Nat Hazards (2016) 80:1495–1513
DOI 10.1007/s11069-015-2035-9

ORIGINAL PAPER

Characterizing the multi-risk with respect to plausible natural hazards in the Balasore coast, Odisha, India: a multi-criteria analysis (MCA) appraisal

Anirban Mukhopadhyay[1] · Sugata Hazra[1] · Debasish Mitra[2] · C. Hutton[3] · Abhra Chanda[1] · Sandip Mukherjee[1]

Received: 7 November 2014 / Accepted: 10 October 2015 / Published online: 15 October 2015

Abstract Coastal zones are often prone to several natural hazards, and where the coastal zone has high population density and infrastructural assets, these hazards can render severe loss to both life and properties. The present paper reports a comprehensive assessment of the multi-hazard and multi-risk (keeping in view the population and assets exposed to multi-hazards) in the Balasore coast, situated in the state of Odisha, India, facing the Bay of Bengal immediately to its east. In most of the multi-hazard and multi-risk assessments, the importance of any one hazard in relation to others is often determined arbitrarily. To overcome this limitation, this work presents a multi-criteria analysis implemented on six hazards, namely coastal erosion, storm surge, sea level rise, coastal flooding, tsunami, and earthquake. The respective hazards were ranked according to their relative weight computed by pair-wise comparison, and the overall multi-hazard map of the coast was prepared using weighted overlay technique in GIS environment. In order to assess the exposure, population density and urban assets of the study area were also mapped. Finally, the population and urban density data were overlain on the multi-hazard map in order to derive the final map portraying the multi-risk of the Balasore coast. Coastal erosion and storm surge inundation are the two most substantial natural hazards that regularly affect this coast. It is also observed that hazard from the perspective of coastal erosion is spatially concentrated along the central part of the coast, while in the southern part, the effect of storm surge is higher. The area in and around Chandipur, which is situated in the central portion of the Balasore coast, has been found to have the highest multi-risk, which also happens to be a popular tourist destination.

✉ Anirban Mukhopadhyay
anirban_iirs@yahoo.com

[1] School of Oceanographic Studies, Jadavpur University, 188 Raja S. C. Mullick Road, Kolkata 700032, India

[2] Department of Marine and Atmospheric Sciences, Indian Institute of Remote Sensing, Dehradun, India

[3] Geo Data, School of Geography and Environment, University of Southampton, Southampton, UK

Keywords Pair-wise comparison · Multi-criteria analysis · Multi-hazard · Exposure · Multi-risk · Balasore coast

1 Introduction

Coastal zones all over the world are often highly populated owing to the service provided by the sea in sustaining livelihoods of millions of people (Neumann et al. 2015). A substantial percentage of the global population lives within 100 km of the coastline (Small and Nicholls 2003; Neumann et al. 2015) due to high resource access. Moreover, due to the aesthetic beauty of the oceans and equitable climate, several sea beaches of the globe have emerged as large-scale tourist spots (Webe and Mikacic 1994; Orams 1999; Marafa and Chau 2014). In addition to this, activities like fishing, agriculture, recreation, or even residential establishments are getting more and more concentrated in the coastal belts all over the world (Loomis and Paterson 2014). The point of concern in this regard is that these coastal milieus are under continuous threat from various natural hazards like cyclones, storm surges, erosion–accretion, coastal flooding, and tsunamis, which lead to both casualties and loss of properties (Ferrario et al. 2014). Therefore, efficient planning and devising management strategies are needed to reduce the socioeconomic damage and loss of life (Boesch et al. 1994; Flannery et al. 2015). Moreover, an assessment of population exposure in the areas which are prone to such hazards is essential for systematic risk reduction and mitigation of their effects.

According to the latest definitions of fifth assessment report of IPCC (2014), the term 'hazard' is defined as 'the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.' 'Exposure' on the other hand is defined as 'the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected' (IPCC 2014). Delineation of both hazards and exposures is extremely crucial in determining the 'risk' of a hazard-prone coastal regime. The concept of 'risk' is defined as 'the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services) and infra-structure' (IPCC 2014).

There are several ways to compute the multi-hazard and multi-risk of an area with respect to a set of threats; however, in most cases the importance of each hazard is assigned arbitrarily or possibly given an equal weighting in the absence of a sound methodological approach to determining potential weightings. Multi-criteria analysis offers this methodology, allowing several criteria to be ranked according to computed weights based on logic appropriate to the study area. The higher the weights given, the more important the criterion is, i.e., higher the chance of an area being affected adversely by it (in this study, a particular type of hazard). In the recent past, GIS has been exhaustively implemented in studies related to natural hazard assessment (Ronco et al. 2015; Torresan et al. 2012). GIS-based analysis provides interactive maps of the coastal landforms and their evolution and dynamics over various timescales (Jeanson et al. 2014). In addition to this, multi-criteria analysis (MCA) provides a collection of techniques in order to structure the decision-making problems and design as well as evaluate the alternative decisions (Malczewski 2006). GIS and MCA complement each other (Chakhar and Martel 2003), and together, both have enabled the development of spatial decision support systems (Goodchild 1993). The fundamental aspects of MCA are criteria selection and decision rule generation (Eastman et al. 1995).

As per our current knowledge, no studies have been reported so far, which adopted the MCA approach to computing the multi-risk of the Balasore coast with respect to multi-hazards. Owing to the history of hazards in this area in the recent past, such studies are essentially required. Hence, the main objective of the present study was to assess the scenario of multi-hazard of the Balasore coast (in eastern India) considering six potent hazards and to finally evaluate the multi-risk of the coastal region (taking into account the population density and urban assets exposure) by implementing multi-criteria analysis and geographical information system (GIS).

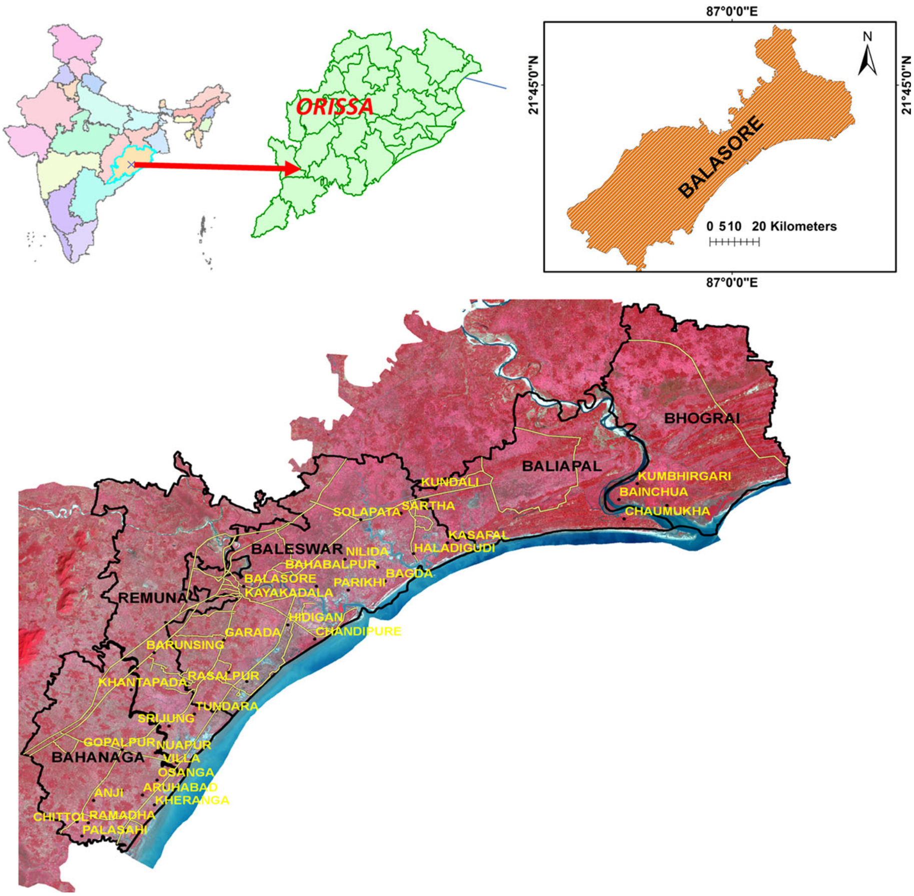

Fig. 1 Location of the study area showing the important places along with the road networks of the Balasore coast

2 Study area

The present study is carried out on the coastal zone of Balasore District, Odisha, situated in the eastern coast of India (Fig. 1). This coast is located between 20.48 and 21.59N latitudes and between 86.16 and 87.29E longitudes. Balasore has an 81-km-long coastline and is mainly known for the Chandipur sea beach (as a tourist spot). This site is also known to have a strategic importance from the perspective of the country's administration. The climate of Balasore is hot and humid. The average temperature of the coast is 28 °C, and the mean annual rainfall is 158 cm.

The geology of Balasore coast is characterized by the Archean–Proterozoic hard rocks, concealed under lateritic blankets, exposed in the northwestern part of the coast, and a vast stretch of Quaternary deposits in the eastern part (Bhatnagar et al. 1970). The northwestern part is composed of Singhbhum granite, mainly tonalite, and is intruded by a series of intrusive like ultrabasic to basic suite of rocks followed by granite and granophyre. This Archean–Proterozoic sequence is directly overlain by Quaternary deposits of varying nature. The quaternaries of the area have been classified into different formations depending upon their lithology, degree of compaction, pedological characteristics, and depositional environment. The coastal plains in the eastern and northeastern part of the coast are characterized by semi-consolidated to unconsolidated Quaternary sediments and alluvial deposits of recent origin, characterized by pebbles, sand, silt, sandy clay with iron nodules, fluvial silt, clay and deltaic deposits, old dune sand and marine clay, clay with calcareous concretions, etc., representing both fluvial and fluvio-marine facies (Bhatnagar et al. 1970).

Around Chandipur, southwest of the Subarnarekha Estuary, the coast can be divided into two broad morphozones: (1) a landward zone characterized by monotonous lowland modified by fluvial processes of the main stream, the River Buribalam, and (2) a seaward zone bordered by a single line of shore-parallel coastal dune lying on old marine terraces. The line of coastal dune is fronted by the open sea tidal flat. The tidal flat has two distinct morphometric facets: (a) a sandy sloping shoreward zone with an average width of 30 m and an average slope of 6°, and (b) a wide silty flat matted with ripples, having an average width of 1.5 km. Near the Buribalam Estuary, the silty intertidal flat is ornamented with clusters of river-mouth bars of varying dimensions, crisscrossed by tidal channels of varying depths (Mukherjee et al. 1987). Texturally, the size characteristics of different intertidal sediments show wide variation. Sedimentological analysis suggests that the upper sandy part of the Chandipur tidal flat is composed mostly of fine sand (2–3 j), whereas in the wide, silty flat more than 80 % of the sediments are finer than 3.5 phi size. Sediments in the river-mouth bars are generally found to be coarser in size. In the Chandipur, tidal flat manifestations of wave energy in the form of swash/backwash system which dominates over tidal energy, the intertidal surface, barring runnels, and tidal channels are observed to be intensely matted with ripples.

The main emphasis pertaining to the present study is given to the coastal zones of Balasore. To assess and spatially characterize the exposure of Balasore coast, the entire coastline is divided into 8 equal sections, each comprising an area of 10 km $\times$ 10 km (Fig. 1).

3 Materials and methods

3.1 Multi-criteria analysis

Criteria are the basic foundation of any evaluation system. They are a group of set rules that determine the desirability of alternative decisions (Hwang and Yoon 1981). There are two types of criteria, namely continuous factors and Boolean constraints (Eastman et al. 1993a, 1995). While a factor is a criterion that enhances or reduces the suitability of a specific alternative for a particular activity, constraints reduce the number of alternatives

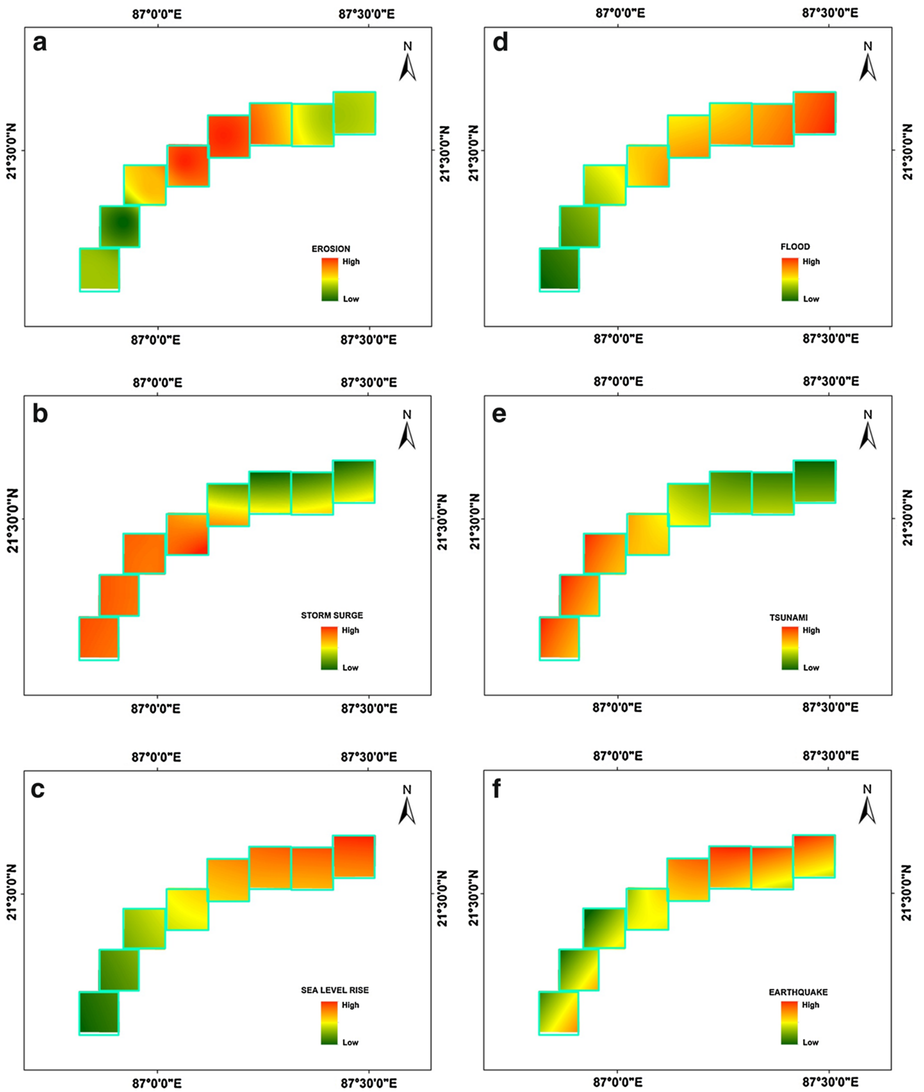

Fig. 2 Hazard map of the Balasore coast with respect to the **a** coastal erosion, **b** storm surge, **c** sea level rise, **d** coastal flooding, **e** tsunami inundation, and **f** earthquake

that are available (Eastman et al. 1995). Once the factors have been identified and sorted, they are reduced to a standardized scale and assigned weights accordingly to determine their relative importance to the objective being considered (Eastman et al. 1993b). This process by which all these criteria are combined to arrive at a particular decision is known as decision rule. A decision rule might involve only one criterion or multiple criteria. The actual implementation of the decision rule using multiple criteria is known as multi-criteria analysis (Eastman et al. 1995).

MCA is a part of spatial decision support system (SDSS) modeling. This technique is extensively used to model spatial thematic information of various kinds within a modeling framework. In the present study, six potential hazards are considered to affect the study area (Fig. 2) and a multi-hazard map has been prepared by following the methods discussed in Sect. 3.1.1 (Fig. 3). The exposure maps of the study area with respect to the population density and urban assets have been prepared following the methodology discussed in Sect. 3.1.2 (Fig. 4). As discussed earlier, the main objective of the study is to prepare a multi-risk map of the Balasore coast (Fig. 5), which has been discussed in Sect. 3.1.3.

3.1.1 Multi-hazard assessment

3.1.1.1 Selection of criteria/factor A list of hazards affecting the Balasore coast is considered in the present study, namely coastal erosion (C_e), storm surge inundation (SS_i),

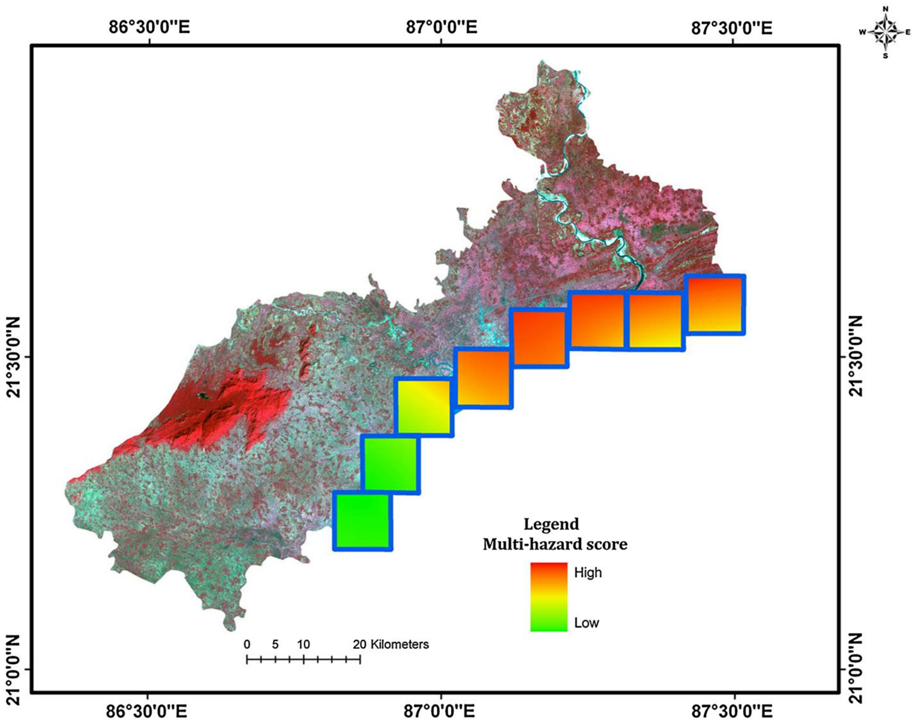

Fig. 3 A map showing the spatial variation of the multi-hazard of Balasore coast taking into account all the natural hazards

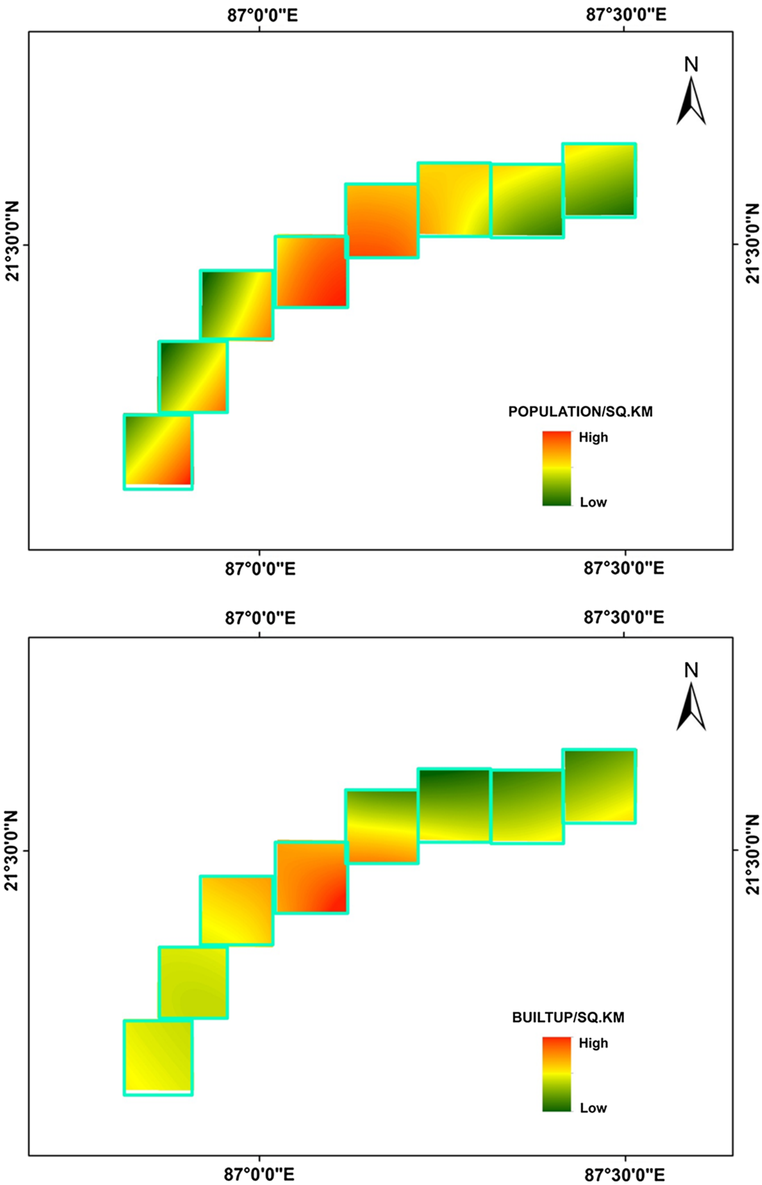

Fig. 4 Exposure map with respect to population and infrastructural urban density of Balasore coast

sea level rise (SLR), coastal flooding (C_f), tsunami inundation (T_s), and earthquake (E_q). The first four hazards are taken into account because coastal Odisha has a pronounced history of being affected by these processes (Srinivasa Kumar et al. 2010), while the hazards like tsunami and earthquake are also taken into consideration since they are always a potential threat to any and every coastal zone.

Almost 70 % of the sandy beaches throughout the world are affected by severe erosion (Bird 2000), and they are mainly attributed to increased storminess, coastal submergence,

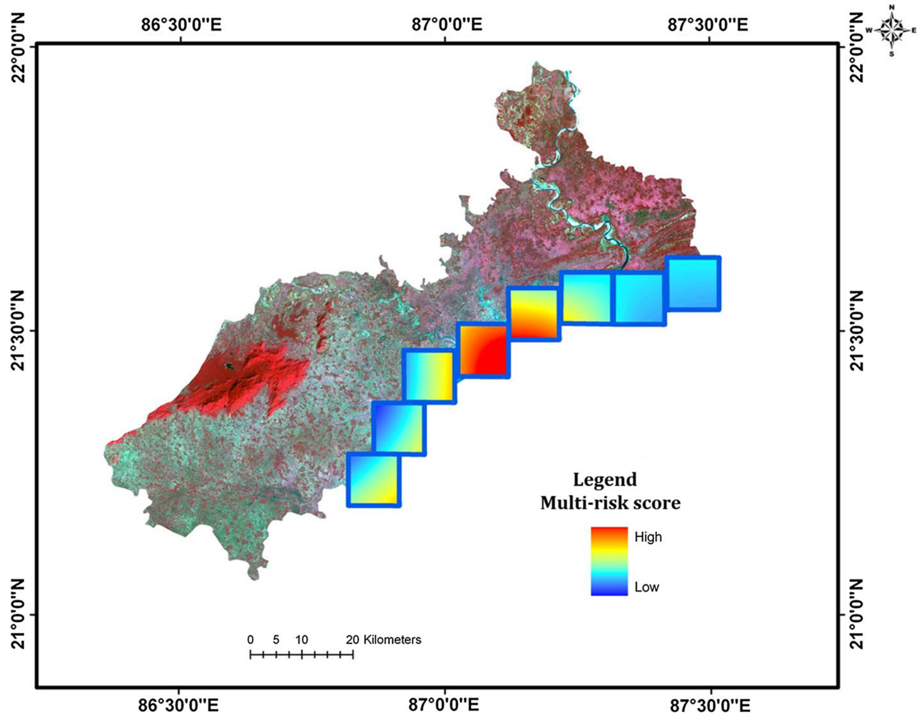

Fig. 5 Multi-risk map of Balasore coast

along with decreased sediment movement, changes in the directional component of wave, climate and human activities (Bryant 2005). Sanil Kumar et al. (2006) pointed out that around 23 % of Odisha's coastline is undergoing erosion at present. It is particularly acute in Puri, Gopalpur, Paradeep, and Satabhaya areas. About 16 km^2 of beach area around Paradeep was eroded between the years 1973 and 2005 due to increased anthropogenic activities (dredging) of Paradeep port (Sarma and Sundar 1988; Mani Murali et al. 2009). Intense erosion was also noticed in Puri (Mukhopadhyay et al. 2012). The coastal erosion is a very slow but continuous phenomenon, and it can be presumed that it is going on in the adjoining coastal areas like Balasore coast as well and causing sure and certain damage to assets and livelihood. Hence, the coastal erosion is given the highest importance in this study.

Storm surge as a consequence of tropical cyclones is yet another potent natural hazard in Odisha. The coastline of Odisha has been the most exposed area with respect to tropical cyclones in India as the past has proved it to be the most preferred spot where a cyclone makes landfall (Sharma and Patwardhan 2008). The average surge height in this region ranged between 3 and 5 m (Rao 1968). In October 1999, coastal Odisha was ravaged by two consecutive tropical cyclones: one from 17th to 19th and the second one from 28th to 30th. The latter was classified as a super-cyclone, with wind speed crossing beyond 350 km/h (Oxfam 2000). As a consequence, the storm surge generated was about 7 m high, which inundated areas that are situated 15–30 km inland from the shoreline (Thomalla and Schmuck 2004). Official estimates suggest that the death toll was about 10,000 although it is likely to be higher. Though this events are episodic, they cause intense damage when occurs; hence, storm surge is given second ranking in criterion selection.

Sea level rise (SLR) is one of the most discussed effects as a consequence of the ongoing global warming (rise in global temperature due to enhanced emission of greenhouse gases). Almost 10 % of global population lives within an elevation of 10 m above mean sea level, which makes it a potent threat in the coastal regions (McGranahan et al. 2007). SLR will affect all parts of the coastal belts such as beaches, lagoons, estuaries, deltas, coral reefs, mangroves (see Nicholls et al. (2007) for a detailed discussion of these effects). Though sea level changes along the east coast of India are comparatively understudied, large-scale fluctuations of the relative sea level are known to occur. Some studies indicate that the sea was 1–4 m above the present mean sea level during Middle Holocene and it is steadily rising in the past few centuries (Banerjee 2000; Mathur et al. 2004). Mukhopadhyay et al. (2011) recently observed an increasing trend in the sea level, and it is taking place all along the Odisha coast. In this paper, the rate of sea level rise is given the third rank.

Flooding is generally of two types: permanent flooding and episodic flooding (Kaiser 2006) which takes place due to a variety of reasons. Excess rainfall along with decreased capacity of the drainage systems to hold the excess water leads to permanent flooding, while episodic flooding is usually the result of surges in ocean water caused by cyclones and tsunamis. In this study, coastal flooding pertains to permanent flooding which is mainly caused by monsoonal rain. This type of flooding is frequently observed all along the coastal belt of Odisha, causing substantial damage. The coastal flooding is given the fourth rank in this study.

Table 1 Data used along with the data source and specification for the assessment of the selected hazards of the Balasore coast

Hazards	Data used	Data specification	Source
Coastal erosion	2001 and 2010 (LANDSAT ETM+ & TM)	1. ETM + L1T, dated: 2001/1/27; spatial resolution 30 m; tide level: 1.52 m 2. TM L1T, dated: 2010/1/28; spatial resolution 30 m; tide level: 1.49 m	http://glovis.usgs.gov/
Storm surge	Predicted storm surge height	Surge values in meter above MSL	http://www.osdma.org/
Sea level rise	Satellite altimeter data	Jason-1, Jason-2, TOPEX/Poseidon Sea Surface Height between the years 2001 and 2010	https://sealevel.jpl.nasa.gov/
Coastal flooding	Historical flood zonation maps	Flood inundation maps from the year 2001–2008	http://www.osdma.org/
Tsunami	TUNAMI N2 model	Parameters for simulation of Tsunami scenarios Earthquake location taken from Kayal et al. (2004) in the nearest seismogenic structure from Orissa coast and other parameters taken from the 2004 Indian Ocean Earthquake (USGS)	Imamura et al. (2006)
Earthquake	Earthquake zonation maps	1. Seismotectonic maps 2. Earthquake zonation maps	Geological Survey of India and http://www.osdma.org/

Tsunamis are considered as underrated hazards owing to the low frequency at which they occur (Bryant 2008); however, the last decade has experienced two major tsunamis (Southeast Asia in 2004 and Japan in 2011) which had devastating consequences in terms of both loss of lives and economic damage. Moreover, smaller tsunamis took place in Samoa and Chile in 2009 and 2010, respectively, that caused severe casualties. Though in the recent past there are no events of Tsunami recorded in the Balasore coast, a future possibility of tsunami cannot be ignored. Accordingly, tsunami is given the fifth rank.

Though no major earthquake has been reported in this coast in the recent past, however, some part of the coastal area falls under earthquake zone III. As earthquake is one of the most deadly hazards of the world, it is also taken into consideration and given sixth rank in the present study.

3.1.1.2 Data used for hazard assessment The data used to assess the hazard score of the Balasore coast with respect to the individual threats and their corresponding sources are shown in Table 1. In order to generate the hazard map of the study area from the perspective of coastal erosion, multi-temporal satellite imageries of the years 2001 and 2010 (LANDSAT ETM+ and TM) are used. The respective imageries (after appropriate corrections) are classified into two classes: land and water. The temporal change of transition from land to water is estimated to compute the degree of erosion during same time of the 2 years having almost same tidal level. The predicted storm surge height derived from Odisha State Disaster Management Authority (OSDMA) for the Balasore coast is considered in the present study. Applying the spline interpolation technique, the hazard map of the Balasore coast with respect to the storm surge is assessed. Spline is basically an interpolation technique which creates a raster surface from points using a two-dimensional minimum curvature technique. The sea level rise is computed in the present study by analyzing the satellite altimeter data of Jason-1, Jason-2, TOPEX/Poseidon Sea Surface Height between the years 2001 and 2010. The flood maps of 2001–2008 obtained from OSDMA are geo-referenced, and the layers of the flood extent are created, and finally, the flood zonation map is prepared to generate the hazard map with respect to coastal flooding. Tsunami inundation hazard map of the present study area is calculated using the TUNAMI N2 model (Imamura et al. 2006). Bathymetric data from C-MAP and coastal elevation data from ASTER-GDEM are merged to prepare the model grid. Using the MATLAB, version 7.1, the combined data are transformed into FORTRAN-readable format. Implementing the several experimental earthquake parameters, the surge heights due to probable tsunamis are computed and based on the coastal elevation, the extent of inundation is assessed. The hazard map from the viewpoint of earthquake is computed by overlaying the seismotectonic maps and earthquake zonation map obtained from OSDMA. The respective hazard maps are shown in Fig. 2.

3.1.1.3 Allocation of weights to the hazards Assigning relative weights to the various criteria under consideration is one of the most crucial attribute in MCA. Among the several methods available, ranking method, rating method, pair-wise comparison method, and trade-off analysis method are mostly used (Malczewski 1999). In this study, the pair-wise comparison method is adopted to compute the respective weights of the hazard. In this method, the decision maker must have a prior knowledge of the relative importance of the different hazards for the area under consideration.

In pair-wise comparison method, firstly a criterion versus criterion matrix is created to compare each pair of criteria and accordingly assign relative ratings using the scale of pair-wise comparison (Saaty 1980). The intensity of importance of one type of hazard with respect to another is categorized into six classes ranging from 1 to 6. Here, the value of 1 for a pair of hazards denotes that the two hazards are of 'equal importance,' while a value of 6 denotes 'strong-to-very strong importance' of one hazard with respect to another. Likewise, the intermediate values between 1 and 6 are defined in Table 2. Table 3 shows the pair-wise comparison of the various hazards used in this study. In this table, we have logically arranged the six respective hazards in the following the order: $C_e >$ SLR $> SS_i > C_f > T_s > E_q$ and accordingly the magnitude of the pair-wise comparison are listed. For example, in the first column of Table 3 the magnitude between C_e and SS_i is 0.5, which denotes that the importance of SS_i is half with respect to the importance of C_e. This relation is equally applicable if we consider the first row of Table 3, where we can see that the magnitude between SS_i and C_e is 2, which denotes the importance of C_e is twice the importance of SS_i. In this fashion, the magnitude of pair-wise comparison is tabulated in the form of a matrix in Table 3, and the summation of the respective columns is computed in the last row. Followed by this, the matrix is normalized by the sum of the column to create another matrix. In this new matrix, the sum of the rows is calculated and then divided by the number of hazards under consideration to get the relative criterion weights (Table 4). In this way, the sum total of all the weights becomes equal to unity.

3.1.1.4 Formulation of the decision rule The most common ways of generating decision rules (used for multi-criteria decision-making problems) are simple additive weighting method, value/utility function method, analytical hierarchy process method, ideal point method, and concordance methods (Malczewski 1999). The simple additive weighting (SAW) method is used in this study owing to its simplicity (Hobbs et al. 1992). Moreover, according to Triantaphyllou and Mann (1989) it gives the most acceptable results for majority of single-dimensional problems. It is based on the concept of weighted average and is also known as the weighted least square method. In this method, the decision maker, based on logic, directly assigns weights of relative importance to each attribute. A score is obtained for each criterion by multiplying the weight assigned for each attribute by the scaled value given to the criteria on that attribute and summing the products of all attributes (Jiang and Eastman 2000):

$$S = \sum_j w_j \times x_{ij} \quad (1)$$

where S = score of a particular criterion, w_j = normalized weight of the jth criterion, and x_{ij} = score of the ith criterion with respect to the jth criterion. For the simple additive method to work, $\sum w_j = 1$.

Table 2 Scale of pair-wise comparison of criteria

Intensity of importance	Definition
1	Equal importance
2	Equal-to-moderate importance
3	Moderate importance
4	Moderate-to-strong importance
5	Strong importance
6	Strong-to-very strong importance

Table 3 Pair-wise comparison of criteria used in this study

Criteria (C)	C_e	SS_i	SLR	C_f	T_s	E_q
C_e	1	2	3	4	5	6
SS_i	0.5	1	2	3	4	5
SLR	0.333	0.5	1	2	3	4
C_f	0.25	0.333	0.5	1	2	3
T_s	0.2	0.25	0.333	0.5	1	2
E_q	0.167	0.2	0.25	0.333	0.5	1
Column sum ($\sum_c$)	2.45	4.283	7.083	10.833	15.5	21

Table 4 Computations of the relative criterion weights

C	C_e	SS_i	SLR	C_f	T_s	E_q	Row sum ($\sum_r$)	Relative criterion weight (RCW = $\sum_R$/ 6)
C_e	0.408	0.467	0.424	0.369	0.323	0.286	2.277	0.379 (0.380)
SS_i	0.204	0.233	0.282	0.277	0.258	0.238	1.492	0.249 (0.249)
SLR	0.136	0.117	0.141	0.185	0.194	0.19	0.963	0.161 (0.161)
C_f	0.102	0.078	0.071	0.092	0.129	0.143	0.615	0.103 (0.103)
T_s	0.082	0.058	0.047	0.046	0.064	0.095	0.392	0.065 (0.065)
E_q	0.068	0.047	0.035	0.031	0.032	0.048	0.261	0.0435 (0.044)
Column sum ($\sum_c$)	1	1	1	1	1	1		1

In this study, individual hazards are classified into four classes and accordingly given a scale ranging from 1 to 4 (low to high).

$$S_t = \int W_1 S_{ct1} + W_2 S_{ct2} + \cdots + W_n S_{ctn} \tag{2}$$

where S_t = total score comprising all the criteria, W_n = weight assigned to the nth criterion, and S_{ctn} = score of the nth criterion.The weights and scores assigned to each criterion are shown in Table 5.

After the scores are computed, finally the multi-hazard index (S_{mhi}) is calculated as:

$$S_{mhi} = f \int_{S_l}^{S_u} \left(C_e, SS_i, SLR, C_f, T_s, E_q\right) \tag{3}$$

Here, in Eq. 1, 'S_l' and 'S_u' denote the lower (l) and the upper (u) scores (S) allotted to the respective hazards. In this way, S_{mhi} is calculated individually for each pixel comprising the 8 blocks of the study area. Assimilating these S_{mhi} values of each pixel, the gradient or variability of multi-hazard index is figured out to prepare the multi-hazard map.

Table 5 Weights and scores assigned to each criterion used in this study

Criteria /alternatives	RCW	Scale		Score
C_e	0.380	Low	1	0.380
		↓	2	0.760
			3	1.140
		High	4	1.520
SS_i	0.249	Low	1	0.249
		↓	2	0.498
			3	0.747
		High	4	0.996
SLR	0.161	Low	1	0.161
		↓	2	0.322
			3	0.483
		High	4	0.644
C_f	0.103	Low	1	0.103
		↓	2	0.206
			3	0.309
		High	4	0.412
T_s	0.065	Low	1	0.065
		↓	2	0.130
			3	0.195
		High	4	0.260
E_q	0.044	Low	1	0.044
		↓	2	0.088
			3	0.132
		High	4	0.176

3.1.2 Exposure assessment

In order to analyze the exposure of the study area, the population density and the built-up or infrastructural density in this coastal zone are mapped utilizing the data from Census of India 2011 and satellite imagery of the year 2011. The term built-up or infrastructure, in this paper, is used to refer to attributes such as houses, roads, railway tracks, and it is discussed in detail in Sect. 4. The village-level population (Primary Census Abstract Data, Census of India 2011) data for Balasore coast of Odisha state (along the 10-km buffer of coastline) are considered in order to compute the population density (population/area) of all the 10 km × 10 km blocks. The geo-centers of the villages are plotted as points and interpolated in the GIS environment using inverse distance-weighted (IDW) interpolation technique to prepare the population density map. Land-use/land-cover classification is performed on the selected study area using Landsat TM image of the year 2011. The built-up area is extracted from this process, and accordingly the percentage of area of the built-up per 10 km × 10 km block is computed.

3.1.3 *Multi-risk assessment*

The multi-hazard map is prepared, which took into account only the physical aspects, i.e., intensity or consequences of all the natural hazards. On the other hand, exposure has been assessed based on the spatial variability of population density and urban asset of the study area. However, the final desired output of the present study is to build a multi-risk map of the Balasore coast. According to the definition of risk (IPCC 2014), it is the potential for adverse consequences on lives as well as infrastructure. Hence, in order to evaluate the risk of a particular area, the physical intensity of an event along with the presence of both lives and assets that are likely to be affected needs to be considered. The final output of multi-risk map is thus prepared by merging the data obtained from the multi-hazard score as well as the exposure. In order to prepare this final multi-risk map, a spatially weighed overlay function is implemented in the GIS domain (ArcGIS 10.0) where the multi-hazard map along with the population density and the urban assets (built-up density) as unitless quantities (and being allotted equal weights) is combined.

4 Results and discussion

4.1 Multi-hazard maps

The computed multi-hazard map of the Balasore coast is based on the threat to populations and assets from various natural hazards. Instead of classifying the coastal hazard zones in some distinct classes, a continuous gradual classification of the hazard is adopted in this study. The classes range from low hazard to moderate hazard to high hazard. The classified hazard maps of Balasore coast from erosion, storm surge, sea level rise, coastal flooding, tsunami, and earthquake are illustrated in Fig. 2, and the multi-hazard map is shown in Fig. 3.

The hazard analysis from the present study reveals that the Balasore coast suffers significantly from coastal erosion problem (Fig. 2a). The rate of erosion seems to increase in the central region of the coast, compared to both southern and northern sections, possibly owing to its westward concave shape. The areas near the estuaries of Subarnarekha and Kasaphal, in northern portion of the coastal zone, and Kasiamohana and Basudebpur in the south do not fall under the threat of coastal erosion; however, in the area near Buribalam Estuary and Chandipur area, the rate of erosion is quite high. The present analysis shows that out of the 8 zones (10 km), almost 400 km^2 area comprising four blocks in the central part (as shown in Fig. 2a) should be given priority while framing coastal management programs. While assessing coastal erosion in the Indian east coast near the present study area, Jana and Bhattacharya (2013) observed extensive erosion in the downdrift areas of man-made infrastructures like seawall, groin, pylons, and jetties. Areas having such artificial structures within those four highly prone blocks are even more prone to coastal erosion problem. Hence, by means of this study, the regions where rigorous attention needs to be paid could be narrowed down at least in an initial sense.

On the Balasore coast, hazard due to storm surge is higher in the southern region. The boundary area of Bhadrak coast through Basudebpur and Rupakhanda is under potential danger with respect to storm surge. The hazard, in this case, gradually decreases northward. Notably, the Balasore coastline has a wider continental shelf associated with a shallow bathymetry compared to the other adjoining coastlines in the state of Odisha. This is a potent factor that might lead to storm surges of enhanced heights and hence bring forth severe devastation along with it. The inundation limit varies from 500 m to 1.5 km along the coastline. From the present analysis (Fig. 2b), it can be depicted that the four southern blocks are very highly prone from the perspective of storm surge. Recently, Barman et al. (2014) observed that there are several tidal inlets in and around the Odisha coast, which in turn are a part of an intricate channel network through which seawater can intrude even during a low-to-moderate storm surge. Moreover, they also pointed out that these storm surges eventually give rise to a 'saline flood' or water logging which can be severely detrimental to agricultural and aquaculture plots. Hence, among the four southern blocks, special emphasis should be given to the low-lying tidal inlets where the impact of storm surge would be worst.

Sea level rise shows just an opposite trend with respect to the storm surge hazard (Fig. 2c). The threats due to sea level rise increase from south to north. The potential threat of coastal flooding also follows the same pattern in Balasore (Fig. 2d). The three main rivers of Balasore coast: Subarnarekha, Kasaphal, and Buribalam meet the sea at the northern portion. Hence, the regions prone to coastal flooding is observed to be consistently on the higher end in the four blocks lying in the northern portion of the coast. Over the last 60 years, an average steady increase in the regional sea level lying adjacent to the Indian subcontinent at the rate of 1.4 mm $year^{-1}$ is observed by Palanisamy et al. (2014). Moreover, Barman et al. (2014) observed that rivers such as Buribalam and Dugdugi carry large freshwater discharge accompanied by huge sediment load and face tremendous resistance from the cross-shore currents of the seawater and incoming tides, resulting in accumulation of water near the river confluence. Together, with the aspect of regional sea level rise, this makes the river confluences situated within this blocks more prone to both flood and sea level rise.

Compared to the above-mentioned four hazards, the remaining two hazards, namely tsunami inundation and earthquake are of lesser importance simply because of their extremely lesser probability of occurrence in the temporal scale; however, preparedness and management strategies should be framed since upon occurring they create massacre and take a long time to recover. Overlaying Fig. 2e on the administrative maps of Balasore coast, it is observed that five coastal blocks, which include 29 gram panchayats (area demarcated by means of smallest governing bodies) and 63 villages in the Balasore coast, have been found to be under the maximum threat from tsunami surge. The tsunami hazard follows the same pattern like that of storm surge; that is, it increases from north to south. Hence, identification of elevated landmarks nearby these respective villages could be done by government authorities, and accordingly local population could be made aware how to act and where to go under extreme circumstances. The seismotectonic map and the OSDMA map of the Odisha show that the northern portion of Balasore coast comes under earthquake zone III and the remaining area falls under earthquake zone II. So, the threat due to earthquake varies accordingly. The hazard map from the viewpoint of earthquake is shown in Fig. 2f. However, Odisha coast has no record of severe earthquake in the recent past.

Implementing all the coastal hazards according to ranking, i.e., first rank: coastal erosion >second rank: storm surge >third rank: sea level rise >fourth rank: coastal flooding >fifth rank: tsunami >sixth rank: earthquake, a multi-hazard map has been prepared for Balasore coast (Fig. 3) taking into account the combined effect of all the hazards discussed so far. This map simply depicts the spatial variability of the multi-hazard from a holistic point of view. Figure 3 shows that on the whole, the multi-hazard is lower in the southern part of the coast and it increases toward the northern part along the coastal areas. Hence, management plans and policy framing may be given priority along the northern parts of the Balasore coast.

4.2 Exposure maps

Figure 4 shows the exposure of the study area based on its population density and built-up density. It is clearly visible from this map that the population density is substantially high in the central region and the northern region encompassing places such as Chandipur, Bagda, and Haladigudi. However, the built-up density shows higher percentages in the central and partly in the southern part, whereas in the northern part where population is substantially high, built-up density is found lowest. In the northern part, there are mostly villages having kaccha (mud) houses. However, it is worth noticing that in the central part, especially near Chandipur, both population and built-up density are substantially high. A higher population density generally implies a higher probability of impact on the human. Similarly, a high built-up density which acts as a proxy of public assets indicates a higher chance of damage from any hazard. Moreover, it is important that exposure assessment be made at smaller scales (Stephen and Downing 2001; Torresan et al. 2008). Hence, the present study is useful in this context.

4.3 Multi-risk map

After incorporating the aspects of exposure (i.e., population density and built-up density data) along with the multi-hazard layers, final multi-risk map (Fig. 5) is prepared, which shows that the area in and around Chandipur in Balasore coast has the maximum exposure comprising all the individual aspects. It is quite low in the northern part, while in the southern part, it is moderate to high. This result is quite justifiable as Chandipur is one of the renowned tourist spots of the eastern coast of India, and perhaps the most popular of the Balasore coast. Owing to the enhanced tourist activity in this area, several man-made structures like beach resorts and hotels have sprung up in the recent past. A substantial part of the local population is also attracted toward this livelihood opportunity which has grown due to the aspect of tourism. As observed earlier, both population and urban density is quite high in this area. Apart from local residents, a significant influx of tourists is maintained throughout the year. Moreover, Chandipur is also a location of India's strategic importance. It is also evident from the multi-hazard map (Fig. 3) that this region shows substantially higher hazard scores. Taking into account the individual hazard maps (Fig. 2), it can be seen that the Chandipur region is prone to hazards such as coastal erosion, flooding, and storm surge. Specifically, coastal erosion and storm surge show higher hazard score in and around the Chandipur region. Though the coastal flooding hazard score is found highest in the northern part of the Balasore coast, still the central part near Chandipur is quite prone to flooding. From the viewpoint of the other hazards (i.e., tsunami, earthquake, and sea level rise), the region is also having a moderate-to-high hazard score. Hence, from the perspective of exposure (i.e., both human life and property) along with the proneness to the selected hazards, this place in particular might be given highest priority while framing coastal disaster management strategies.

5 Conclusion

The coastal zone presents a unique set of challenges to those professionals who are charged with its disaster management. Being the dynamic interface between land, air, and sea, coastal systems are interrelated in complex ways that, at present, are inadequately understood. An improved understanding of these systems is thus necessary to develop effective policies for the management of the coastal zone. The present study aims to contribute toward this at an initial level by means of analyzing the multi-hazard of one of the most hazard-prone coastlines of India, along with characterizing the spatial variation of the exposure and eventually the multi-risk. Coastal erosion and storm surge are the two most potent geo-hazards befalling the present study area of Balasore. The proneness of the coast to different hazards considered in this study is spatially variable; however, the multi-risk is found highest in the Chandipur coastline which happens to be a popular tourist destination as well. Hence, proper planning and management may be done emphasizing the identified areas from this study, by the competent authorities to ensure the safety of human lives and properties.

Moreover, accuracy of multi-risk analysis of any region depends on the parameter selected for the study and the corresponding weights given. Data requirement to represent the parameter is of prime importance for this approach. Prior knowledge about the area will add to the accuracy of the result. Overall, results need to be validated at the time of extreme events and consequent fine-tuning of the weights given to the specific parameters can be altered accordingly. Multi-temporal/multi-sensor satellite data along with geo-spatial technology can be implemented to help us better understand the multi-hazard phenomena in the coastal area and can be of great help for the decision makers for the coastal zone management, as observed in this study. This study can be taken one step forward by crucially analyzing the socioeconomic aspects of the Balasore coast in the context of vulnerability and overlaying it on the multi-risk derived from this study to finally assess the multi-vulnerability of this region from natural hazards.

Acknowledgments The authors gratefully acknowledge Jadavpur University, Kolkata, India, and Indian Institute of Remote Sensing, Dehradun, India, for providing all the necessary support and infrastructure to carry out the present work. We are also grateful to Geological Survey of India (GSI), Odisha State Disaster Management Authority (OSDMA) and NASA for providing the data required. We also humbly acknowledge the efforts of Mr. Rajarshi Dasgupta for enhancing the quality of the manuscript. A Chanda is grateful to Department of Science and Technology for providing the INSPIRE fellowship. A. Mukhopadhyay is grateful to Indian National Centre for Ocean Information Services (INCOIS) for their support.

References

Banerjee PK (2000) Holocene and late Pleistocene relative sea level fluctuations along the east coast of India. Mar Geol 167:243–260

Barman NK, Chetterjee S, Khan A (2014) Spatial variability of flood hazard risks in the Balasore coastal block, Odisha, India. J Geogr Nat Disast 4:1–7. doi:10.4172/2167-0587.1000120

Bhatnagar NC, Sundara Rajan GV, Raghav Rao KV, Krupanidhi KVJR, Krishna Rao IVR, Ahmad M, Radhakrishna TS, Siddiquie HN, Jha BN, Kripakaran V, Kameswaran N (1970) Geology and ground water resources of parts of Balasore and Cuttack coasts, Odisha, Bull, GSI Series B-Engineering Geology and Ground Water

Bird ECF (2000) Coastal geomorphology: an introduction. Wiley, Chichester, p 322

Boesch DF, Josselyn MN, Mehta AJ, Morris JT, Nuttle WK, Simenstad CA, Swift DJP (1994) Scientific assessment of coastal wetland loss, restoration and management in Louisiana. J Coast Res 20:1–103

Bryant E (2005) Natural hazards, 2nd edn. Cambridge University Press, Cambridge

Bryant E (2008) Tsunami: the underrated hazard, 2nd edn. Springer, Heidelberg

Census of India (2011) Provisional population totals Paper 2 of 2011: Odisha. http://www.censusindia.gov.in/2011-prov-results/paper2/data_files/Odisha/Data-sheet-Odisha.pdf. Accessed 17 June 2012

Chakhar S, Martel JM (2003) Enhancing geographic information system capabilities with multi-criteria evaluation functions. J Geogr Inf Decis Anal 7:47–71

Eastman JR, Kyem PAK, Toledano J, Jin W (1993a) GIS and decision making. UNITAR, Geneva

Eastman JR, Toledano J, Weigen J, Kyem PAK (1993b) Participatory multi-objective decision making in GIS. In: McMaster RB, Armstrong MP (eds) Proceedings of eleventh international symposium on computer-assisted cartography (AUTOCARTO XI). ACSM-ASPRS, Minneapolis, pp 33–42

Eastman JR, Weigen J, Kyem PAK, Toledano J (1995) Raster procedures for multi-criteria/multi-objective decisions. Photogramm Eng Remote Sens 61:539–547

Ferrario F, Beck MW, Storlazzi CD, Micheli F, Shepard CC, Airoldi L (2014) The effectiveness of coral reefs for coastal hazard risk reduction and adaption. Nat Commun 5(3794):1–9

Flannery W, Lynch K, Cinnéide MO (2015) Consideration of coastal risk in the Irish spatial planning process. Land Use Policy 43:161–169

Goodchild MF (1993) The state of GIS for environmental problem-solving. In: Goodchild M, Parks B, Steyaert L (eds) Environmental modeling with GIS. Oxford University Press, Oxford, pp 8–15

Hobbs BJ, Chankong V, Hamadeh W, Stakhiv E (1992) Does choice of multicriteria method matter? An experiment in water resource planning. Water Resour Res 28:1767–1779

Hwang CL, Yoon K (1981) Multiple attribute decision making: methods and applications. Springer, Berlin

Imamura F, Yalciner AC, Ozyurt G (2006) TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near field tsunamis version 2) Manual draft. http://www.tsunami.civil.tohoku.ac.jp/hokusai3/E/projects/manual-ver-3.1.pdf

IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change (IPCC), Geneva, p 151

Jana A, Bhattacharya AK (2013) Assessment of coastal erosion vulnerability around Midnapur-Balasore Coast, eastern India using integrated remote sensing and GIS techniques. J Indian Soc Remote Sens 41(3):675–686. doi:10.1007/s12524-012-0251-2

Jeanson M, Dolique F, Anthony EJ (2014) A GIS-based coastal monitoring and surveillance observatory on tropical islands exposed to climate change and extreme events: the example of Mayotte Island, Indian Ocean. J Coast Conserv 18:567–580

Jiang H, Eastman JR (2000) Application of fuzzy measures in multi-criteria evaluation in GIS. Int J Geogr Inf Sci 14:173–184

Kaiser G (2006) Risk and vulnerability analysis to coastal hazards- an approach to integrated assessment, unpublished Ph.D thesis, Christian Albrecht University of Kiel

Kayal JR, Gaonkar SG, Chakraborty GK, Singh OP (2004) Aftershocks and seismotectonic implications of the 13 September 2002 earthquake (Mw 6.5) in the Andaman Sea basin. Bull Seismol Soc Am 94(1):326–333

Loomis DK, Paterson SK (2014) The human dimensions of coastal ecosystem services: managing for social values. Ecol Indic 44:6–10

Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, New York

Malczewski J (2006) GIS-based multicriteria decision analysis: a review of literature. Int J Geogr Inf Sci 20:703–726

Mani Murali R, Shrivastava D, Vethamony P (2009) Monitoring shoreline environment of Paradip, east coast of India using remote sensing. Curr Sci 97:79–84

Marafa LM, Chau KC (2014) Framework for sustainable tourism development on coastal and marine zone environment. Tour Leis Glob Change 1:1–11

Mathur UB, Pandey DK, Bahadur T (2004) Falling late Holocene sea-level along the Indian coast. Curr Sci 87:439–440

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risk of climate change and human settlements in low elevation coastal zones. Environ Urban 19:17–37

Mukherjee KK, Das S, Chakrabarti A (1987) Common physical sedimentary structures in a beach-related open sea siliciclastic tropical tidal flat at Chandipur, Odisha and evaluation of weather conditions through discriminant analysis. Senckenbergianamaritima 19:261–293

Mukhopadhyay A, Mukherjee S, Hazra S, Mitra D (2011) Sea level rise and shoreline changes: a geoinformatic appraisal of Chandipur coast, Odisha. Int J Geol Earth Environ Sci 1:9–17

Mukhopadhyay A, Dasgupta R, Hazra S, Mitra D (2012) Coastal hazards and vulnerability: a review. Int J Geol Earth Environ Sci 2:57–69

Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015) Future coastal population growth and exposure to sea-level rise and coastal flooding—a global assessment. PLoS One 10(3):e0118571. doi:10.1371/journal.pone.0118571

Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. Climate change. In: Parry ML, Canziani OF, Palutikof JP, van den Linden PJ, Hanson CE (eds) impacts, adaptation and vulnerability. Contributions of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 315–356

Orams M (1999) Marine tourism: development, impacts and management. Routledge, London

Oxfam (2000) India disasters report. Oxford University Press, New Delhi

Palanisamy H, Cazenave A, Meyssignac B, Soudarin L, Woppelmann Becker M (2014) Regional sea level variability, total relative sea level rise and its impacts on islands and coastal zones of Indian Ocean over the last 60 years. Glob Planet Change 116:54–67

Rao NSB (1968) On some aspects of local and tropical storms in the Indian Ocean area, Ph.D. thesis. Jadavpur University, Kolkata, p 325

Ronco P, Bullo M, Torresan S, Critto A, Olschewski R, Zappa M, Marcomini A (2015) KULTURisk regional risk assessment methodology for water-related natural hazards–Part 2: application to the Zurich case study. Hydrol Earth Syst Sci 19:1561–1576

Saaty TL (1980) The analytical hierarchy process. McGraw-Hill, New York

Sanil Kumar V, Pathak KC, Pednekar P, Raju NSN, Gowthaman R (2006) Coastal processes along the Indian coastline. Curr Sci 91:530–536

Sarma KGS, Sundar V (1988) Analysis of nearshore profiles off Paradip port, east coast of India. Indian J Mar Sci 17:94–98

Sharma U, Patwardhan A (2008) Methodology for identifying vulnerability hotspots to tropical cyclone hazard in India. Mitig Adapt Strat Glob Change 13:703–717

Small C, Nicholls RJ (2003) A global analysis of human settlements in coastal zones. J Coast Res 19:584–599

Srinivasa Kumar T, Mahendra RS, Nayak S, Radhakrishnan K, Sahu KC (2010) Coastal vulnerability assessment for Odisha state, east coast of India. J Coast Res 26:523–534

Stephen L, Downing TE (2001) Getting the scale right: a comparison of analytical methods for vulnerability assessment and household-level targeting. Disasters 25:113–135

Thomalla F, Schmuck H (2004) "We all knew that a cyclone was coming": disaster preparedness and the cyclone of 1999 in Odisha, India. Potsdam EVA Working Paper 8:1–23

Torresan S, Critto A, Valle MD, Harvey N, Marcomini A (2008) Assessing coastal vulnerability to climate change: comparing segmentation at global and regional scales. Sustain Sci 3:45–65

Torresan S, Critto A, Rizzi J, Marcomini A (2012) Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. Nat Haz Earth Syst Sci 12:2347–2368

Triantaphyllou E, Mann SH (1989) An examination of the effectiveness of multi-dimensional decision making methods: a decision-making paradox. Decis Supp Sys 5:303–312

Webe S, Mikacic V (1994) The importance of market research in planning the development of nautical tourism in Croatia. Turizam 42:71–74