and administrators for better planning to mitigate the losses due to hazards as well as for prioritization of areas for evacuation during disasters.

Table 3. *Risk classes for different parameters and resultant CVI.*

S. No	Parameter	Length (km)		
		Low	Medium	High
1	Shoreline change rate	231	194	55
2	Significant wave height	0	480	0
3	Sea-level change rate	23	166	292
4	Tidal range	141	302	37
5	Coastal regional elevation	91	182	207
6	Coastal slope	10	41	429
7	Tsunami run-up	31	327	121
8	Coastal geomorphology	39	74	367
9	CVI	76	297	107

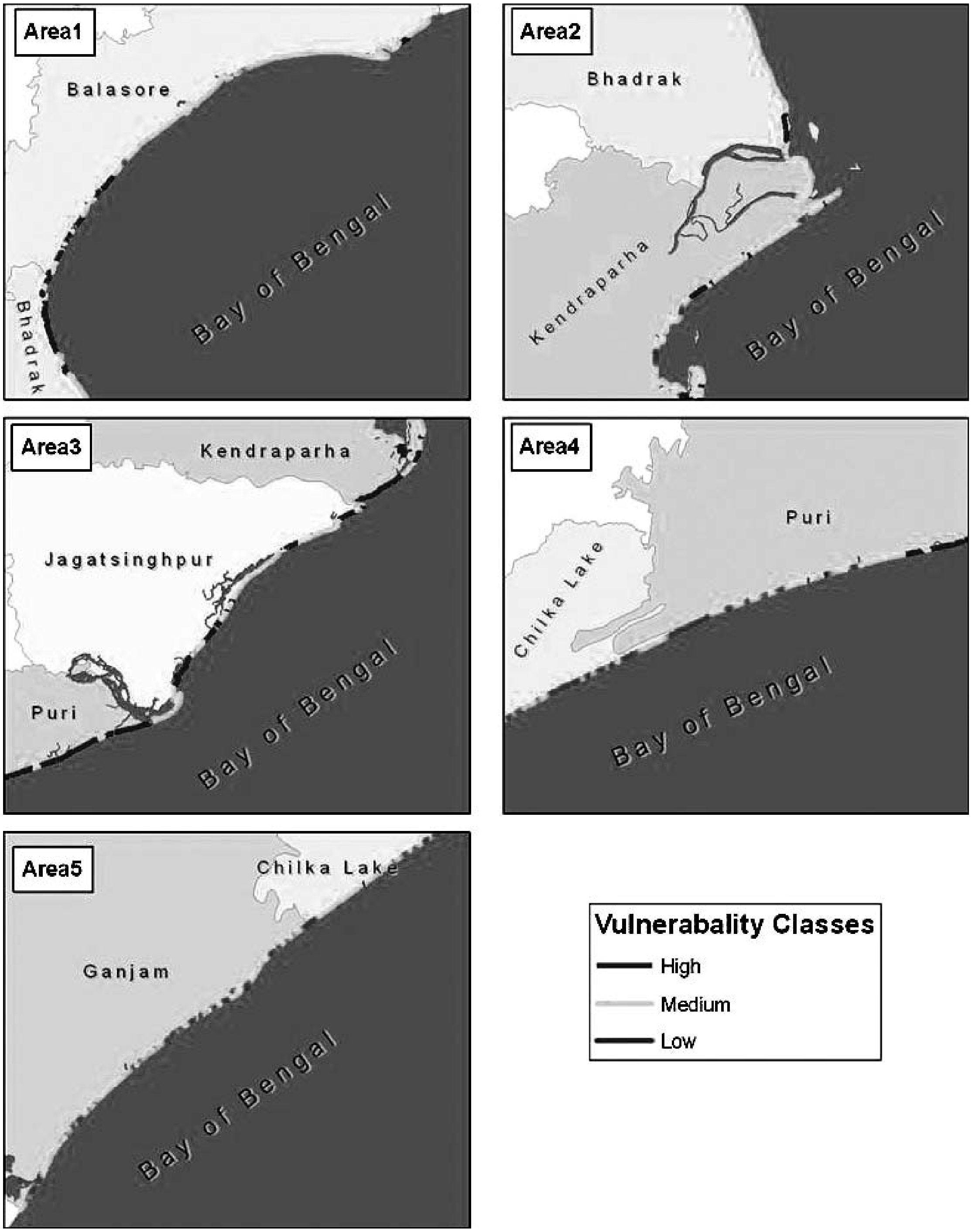

Figure 11. Enlarged portions of the CVI classes in the area 1–5 shown in the Figure 10.

ACKNOWLEDGMENTS

The authors thank Dr. P.S. Goel, former secretary, Ministry of Earth Sciences for his encouragement. The authors would like to thank Global Observatory for Ecosystem Services (GOES), Michigan State University, for the Landsat data, Global Sea Level Observing System (GLOSS) for the sea level data, and USGS for the making available the Digital Shoreline Analysis Software (DSAS) on their website.

LITERATURE CITED

Anderson, K.E.; Cahoon, D.R.; Guitierrez, B., and Thieler, E.R., 2005. The Physical Environment. Public Review Draft. Washington, DC: US Climate Change Science Program, Environmental Protection Agency, pp. 55–60.

Ashok Kumar, K.; Raju, N.S.N., and Sanil Kumar, V., 2005. Wave Characteristics off Visakhapatnam Coast during a Cyclone. Annual Report. Goa, India: National Institute of Oceanography, Ocean Engineering Division.

Bankoff, G.; Frerks, G., and Hilhorst, D., 2003. *Mapping Vulnerability: Disasters, Development and People*, chapter 3. London: Earthscan Publishers.

Belperio, T.; Bourman, B.; Bryan, B., and Harvey, N., 2001. Distributed process modeling for regional assessment of coastal vulnerability to sea-level rise. *Environmental Modeling and Assessment*, 6(1), 57–65.

Church, J.A. and Gregory, J.M., 2001. Climate Change 2001: Working Group I: The Scientific Basis, chapter 11. Location: International Panel on Climate Change.

Cummins, P.R., 2007. The potential for giant tsunamigenic earthquakes in the northern Bay of Bengal. *Nature*, 449, 75–78.

Dinesh Kumar, P.K., 2006. Potential vulnerability implications of sea level rise for the coastal zones of Cochin, southwest coast of India. *Environmental Monitoring and Assessment*, 123, 333–344.

Dominey-Howes, D. and Papathoma, M., 2003. Tsunami vulnerability assessment and its implication for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece. *Natural Hazards and Earth System Sciences*, 3, 733–747.

Dotsenko, S.F., 2005. Run-up of a solitary tsunami wave on a sloping coast. *Journal of Physical Oceanography*, 15(4), 211–219.

Gornitz, V., 1990. Vulnerability of the east coast, U.S.A. to future sea level rise. *Journal of Coastal Research*, 9, 201–237.

Hegde, A.V. and Reju, V.R., 2007. Development of coastal vulnerability index for Mangalore coast, India. *Journal of Coastal Research*, 23, 1106–1111.

IPCC (Intergovernmental Panel on Climate Change). 2001. IPCC Report, Working Group-I, Climate Change–2001: The Scientific Basis. Cambridge, UK: Cambridge University Press. http://www.ipcc.ch/ipccreports/tar/wg1/408.htm (accessed April 10, 2007).

Klein, R. and Nicholls R., 1999. Assessment of coastal vulnerability to climate change. *Ambio*, 28(2), 182–187.

Klein, R.J.T.; Reese, S., and Sterr, H., 2000. Climate change and coastal zones: an overview of the state-of-the-art on regional and local vulnerability. *In:* Giupponi, C. and Shechther, M. (eds.), *Climate Change in the Mediterranean: Socio-economic Perspective of Impacts, Vulnerability and Adaptation*. Camberley, UK: Edward Elgar Publishing, pp. 245–278.

Mansinha, L. and Smylie, D.E., 1971. The displacement fields of inclined faults. *Bulletin of the Seismological Society of America*, 61, 1433–1440.

Mimura, N. and Nicholls, R.J., 1998. Regional issues raised by sea-level rise and their policy implications. *Journal of Climate Research*, 11, 5–18.

Michigan State University. 2008. Global Observatory for Ecosystem Services. www.landsat.org (accessed July 2, 2008).

Nicholls, R.J., 1995. Coastal megacities and climate change. *Geojournal*, 37(3), 369–379.

Pendleton, E.A.; Thieler, E.R., and Jeffress, S.W., 2005. Coastal Vulnerability Assessment of Golden Gate National Recreation Area to Sea-Level Rise. USGS Open-File Report 2005-1058.

Pethick, J.S. and Crooks, S., 2000. Development of a coastal vulnerability index: a geomorphological perspective. *Environmental Conservation*, 27, 359–367.

Pradeep Kumar, A. and Thakur, N.K., 2007. Role of bathymetry in tsunami devastation along the east coast of India. *Current Science*, 92(4), 432–434.

Rajawat, A.S.; Bhattacharya, S.; Jain, S.; Gupta, M.; Jayaprasad, P.; Tamilarasan, V.; Ajai, and Nayak, S., 2006. Coastal Vulnerability Mapping for the Indian Coast. Second International Symposium on "Geoinformation for Disaster Management" (Dona Paula, Goa, India, International Society for Photogrammetry and Remote Sensing).

Thieler, E.R., 2000. National Assessment of Coastal Vulnerability to Future Sea-Level Rise. USGS Fact Sheet, fs-076-100.

Thieler, E.R., and Hammar-Klose, E.S., 1999. National Assessment of Coastal Vulnerability to Sea-Level Rise, U.S. Atlantic Coast: U.S. Geological Survey Open-File Report 99-593, 1 sheet.

UNEP (United Nations Environment Programme), 2007. Physical Alteration and Destruction of Habitats. www.unep.org (accessed February 27, 2008).

USGS (U.S. Geological Survey), 2001. National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Gulf of Mexico Coast. http://pubs.usgs.gov/of/2000/of00-179/pages/risk.html (accessed August 20, 2008).

USGS, 2005. The Digital Shoreline Analysis System (DSAS) version 3.0, an ArcGIS Extension for Calculating Histrionic Shoreline Change, Open-File Report 2005-1304. http://woodshole.er.usgs.gov/project-pages/DSAS/version3/ (accessed February 27, 2008).