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Risk of extreme events in delta environment: A case study of the Mahanadi delta

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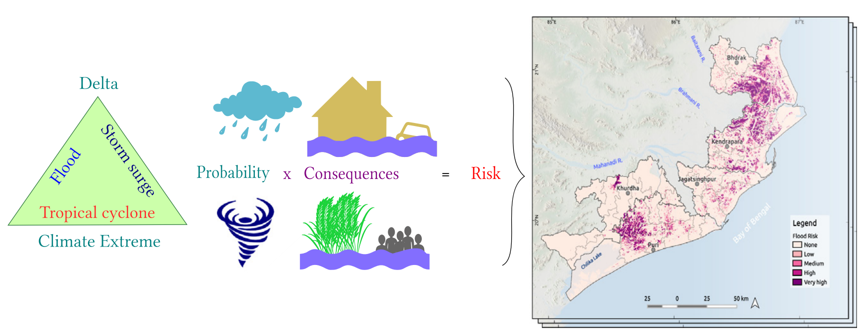
HIGHLIGHTS

- Mahanadi delta is exposed to extreme events and climate change impacts.
- Hazard specific risk estimation is helpful to perceive effective adaptation strategy.
- Higher extent of socio-economic sensitivity often increases future risks.
- Low lying coastal areas of the delta are mostly with probable high risk.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic climate change is considered as one of the greatest environmental, social and economic threats to the future world. Low lying deltas all over the world are increasingly subjected to multidimensional risk of sea level rise, cyclone, surges and salinisation. The life and livelihood of the communities of such deltas are endangered due to climate change acting as risk multiplier. The Mahanadi delta in the state of Odisha, India is one of the such populous deltas with estimated 8 million population in 2011 with a density of 613 persons/km^2. Over the past decades, it experienced major climatic threats in the form of cyclone, surge inundation and flooding with variable intensities and impacts along and across the coast. The present research assessed the risk of climatic extreme events and their variability in the delta, with an intention of mitigation or adaptation to possible impacts in specific region. Synthetic Aperture Radar (SAR) data and daily rainfall data were used to extract flood inundation. Tropical Cyclone Risk Model (TCRM) along with surge decay function was used to estimate cyclonic wind speed and surge inundation and risk indices were computed using fuzzy logic based approach. The result shows that in the coastal districts, risk of severe cyclones rank above the heavy floods. Agriculture, the main livelihood of these districts (71%) is impacted adversely making the delta community vulnerable to such extreme events. Kendrapara followed by Bhadrak and Jagasinghpur districts appear to be most risk prone segment in the delta making the northern part comparatively more risk prone where focused mitigation and adaptation actions are needed.

1. Introduction

Since the inception of civilization, river deltas have attracted humans. Access to fishing and the extremely fertile land of deltas provide an ample amount of food as the very basic need for survivable. Ports and harbours in the deltas provide required facilities for trade and business. Today, about 500 million people live in or near river deltas (Kuenzer and Renaud, 2012). Average population density in deltas is estimated to be ~500 persons/km^2, as a comparison to the world population density of 44.7 persons/km^2 (UN, 2007). Yet deltas are also much susceptible to natural hazards because of their low lying flatland, the presence of shallow bed rivers, and open to oceanic disturbances (Vörösmarty et al., 2009; Syvitski, 2008).

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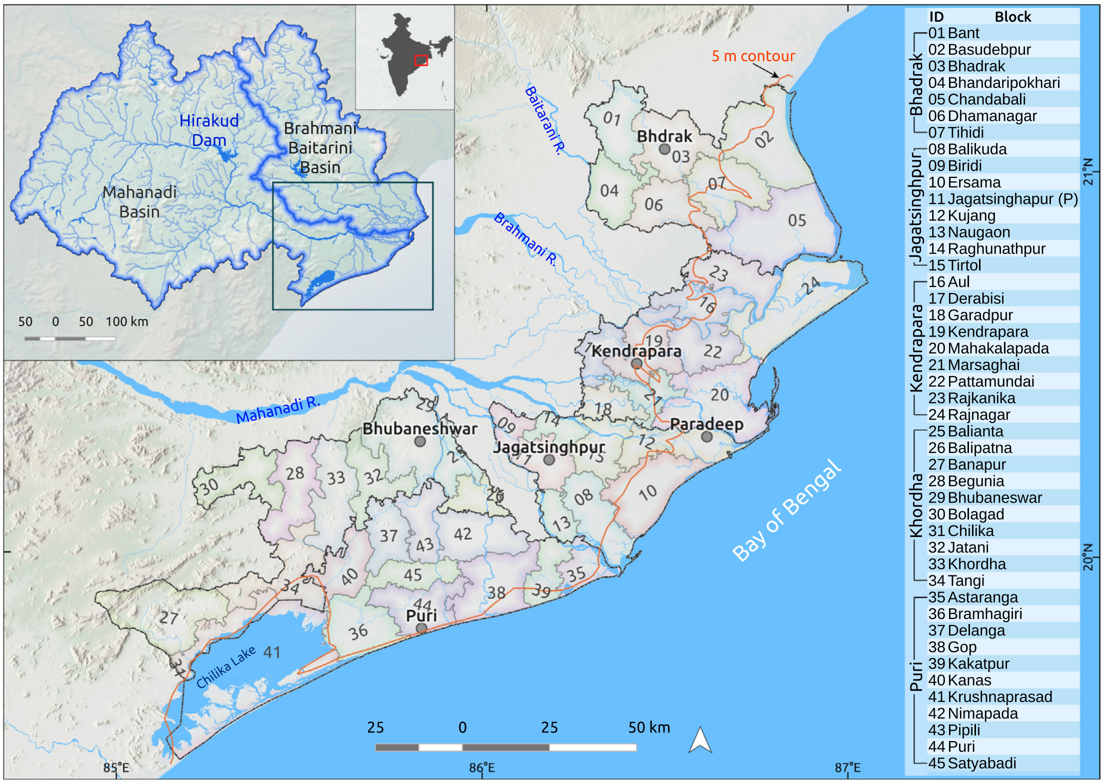

Fig. 1. Location map of the study area.

The dawn of the third millennium is attributed to human-induced large-scale changes in the earth's environments. It includes alteration of climate, land use and its productivity, atmospheric chemistry, water resources and ecosystem which may threat sustainability of life in the earth (Eissa and Zaki, 2011). Climate change is one of the major concerns among these changes. Natural resource and people of the deltas are now facing consequences of the increased human interference on climate system (Nicholls et al., 1999). It is likely that climate changes have contributed to the intensification of extreme temperature, extreme precipitation, increase in extreme coastal high water and the confidence is low with regards to tropical cyclone at the global scale (Field et al., 2012). Sea level rise (SLR), the rise in sea surface temperature, climate induced extreme weather events like heavy precipitation, tropical cyclone and storm surges are the

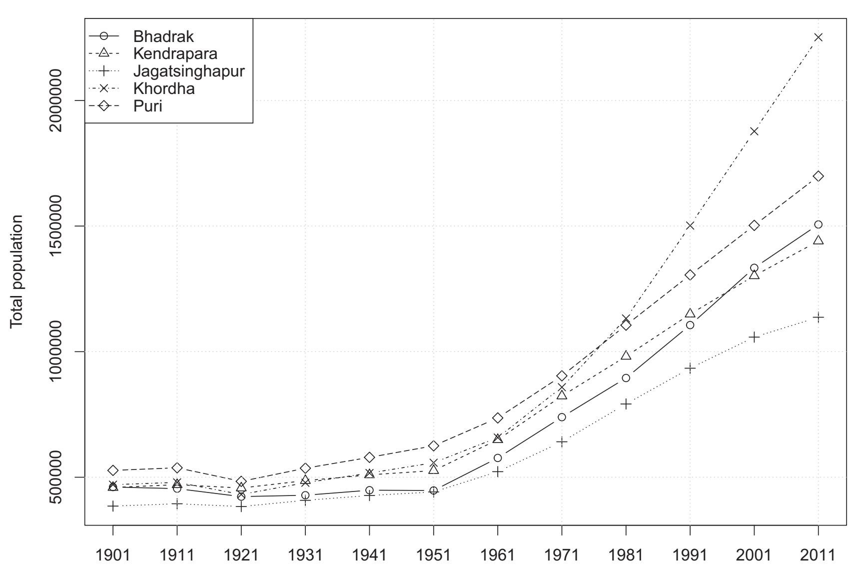

Fig. 2. Decade wise growth of population in the delta.

Table 1
Flood events observed in delta during the period 2005–2013.

Sl. no.	Date	Sl. no.	Date	Sl. no.	Date
1	06-06-05	15	21-08-07	29	12-09-09
2	07-08-05	16	23-08-07	30	18-06-11
3	24-09-05	17	23-09-07	31	22-06-11
4	27-10-05	18	24-09-07	32	05-09-11
5	09-07-06	19	17-06-08	33	08-09-11
6	04-08-06	20	19-07-08	34	12-09-11
7	19-08-06	21	20-09-08	35	14-09-11
8	26-08-06	22	21-09-08	36	01-10-11
9	02-09-06	23	14-07-09	37	12-10-13
10	04-09-06	24	22-07-09	38	14-10-13
11	26-09-06	25	24-07-09	39	15-10-13
12	04-07-07	26	27-07-09	40	17-10-13
13	06-07-07	27	29-07-09	41	25-10-13
14	13-07-07	28	08-09-09		

most likely climate-related changes that will be witnessed over 21st century (Syvitski, 2008; Foufoula-Georgiou et al., 2011; Field et al., 2012; Hinkel et al., 2014). About 20 cm of global sea level has risen since 1870 (Church and White, 2006). This could result in a substantial increase in areas (~50%) that are vulnerable to coastal flooding (Noone, 2013; Syvitski, 2008). These changes are expected to have a range of physical, economic and social impacts in deltas (IPCC, 2013, 2007; Solomon et al., 2007).

The populous deltas across the globe are facing climate change related issues and are at risk. For example, the world's largest delta, Ganges-Brahmaputra-Meghna delta having vast low-lying coastal plain and densely populated is perceived to be at great risk of increased flooding and submergence from SLR (Auerbach et al., 2015; Brammer, 2014). The Nile Delta of Egypt is the second largest delta in terms of population. The risk of extreme events along with the impacts of SLR and subsidence are quite high in this delta (Sušnik et al., 2015). The growing population will be exposed to extreme events like flooding, storm surges and will put immense pressure on available resources for sustaining on the delta (El-Nahry and Doluschitz, 2010). The Vietnamese Mekong Delta is also susceptible to the impacts of extreme climatic events and climate variability (Smajgl et al., 2015; Tuan and Chinvanno, 2011). Yangtze Delta demonstrates that climate transition intensified the flood and drought variation. The delta is densely populated and developed which make it more risk-prone to natural hazards (Zhang et al., 2008; Gu et al., 2011). The Ebro Delta is already vulnerable because of low sediment delivery to the mouth and the proximity of the hinterland to the present sea level (Fatorić and Chelleri, 2012).

This study is aimed to estimate the spatial distribution of hazards and risk due to extreme events like flood and tropical cyclone in one of the important deltas in India, the Mahanadi delta. The main objectives are to assess the nature, extent, magnitude and impacts of these extreme events on human and resources and to understand what types of risk they pose in the delta. Individual study of these events only focuses on the risk of that particular event. Understanding the multi-hazard risks as a whole is essential to know the types of future changes, their type, magnitude and variability and their impact on the densely populated deltas in India. The integrated risk assessments will permit us to produce much more realistic scenarios of impacts of these events and to propose possible adaptation solutions to minimize the risk. Such information are essential to formulate disaster mitigation and climate change adaptation policies.

2. Materials & methods

2.1. Study area

Mahanadi delta is one of the important deltas in the east coast of India. The River Mahanadi originates in the southeastern part of the state of Madhya Pradesh as a small stream draining the eastern part of the Chhattisgarh Plain. It enters the state of Odisha below Baloda Bazaar and crosses the Eastern Ghats to enter the delta plain near Naraj and finally debouch into the Bay of Bengal. The delta is drained by a network of three main rivers, Mahanadi, Brahmani and Baitarini, pouring into the Bay of Bengal (Mahalik et al., 1996). The coastline is about 200 km long which stretches from Chilika in the south to Dhamra River in the north. The study area boundary is defined by five districts within the 5 m elevation contour, likely to be affected adversely by sea level rise. It covers an area of about 13,109 km^2. There are forty-five administrative blocks (sub-districts) within the selected districts (Fig. 1).

The alluvial coastal plain is densely populated. This area has 8 million population with a density of 613 persons/km^2. The population density is much higher than that of the entire Odisha state (270 persons/km^2) as well as India (382 persons/km^2). The most populated district is Khordha with a population of 2.25 million, of which male and female are 1.17 million (52%) and 1.08 million (48%) respectively (GoI, 2011).

Fig. 2 shows decadal growth of population since 1901 in all the districts of the delta. An accelerated growth of population can be seen after the year 1951 with establishment of the capital city of Bhubaneswar in 1948. The annual growth rate of population is 1.4% during the years 2001 to 2011, which is continuously placing growing demands on coastal resources. The rural population (~78%) of this delta are mainly dependent on agriculture. High percentage (53%) of dependent population in the working age group not only indicates high rate of unemployment but also contributes to the 'social vulnerability' of the delta (GoI, 2011). Distress induced migration is common in some of the coastal districts due to the repeated crop loss and lack of returns from existing livelihood (OSDMA, 2016). On the other hand, Khordha and Puri districts are preferred destinations of migration of rural communities from the adjoining hazard areas of the Mahanadi delta (Das et al., 2016).

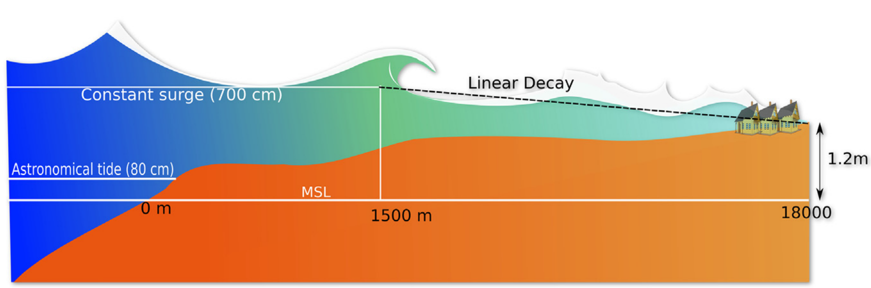

Fig. 3. Surge height reduction factor.

Flooding and cyclone are the most common extreme weather events in the delta region. Sinha (1999) reported that the total number of the floods were 125 in River Mahanadi, 100 in River Brahmani and 92 in River Baitarini in the period 1875–1987. Recently, in the years 2003, 2008, 2011 and in 2014 the delta experienced major floods due to heavy rainfall which caused extensive damages in the delta. The heavy rainfall during monsoon causes severe floods in these rivers. The flat coastal terrain with poor drainage condition, high amount of siltation, encroachment of the rivers, breaching of the embankments and spilling of monsoonal runoff are the major causes of severe floods. Hirakud Dam was built across Mahanadi River about 15 km away from Sambalpur to prevent floods in the delta. It could, however, reduce the occurrences of floods to a certain extent (Kar et al., 2010). Flooding continued routinely during the monsoon season in the populated delta, the down stream (Parhi et al., 2012). On an average, the basin receives 75% (1088 mm) of it's annual rainfall quota (1451 mm) in four months (mid-June to mid-October) only. It is imperative that the delta is subject to annual floods, varying with increasing precipitation intensity and amount (Gosain et al., 2006). Several other studies, in the context of trend and characteristics of climatic variables like precipitation, temperature and stream-flow had similar observations (Rao, 1993; Ghosh et al., 2010; Kar et al., 2010; Gosain et al., 2006). The delta is susceptible to tropical cyclones, storm surges with a record of severe damages and loss of life due to such events (OSDMA, 2016). A large number of tropical depression or cyclone have been observed in the Bay of Bengal. The frequency has increased in recent years. For example, the total number of storms including both the depressions and cyclonic storms which caused heavy rainfall were 12 in 2006 and 14 in 2007 (Sahoo and Bhaskaran, 2016). The intensity of cyclone has also increased as observed in the last decade (1999, 2007, 2013). Unnikrishnan et al. (2011) predicted an increasing trend for the occurrence of cyclones during the late monsoon season in 2071–2100 compared to the baseline scenario in the Bay of Bengal. This implies increasing risk to life and livelihood unless proper measures are undertaken in the delta.

2.2. Flood hazards mapping

Flood assessment method ranges from simple hydrograph to adaptive neuro-fuzzy inference system (Goyal and Harmsen, 2017; Hong et al., 2018). A satellite data based methodology has been adopted in the present study. The scarcity of required data is one of the major problems in mapping the flood extent and magnitude effectively. In this study, 25′ × 25′ gridded precipitation data of India Meteorological Department (IMD) in combination with Synthetic Aperture Radar (SAR) data (Radarsat 1/2 and Risat 1/2 of resolution 10 to 100 m) have been used to map the flood inundated areas at specified return periods. The computation of return period of annual maximum precipitation was carried out using generalized extreme value (GEV) distribution (EV type I or Gumbel distribution) model (Gumbel, 1941; Kidson and Richards, 2005; Coles, 2013). The equation for fitting this distribution to the observed series of rainfall at different return periods T is

$$X_T = \bar{x} - \frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\}s \quad , \tag{1}$$

where, X_T denotes the magnitude of the T year precipitation events, $\bar{x}$ and s are the mean and the standard deviation of the maximum precipitation respectively.

The satellite era is relatively new in comparison to the available rainfall records. Therefore, SAR data of recent flood events coinciding with specific return period precipitation events have been selected for the analysis (Table 1). The thresholding of SAR backscattering values has been adopted to map the inundated pixels. A reasonable

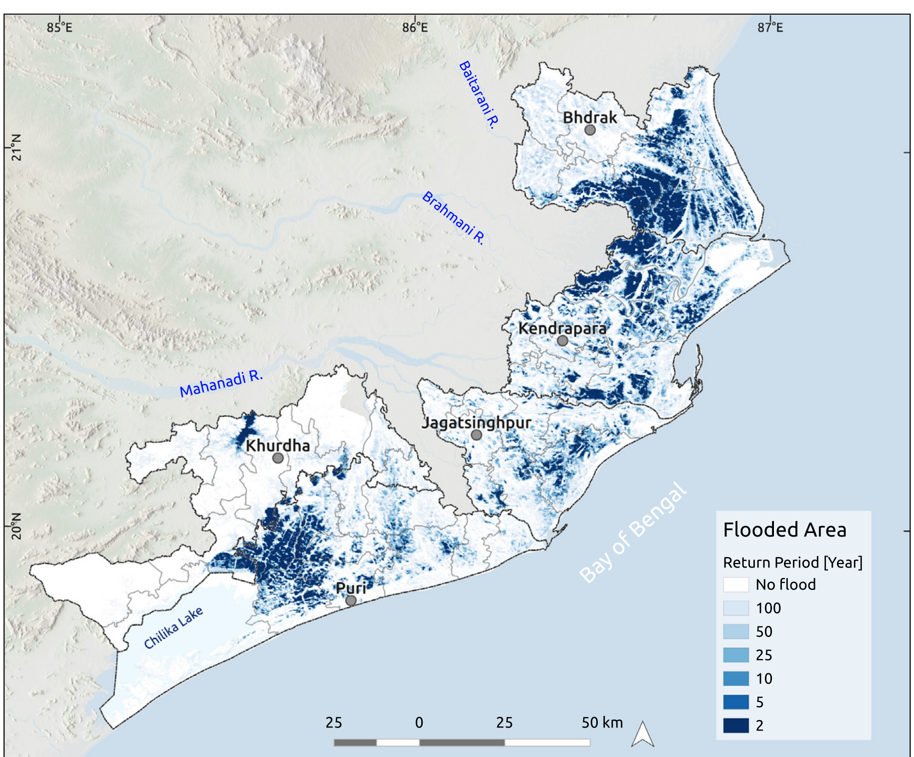

Fig. 4. Flooded area at various return periods.

threshold has been estimated by inspecting the histogram of each data and comparing with IRS-LISS VI images (Linear Imaging Self Scanning IV sensor of Indian Remote Sensing Satellite Resourcesat 2) (Hirose et al., 2001; Yamada, 2001). Regular water bodies were removed from the resultant layers to get the area of inundation.

Storm surge is another major cause of flooding in the delta. The delta experienced such events as a result of the frequent tropical cyclones. The onshore topography derived from SRTM data to demarcate the extent of flooding by projection of the water level on it. In general, it is assumed that a 5 m surge would have flooded up to 5 m elevation and a 10 m of the surge would have flooded up to 10 m elevation, this approach might have, however, overestimated the extent of inundation (Dube et al., 2009; Rana et al., 2010). To overcome such a situation, a surge height reduction factor was estimated using the following empirical relation:

$$\text{surge height reduction factor} = \frac{\text{surge height} - \text{land elevation at surge}}{\text{extent of inundation} - \text{extent of constant surge}} = \frac{700\ \text{cm} - 120\ \text{cm}}{18000\ \text{m} - 1500\ \text{m}} = 0.35\ \text{cm/m}$$

A graphical depiction of the relationship is given in Fig. 3. The surge information of 1999 super cyclone was used to estimate the spatial distribution of inundation (Dube et al., 2009). SRTM 1 arc second digital elevation model (DEM) was used to map the spatial extent of surge inundation (NASA JPL, 2013). Land-use/land-cover data of the delta was prepared using IRS LISS IV images for the years 2012 and 2013 to estimate the amount of cropland under risk. The object-based image classification using the mean-shift segmentation algorithm was used to classify land-use/land-cover in the delta (Inglada and Christophe, 2009; Michel et al., 2015).

2.3. Cyclone hazards mapping

Tropical Cyclone Risk Model (TCRM) was used to estimate the annual exceedance probability of wind hazard in the delta (Arthur et al., 2008). It is an autoregressive model to generate synthetic cyclone track based on speed, intensity, bearing, size and genesis location of a historical record of tropical cyclone events. 5000 such synthetic events were simulated based on the historical track data from the International Best Tracks Archive for Climate Stewardship for the period 1981–2011 (Knapp et al., 2010). To compute the maximum

Table 2
Block wise flood affected population at various flood return period.

Block	District	100 years	50 years	25 years	10 years	5 years	2 years
Bant		87,597	63,411	19,801	1,855	–	–
Basudebpur		156,334	130,919	83,249	52,945	25,131	6,295
Bhadrak		109,699	75,417	23,874	6,031	1,088	42
Bhandaripokhari	Bhadrak	87,979	69,136	28,085	6,617	1,085	–
Chandabali		221,761	202,826	153,686	114,068	66,393	22,165
Dhamanagar		154,779	127,959	89,255	65,995	42,922	16,847
Tihidi		155,185	138,316	104,412	79,149	47,953	15,882
Balikuda		117,035	85,524	43,187	23,119	5,295	39
Biridi		42,042	26,229	10,544	4,530	650	–
Ersama		119,865	107,600	79,168	53,642	20,320	1,363
Jagatsinghapur (P)	Jagatsinghpur	74,978	49,863	19,962	7,887	894	–
Kujang		122,650	89,230	46,966	24,095	7,208	526
Naugaon		51,473	37,587	19,976	11,781	4,155	244
Raghunathpur		36,042	23,181	11,597	5,996	677	5
Tirtol		95,997	69,684	36,498	18,407	3,979	100
Aul		129,068	115,470	94,521	76,567	52,131	17,537
Derabisi		83,342	55,452	25,063	12,789	4,675	593
Garadpur		73,404	53,627	26,911	12,225	3,389	28
Kendrapara		119,687	92,925	48,164	25,111	5,465	36
Mahakalapada	Kendapara	162,042	133,964	82,157	52,602	26,767	6,306
Marsaghai		89,710	63,478	29,072	16,703	7,968	1,821
Pattamundai		143,545	122,608	89,642	65,232	32,389	9,110
Rajkanika		120,288	109,378	82,696	60,718	35,661	10,109
Rajnagar		123,865	108,592	75,285	50,954	20,062	1,790
Balianta		48,424	31,429	8,558	1,399	63	–
Balipatna		55,168	36,689	15,666	4,979	246	–
Banapur		16,865	2,324	–	–	–	–
Begunia		49,810	31,777	16,222	9,070	5,029	2,104
Bhubaneswar	Khordha	43,753	25,215	7140	2,852	177	–
Bolagad		35,959	16,042	754	31	–	–
Chilika		11,617	3,347	694	378	1	–
Jatani		50,934	31,671	9,963	5,247	2,535	862
Khoordha		59,403	39,765	20,291	14,467	10,529	6,736
Tangi		46,653	23,807	8,615	4,906	2,126	252
Astaranga		38,272	22,571	7,747	1,896	2	–
Bramhagiri		93,391	86,184	71,233	58,796	37,780	11,770
Delanga		93,533	78,017	51,133	33,921	16,923	3,028
Gop		131,612	100,545	56,829	31,662	6,540	16
Kakatpur		53,397	29,215	9,677	3,908	216	–
Kanas	Puri	141,114	131,931	109,464	92,137	66,600	28,633
Krushnaprasad		16,723	7,558	1,198	646	–	–
Nimapada		135,132	95,366	45,924	19,018	1,839	–
Pipili		82,633	54,061	17,285	5,960	990	326
Puri		121,477	102,544	71,864	48,829	22,677	2,798
Satyabadi		88,039	73,733	51,914	36,616	18,085	4,338

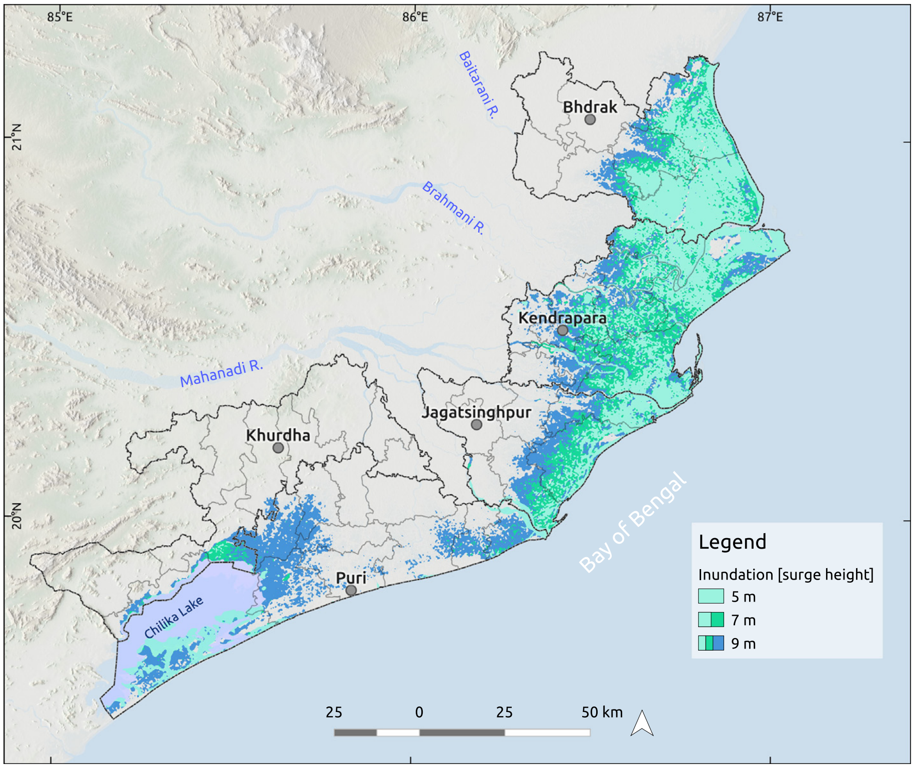

Fig. 5. Inundation due to storm surge.

wind speed over the life of each event, a parametric wind field and boundary layer model were applied to each synthetic track (Powell et al., 2005; Kepert, 2001). For each grid location, the generalized extreme value (GEV) distribution was used to fit the maximum wind speed values (Hosking, 1990; Coles, 2013). A total of 9 return periods were specified in model configuration to estimate the wind speed of tropical cyclones. Tropical cyclones of specific return periods of 5, 10, 25, 50, 100, 500, 1000, and 2000 years were modeled to estimate the speed of such cyclones over the delta.

2.4. Estimation of risk

The term "risk" has several meanings, dimension and interpretation based on objective and discipline (Kelman, 2003). Characteristics of risk are defined by the decision makers' own interpretation of the likelihood of being exposed to the conditions propagating risk. There is a distinction between risk and hazard. Risk can be defined as the function of the chance or probability of an event with the damage that the event would cause if occurred (Sayers et al., 2002). Therefore it can be given by

$$Risk = Probability \times Consequences \tag{2}$$

The conceptualization proposed by Gouldby et al. (2009) was used to estimate the qualitative risk of extreme events in the delta. In this framework, a risk arises when there are hazards that consist of a source, a receptor (exposure) and susceptibility of a receptor to be damaged (vulnerability). Hence, a hazard alone can not lead to a harmful impact, actual damage depends on the exposure susceptibility of the receptor. In this study risk was assessed using the following empirical relation,

$$R = P \times D_p \times IM, \tag{3}$$

where R is the risk, P is the probability of occurrence of the hazard event, D_p is the population density and IM is the impact multiplier (value between 0 and 1). Percentage of earthen houses (2011 census) was used as an impact multiplier. The reason behind choosing percentages of the earthen house as impact multiplier is the high correlation of it with the lack of economic well-being or, the social vulnerability of the deltaic community.

Uncertainties, however, exist in the subjectivity of the risk classes while classifying the index into a Likert scale. The fuzzy system can be employed to overcome such limitations and to increase the fidelity and robustness of the index (Kazakis et al., 2018). This method was effectively used in various studies involving uncertain data or parameters (Kazakis et al., 2018; Adriaenssens et al., 2004; Ki and Ray, 2014; Cabanillas et al., 2012; Adriaenssens et al., 2004). Unlike a crisp set, in fuzzy logic, the parameters are represented by the means of conditional forms of being a member of two classes. It involves transformations of parameter values into the degree of membership values of 1 to 0 (Zadeh, 1965). Membership values close to 1 reflect a greater risk of extreme events, while membership values near 0 indicate negligible risk. GRASS GIS's fuzzy inference system, one of the robust spatial fuzzy systems has been used to classify the risk index into several risk categories (Jasiewicz, 2011). The S-shaped membership function along with the set of fuzzy rules of the if-then type were defined to connect the input parameters with five output risk classes (very high, high, medium, low and none).

3. Results & discussions

3.1. Impacts of flood

The probability of occurrence of the flood is very high in the Mahanadi delta. At almost every year, there are two to three flood events in the delta (Table 1). Flooding is the most common hazard in the Mahanadi delta. It can be seen from the hazard map that two spatially distinguishable zones are present in the delta (Fig. 4). The one is present in the Bhadrak and Kendrapara districts, the other one is in the Puri district. These areas were flooded very frequently as most of the area come under flood events of 2 and 5 years return periods. For example, 16% in Bhadrak and 14% in Kendrapara and 10% of the area in Puri district were inundated by floods of 5-year return period. Low elevation, meandering of rivers, siltation on the riverbed and high intensity of precipitation are the major causes of flooding in these areas (GoO, 2004). Most part of the flooded region is densely populated, with more than 800 persons/km^2 density (GoI, 2011). It is observed from the overlay analysis of flood frequency on the village wise population density that the people of every administrative block of the Kendrapara district suffered from floods. About 77% of the people of this district come under the impact of 100-year return period flood. Aul is the severely affected block in this district with large numbers of people those are living with the flood of all frequencies. The statistics show that 92% at 100-year, 83% at 50-year and to the lowest degree of 2-year return period flood 12% of people in this block are under the flood-affected zone. Bhadrak is the second largest district in terms of people living in flood-affected zones followed by Jagatsinghpur and Puri districts. In the less affected district Khordha, about 33% of the people live in flood-affected zones of 100-year return period. Table 2 gives an account of the number of people living in the flood affected region of various return periods. These data have been extracted from the village wise population density map overlayed on the flood frequency map. These statistics indicate that a high number of the people are living with floods.

The contribution of agriculture to the delta's GDP is 27.3% (Cazcarro et al., 2018). However, nearly 70% of the population depends directly or indirectly on the agriculture for subsistence (GoI, 2011). The per capita agricultural land holding in the delta is very low, around 0.12 ha only. Therefore, the damage to the agricultural production directly affects the livelihood of these people. Repeated crop loss forced them to migrate in search of alternative livelihoods (Das et al., 2016). From the overlay analysis it was found that, for flood events at 100-year return period, nearly 418 km^2 (97%) of cropland is flooded in Chandabali block, 298 km^2 (86%) in Basudebpur, 290 km^2 (89%) in Mahakalpara, 251 km^2 (91%) in Rajnagar, 212 km^2 (89%) in Tihidi, 211 km^2 (95%) in Ersama, 206 km^2 (90%) in Pattamundai block. Other most affected blocks in terms of percentages of flooding are Kanas (96%), Bramhagiri (93%), Gop (83%), Rajkanika (93%), Nimapada (75%), Dhamnagar (86%), Kendapara (86%), Aul (91%) etc. In terms of percentage of total area, Kendrapara (88%) is the worst affected district at 100-year flood followed by Bhadrak (83%), Jagatsinghpur (78%), Puri (77%) and Khordha (44%). The amount of damages to crops in the delta gives an indirect estimate and magnitude of the risk. Creation of alternative livelihood by implementing proper adaptation strategies remain the only option for risk reduction in the delta.

3.2. Impacts of storm surge

During cyclones, inundation due to storm surges are quite common in the delta, particularly in the low lying northern part. Fig. 5 shows the extents of inundation during a 7 m high storm surge caused by the 1999 super cyclone and extent of two additional events of modeled surge height of 5 m and 9 m. The number of people affected due to the surge of a 7 m is very high in Chandabali (238,175 persons, 95%), Mahakalpara (157,393 persons, 74%), Basudebpur (144,967 persons, 66%), Rajnagar (138,333 persons, 81%) followed by Rajkanika(79%), Pattamundai (64%), Kujang (55%), Tihidi (44%), Aul (61%), Ersama (57%), Kendapara (34%) and Khurshanprasad (42%). These blocks are largely affected in terms of inundation of cropland. For instance, 421 km^2 (97%) in Chandabali, 280 km^2 (86%) in Mahakalpara, 263 km^2 (95%) in Rajnagar, 256 km^2 (73%) in Basudebpur, 183 km^2 (88%) in Rajkanika, 176 km^2 (64%) in Tihidi, 152 km^2 (65%) in Pattamundai, 148 km^2 (66%) in Ersama and so on. The extrapolated 5 m surge event shows some linear decrease in the area of inundation, however, a 9 m surge can inundate a few more blocks such as Krushnaprasad, Kanas, Astaranga, Bramhagiri, Marsaghai Kakatpur etc. The increase in 'likely to be affected' croplands range from 30 to 70% compared to the land affected in 7 m events. Fig. 6 portrays the damage cost estimated for the 100-year flood and a 7 m surge event. The estimation is based on the districts wise average yield rate of paddy for the period of 2001 to 2014. The cost exceeds as much as \$20 million$_{2014}$ in Chandrabali block during both the events. Some other blocks, like Mahakalpada, Rajnagar, Basudebpur, Rajkanika, Ersama are affected by flood and surge of that highest magnitudes.

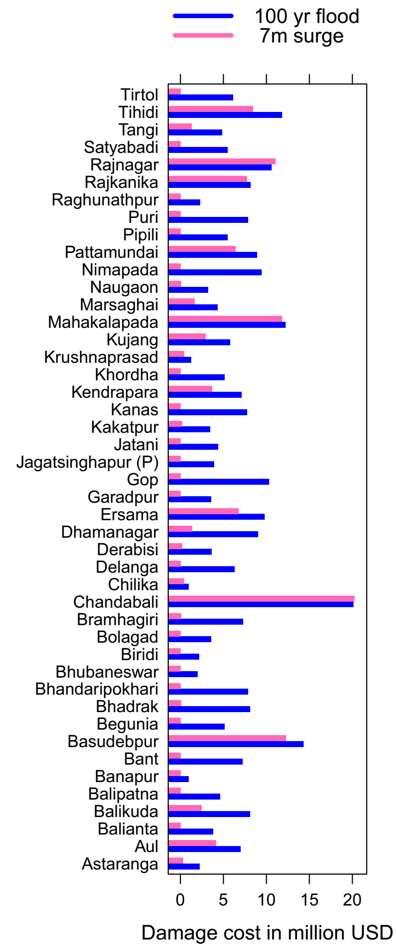

Fig. 6. Block wise damage cost estimated for 100-year flood and 7 m surge events.

These coastal areas are at high risk due to such extreme events. SLR may also increase the extent of surge inundation in future, accelerated erosion may lead to permanent inundation and land loss (Mukhopadhyay et al., 2018), which in tern increases the risk of these areas. Hence, adaptation and mitigation are essential in these blocks to minimize the risks of extreme events vis-a-vis the impact of climate change. Dykes and storm surge barriers can be constructed to protect the land at Kendrapara, Bhadrak, Jagatsinghpur districts. Vegetation canopy can also minimize the impact of a surge. Salt tolerant crop species are other appropriate options for areas susceptible to surge inundation.

3.3. Impacts of cyclonic wind

Cyclonic wind is the other most destructive hazard in the Mahanadi delta. Fig. 7 shows wind speed of cyclones for various

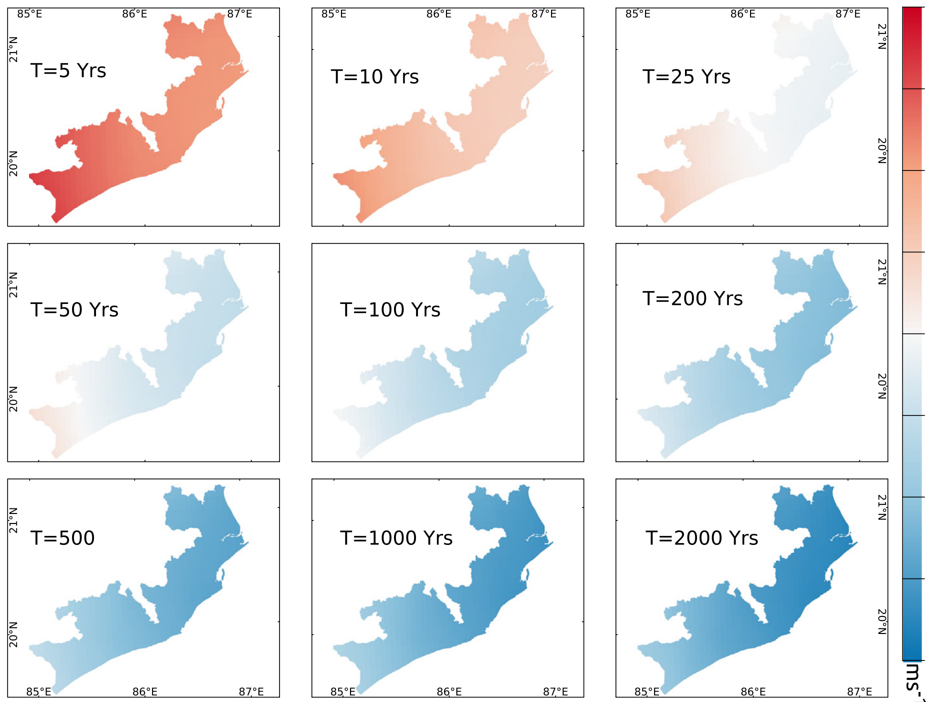

Fig. 7. Wind speed of cyclone at various return periods.

return periods simulated using the TCRM model. In a storm with 100-year return period, the wind may reach about 50 ms^{-1} which is devastating in nature. Mahanadi delta witnessed number of devastating cyclones mostly in the month of September–November throughout the last century (Chittibabu et al., 2004). In 1931 a cyclone killed about 20,000 people in the delta, more than 1,000 people died in 1971 cyclone. During 1999 super cyclone, more than 8,000 people were killed in Jagatsinghpur district (IMD, 2000). A cyclone of category 5 on the Saffir-Simpson scale struck the delta in 2013 (De et al., 2005; Froberg, 2013). However, reported loss of human life was very few, thanks to early warning and efficient evacuation, huge damage to infrastructure and crops could not be avoided in the delta (Pal et al., 2017). There were 54,1200 houses damaged in the state due to cyclonic hazard in the years 2013 and 2014 (OSDMA, 2016). The data also indicated the high number of earthen houses in the delta that acted as risk multiplier. The northern part of the delta is more susceptible to high wind speed, hence, is at high risk (Fig. 8).

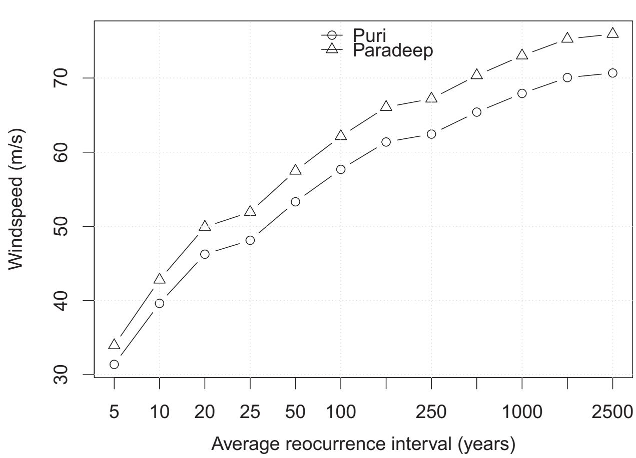

Fig. 8. Wind speeds of tropical cyclone at Paradeep and Puri.

3.4. Risk indices

The risk of cyclonic wind is very high in the northern part of the delta due to the poor infrastructure, a high percentage of the earthen houses (50 to 70% as per 2011 census) aggravating the vulnerability. Dhamanagar, Tihidi, Rajnagar, Marsaghai, Mahakalpara happened to be the very high-risk prone administrative blocks in the delta. This made Bhadrak and Kendrapara to be two most risk-prone districts with about 33% and 30% of land in the high-risk indices zones respectively. Khordha and Puri appeared to be at low-risk zone with more than 70% of their land safe from the impacts of cyclonic wind (Fig. 9). Early warning and efficient evacuation may reduce the loss of life significantly, however, to prevent loss of property and infrastructure, proper structural design needs to be undertaken considering the maximum expected wind speed of 70 ms^{-1} and respective building codes.

Fig. 10 portrays the flood risk hotspot in the delta. The risk is high where the percentage of Kuccha house (earthen houses) is higher in the region. Bhadrak is one of the most flood risk-prone districts with 16% area in high risk zone followed by Kendrapara (14%) and Puri (6%). Administrative blocks like Tihidi, Dhamnagar, Chandabali, Rajkanika, Aul, Kanas, Delenga are at higher risk. The spatial distribution of flood risk is more localised while the distribution of wind risk is more extensive. High flood risk zones, however, mostly coincide with the high wind risk zones.

4. Conclusion

This study was conducted in the Mahanadi delta to estimate the spatial distribution and variability of hazards and risk due to climatic extreme events like flood, tropical cyclone and storm surge. In the context of climate change, risks of the climatic extreme are inevitable and are often exacerbating. A proper understanding of such risks is essential to understand the future vulnerability and risk scenarios in the delta. The analysis indicated that the northern part of the delta, specifically, administrative blocks like Chandabali,

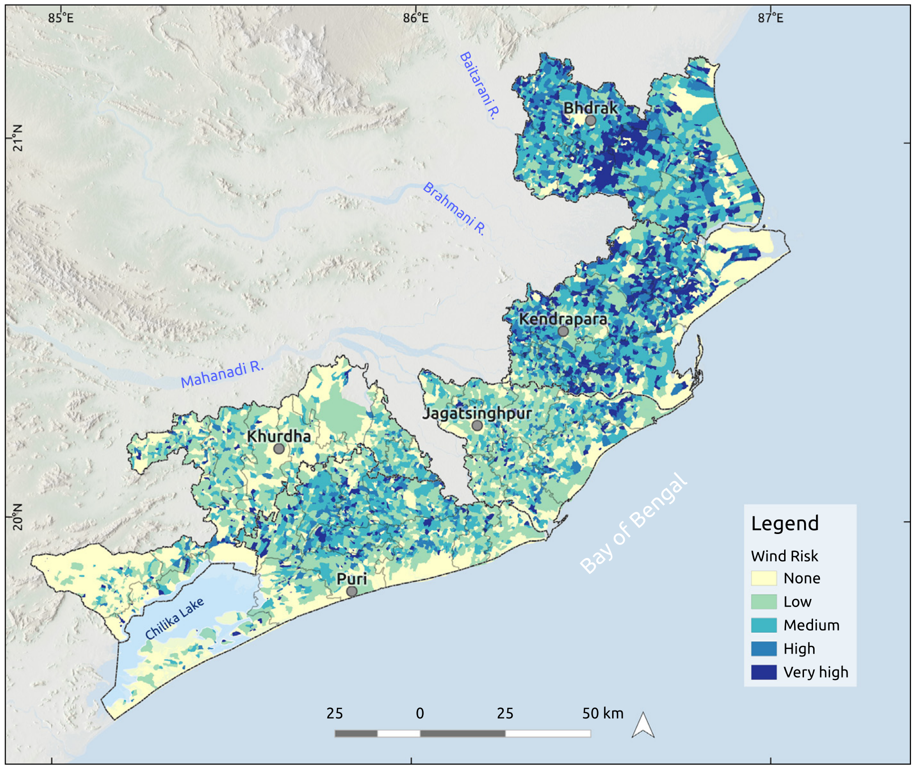

Fig. 9. Wind risk map of the delta.

Basudebpur, Mahakalpara, Rajnagar, Tihidi, Ersama, Pattamundai, Aul, Kujang are at a very high-risk zone and require immediate risk reduction measures and adaptation initiative. In a scenario of flood with 100-year return period, more than 80% of the land of these blocks likely to be affected. Kendrapara is the most risk-prone district, experiences almost every variety of extreme event. About

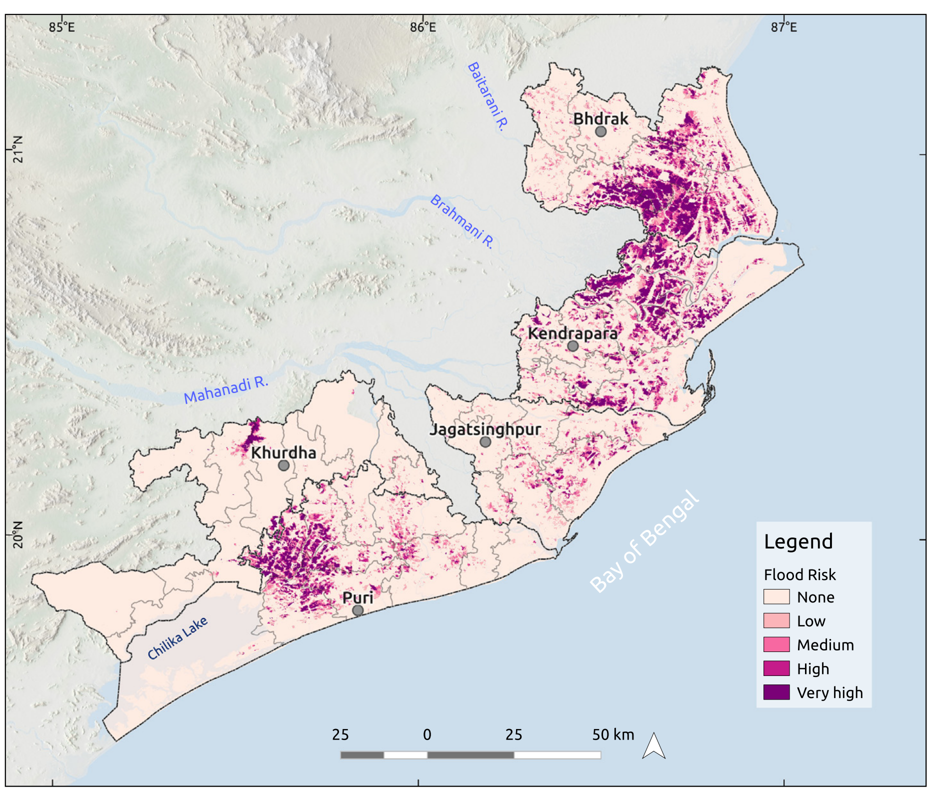

Fig. 10. Flood risk map of the delta.

88% of the cropland likely to be affected in 100-year flood and a 7 m storm surge event. Moreover, 80% people in some blocks like Chandabali, Mahakalpara, Rajnagar, would be affected due to a surge of 7 m. While, Bhadrak and Jagatsinghpur are found to be the most risk-prone districts. Khordha happened to be the least risk-prone one. The higher dependency on agriculture (~71%) and the high percentage of kutcha houses (50 to 70%) make the northern districts more vulnerable to extreme events. Therefore, risk reduction activities should be prioritized for this region to address the adaptation deficit. Spatial information regarding hazards and risk are important to prepare appropriate adaptation plan in the region. To be effective, adaptations must consider the magnitude and extent of risk of climate extremes and existing social and physical vulnerabilities. This type of study will help policy makers to formulate appropriate adaptation plan. However, more in-depth research and modelling are prerequisites to understanding the sensitivity of adaptations and their socio-ecological impacts.

The present study has some limitations with the resolution of data, like the digital elevation model (DEM) used is of moderate spatial resolution, which, if replaced with a high resolution one, would improve the precision of some estimations.

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