



Cyclone-induced coastal vulnerability, livelihood challenges and mitigation measures of Matla–Bidya inter-estuarine area, Indian Sundarban

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Abstract

Indian Sundarban is highly susceptible to tropical cyclones and resultant impacts such as storm surge-induced floods, embankment breaching, and saline water intrusion. It affects life and livelihood in severe ways. Mitigation and policy measures are therefore very important, based on information gathered at the grassroots level. Hence, this study is designed to assess inter-village variation in cyclone vulnerability, considering physical vulnerability, social vulnerability, and mitigation capacity. This study also highlights livelihood challenges faced by coastal dwellers. Geospatial and quantitative methods were used to assess the composite vulnerability index (CVI). Remote sensing data and climatic data were integrated to assess physical vulnerability and various socioeconomic data were incorporated to determine the social vulnerability. Moreover, an intensive field survey (2020–2021) was also conducted to understand the livelihood challenges of local people and accordingly suggest mitigation measures to cope with natural hazards. According to this analysis, nearly 18% of the total population living in the southern and eastern parts of the Matla–Bidya inter-estuarine area (MBI) are extremely vulnerable ($CVI > 0.544$) due to their geographical location and high exposure to coastal hazards. Almost 51% of the total populations inhabited in 46% of the total MBI villages are experiencing high to moderate vulnerability. Conversely, MBI villages in the northern part, where 32% of the total population lives, show low vulnerability ($CVI < 0.387$) due to less exposure and high resilience. Coastal low-lying villages are often hardest hit by tropical cyclones. Therefore, effective mitigation strategies and coping mechanisms are essentially needed to reduce the adverse impacts of cyclones.

Keywords Tropical cyclone · Vulnerability assessment · Livelihood challenges · Mitigation measures · Indian Sundarban

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1 Introduction

Tropical cyclones are the world's most deadly natural disasters, causing innumerable deaths and property damage (Alam et al. 2003; Ramsay 2017; Islam et al. 2020). Global climate change leads to significant increases in ocean temperatures, leading to more frequent and severe cyclones across the globe (Sahoo and Bhaskaran 2016; Knutson et al. 2020). Each year, 80–100 destructive tropical cyclones strike different parts of the world and cause approximately 20,000 deaths and huge economic losses estimated at \$6–7 billion (Shultz et al. 2005). Coastal people in Sundarbans suffer significantly from the effects of tropical cyclones and their aftermath effects, such as embankment breaching, flood inundation, saline water infiltration, and waterlogging in agricultural land (Ali et al. 2020; Ghosh and Mistri 2020a; Hoque et al. 2021). The excessive concentration of population, which accounts for 40% of the total population of India, lives within 100 km of the coastline and every year, near about 340 million people have been severely affected by tropical cyclones (Rehman et al. 2021). The Bay of Bengal and the Arabian Sea are the sites of cyclogenesis along the east and west coasts of the Indian subcontinent (NCRMP 2011). The North Indian Ocean recorded 7–10% of global cyclonic events (Mondal et al. 2021). However, the Bay of Bengal is more prone to cyclonic activity in comparison with the Arabian Sea which is severely affected the Indian states of Orissa, West Bengal, Tamil Nadu, and Andhra Pradesh (Alam et al. 2003; Singh and Roxy 2022). Sundarbans, which is situated at the apex of the Bay of Bengal, has the richest mangrove biodiversity on the earth. These mangrove forests protect Sundarbans to a considerable extent from the direct impact of cyclonic damage and devastations. Large-scale destruction of the Sundarban mangrove forest began during the British colonial era, primarily for land reclamation and to increase revenue from agricultural activities on reclaimed land (Ghosh and Mistri 2020b). Deforestation of mangrove forests, however, has led to increased coastal vulnerability for 4.5 million residents of the Indian Sundarban at the edge of tropical cyclones (Ghosh et al. 2015). In the last two decades, tropical cyclones such as Sidr in November 2007, Aila in May 2009, Fani in May 2019, Bulbul in November 2019, Amphan in May 2020, Yaas in May 2021, and Sitrang in October 2022 have wreaked havoc impacts on the life and livelihood of coastal communities in both the Indian and Bangladesh Sundarbans. These cyclone-induced coastal disasters also caused thousands of deaths and multi-million dollar economic loss as shown in Table 1 (Mondal et al. 2021; Mishra et al. 2021). Therefore, the need for an effective mitigation strategy is imperative to minimize the vulnerability levels associated with cyclonic disasters.

Theoretically, vulnerability is the degree to which individuals, resources, and environments are susceptible to the impact of hazards (Joseph 2013). It is determined by factors such as physical, environmental, and socioeconomic factors (UNDRR 2009). A comprehensive assessment of cyclone vulnerability can bring out sufficient information for effective mitigation measures. Previously, the cyclone-induced coastal vulnerability was assessed mostly for the part of Bangladesh Sundarbans (Islam et al. 2013; Quader et al. 2017; Mullick et al. 2019; Hoque et al. 2021). However, Ali et al. (2020) derived the cyclone risk map for Indian Sundarbans using the weighted overlay analysis method. Similarly, Mondal et al. (2021) prepared cyclone-induced multi-hazard risk map for the Kakkdip sub-division of coastal West Bengal. Moreover, some scholars have attempted to evaluate the impact of tropical cyclones like Aila in 2009, Bulbul in 2019, and Amphan in 2020 on coastal environments and rural livelihoods (Mallick et al. 2011; Kar and Bandyopadhyay 2015; Hassan et al. 2020; Das et al. 2020; Mishra et al. 2021; Halder et al.

Table 1 Major tropical cyclones (TCs) in the Bay of Bengal during 2005–2022

Cyclone (Category)	Date & year	Landfall	Distance from MBI (Approx)	Pressure at landfall	Wind Speed (km/h)		Tidal status during landfall	Storm surge height	Casualties	Damage (Million USD)
					Average	Max				
Sidr (ESCS ¹)	November 11, 2007	Barisal Coast, Bangladesh Coast	155 km	918 mb	216	281	Low tide	3 m	3447	982
Akash (CS ²)	May 14, 2007	South of Chittagong, Bangladesh Coast	300 km	988 mb	85	120	Low tide	1.5 m	14	982
Aila (SCS ³)	May 25, 2009	Sagar Island, Indian Sundarbans	70 km	967 mb	110	120	High tide (New Moon)	2–3 m	618	618
Phailin (ESCS ¹)	October 04, 2013	Near Gopalpur, Orissa Coast	500 km	940 mb	215	260	Low tide	2.3 m	46	1500
Mahasen (CS ²)	May 16, 2013	NW of Chittagong city, Bangladesh Coast	300 km	990 mb	85	85	Low tide	2 m	107	35.3
Roanu (CS ²)	May 21, 2016	NW of Chittagong city, Bangladesh Coast	300 km	983 mb	85	110	Low/high tide	3–5 m	135	2030
Mora (SCS ³)	May 30, 2017	Near Chittagong, Bangladesh Coast	300 km	978 mb	110	150	Low tide	1.5 m	135	297
Titli (VSCS ⁴)	October 10, 2018	Palasa, Andhra Pradesh	600 km	972 mb	150	195	Low tide	1 m	89	920
Bulbul (VSCS ⁴)	November 10, 2019	Sagar Island and Frazerganj, Indian Sundarbans	70 km	976 mb	140	155	Low tide	1–2 m	43	3370

Table 1 (continued)

Cyclone (Category)	Date & year	Landfall	Distance from MBI (Approx)	Pressure at landfall	Wind Speed (km/h)		Tidal status during landfall	Storm surge height	Casualties	Damage (Million USD)
					Average	Max				
Fani (ESCS ¹)	May 03, 2019	Puri, Orissa Coast	400 km	932 mb	215	260	Transition from low tide to high tide	1.5 m	89	8100
Amphan (SUCS ⁵)	May 20, 2020	Bakkhali, Indian Sundarbans	72 km	925 mb	240	270	High tide (New Moon)	5.45 m	98	13,400
Yaas (VSCS ⁴)	May 23, 2021	South of Balasore, Orissa Coast	200 km	970 mb	140	155	High tide	2–4 m	20	284
Sitrang (SCS ³)	October 25, 2022	Patuakhali in Barisal, Bangladesh Coast	173 km	994 mb	80–90	110	High tide (New Moon)	2.4 m	35	Unknown

ESCS¹—Extremely Severe Cyclonic Storm, CS²—Cyclonic Storm, SCS³—Severe Cyclonic Storm, VSCS⁴—Very Severe Cyclonic Storm, SUCS⁵—Super Cyclonic Storm

2021; Biswakarma et al. 2021). Despite this vast literature, the assessment of cyclone-induced coastal vulnerability for micro-administrative units of MBI over the last fifty years (1971–2021) has received little attention in recent times. Besides, livelihood challenges caused by tropical cyclones have been less highlighted through ground surveys. For mitigation planning and policy rationale, it is essentially required ground-based information in addition to satellite-driven data and also needs to incorporate the perception and experience of local people in policy implication which they have experienced over the years to adapt to this challenging environment. To fulfill these research gaps, the first objective of this study is to assess the inter-village variation of cyclone vulnerability of MBI. Furthermore, this study aims to shed light on how cyclones impact local livelihoods. Finally, several mitigation measures have been proposed to improve coastal dwellers' resilience to tropical cyclones. The present study can be used to plan disaster mitigation to reduce the risk of cyclonic disasters in anticipation of cyclones.

2 Study area

During the Quaternary Period, Sundarban was formed predominantly by alluvium deposition from the Ganga Brahmaputra and Meghna Rivers over both India and Bangladesh. The Indian Sundarban is near about 9630 sq. km. Out of the total area, dense mangrove forests cover 4200 km². The delta is low-lying and mostly protected by earthen embankments. The delta consists of 19 community development Blocks, among them 13 Blocks from South 24 Parganas and six Blocks from North 24 Parganas districts. The present study area, Matla–Bidya inter-estuarine (MBI), consists of three Blocks, namely Canning II, Basanti, and Gosaba. The present study area extends from 21°57'N to 22°45'N latitudes and 88°35'E to 88°53'E longitudes (Fig. 1). The total numbers of villages under Canning II, Basanti, and Gosaba Blocks are 39, 67, and 18, respectively. Matla and Bidya Rivers encircle this region on the east and west sides, respectively. The southern part is demarcated by Herobhanga Reserved Forest. The average elevation is almost 6 m from the mean sea level and most of the area lies below the high tide line. Therefore, saline water intrusion, waterlogging, and prolonged inundation are the most common phenomena during natural calamities. Similar impacts were observed during recent cyclonic disasters when the storm surge height reached up to 7 m. The total population of the study area is nearly 6,51,226 people (Census of India 2011). The maximum number of people still living below the poverty level accounts for 51%. The average population density of this study area is 946 people per sq. km and the household density is 200 households per sq. km (Census of India 2011). More than 70% of the population still relies on primary activities such as agriculture, forestry, and pisciculture (Ghosh and Mistri 2020c). The region experiences a tropical monsoon climate, so farming activities are highly dependent on rainfall. The average annual rainfall ranges from 180 to 200 cm, with 80% of the rain occurring during the rainy season.

3 Datasets and sources

In the present study, a total of 25 indicators were selected to assess the cyclone vulnerability index integrating physical vulnerability, social vulnerability, and mitigation capacity. These spatial datasets were collected from different sources as shown in Table 2 using geo-spatial techniques. The criteria considered under physical vulnerability such as elevation

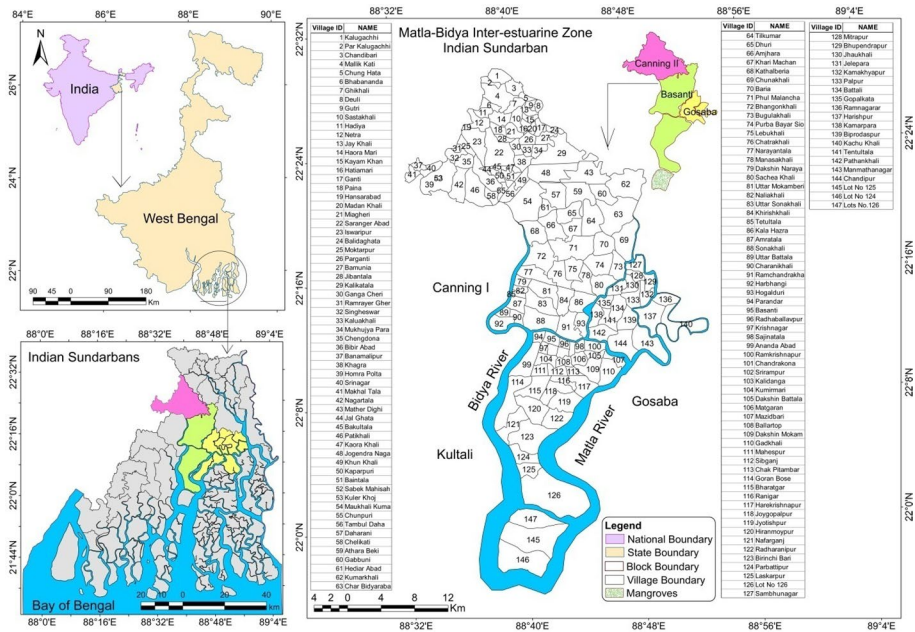


Fig. 1 Location of the study area

and slope derived using the SRTM-DEM of 2015 (Shuttle Radar Topographic Mission-Digital Elevation Model). The Landsat 8 OLI dataset of 2020 was used to digitize drainage networks and was also incorporated to assess coastal proximity. These datasets were downloaded from USGS (United States Geological Survey) Earth Explorer (<https://earthexplorer.usgs.gov>). The rainfall data of various rain gauge stations in the study area were collected from Irrigation and Waterways Department, Govt. of West Bengal. The map of the cyclone track was extricated from the cyclone e-atlas, Indian Meteorological Department (http://www.imdchennai.gov.in/cyclone_eatlas.htm) for the period of the last 50 years (1971–2021). The 100-year return period storm surge data were collected from India-Water Resource Information System (<https://indiawris.gov.in/wris/>). The demographic datasets considered under social vulnerability and mitigation capacity were compiled from the available last census record of 2011. Moreover, the field survey was also conducted during 2020–2021 to collect information through a questionnaire survey for various criteria particularly considered under mitigation capacity. The purposive random sampling method was adopted in the study area for the questionnaire survey. In both an open-ended and a close-ended format, the questionnaire was written in Bengali to obtain more relevant information from respondents. Based on Yamane’s (1967) formula with a 95% confidence interval, 5% of the households were surveyed.

$$n = \frac{N}{1 + Ne^2} \tag{1}$$

when n = sample size, N = population, and e = confidence interval.

The primary data collected during the field survey provide insight into the livelihood challenges faced by local people immediately following recent cyclones. The villagers

Table 2 Detailed description of datasets

Dataset	Source	Date	Purpose of uses
Landsat 8 OLI	USGS Earth Explorer (https://earthexplorer.usgs.gov)	02/02/2020	Extraction of drainage network and proximity analysis
SRTM-DEM	USGS Earth Explorer (https://earthexplorer.usgs.gov)	02/01/2015	Land elevation and slope
Rainfall data	Irrigation and Waterways Department, Govt. of West Bengal	2012–2017	Rainfall deviation map
Cyclone data	Cyclone e-atlas, Indian Meteorological Department (IMD) (http://www.imdchennai.gov.in/cyclone_eatlas.htm)	1970–2021	Cyclone frequency, intensity, track density analysis
Proximity analysis	Landsat 8 OLI image and Google Earth Pro	02/02/2020 10/05/2020	Distance for coast, nearness to cyclone shelter, distance from primary health center
Demographic data	Primary Census Abstract of 2011 (Part A & B) https://censusindia.gov.in/2011	2011	Population density, household density, SC, ST, women population, dependency ratio, poverty level, kutcha house (%), net sown area, literacy rate
Base map	The official portal of the Government of West Bengal (http://wbmdm.gov.in)	2013	Geo-reference based outline map
Others data	Field visit	2020–2021	Availability of cyclone shelter, early warning system, medical facilities, electricity, internet accessibility, livelihood challenges, coping mechanisms

also provided information about their needs for disaster risk management and mitigation. All these datasets collected from different sources were incorporated into the GIS environment. In this study, ArcGIS 10.8, ERDAS IMAGINE 2014, and OriginPro 8.6 were utilized for mapping and analysis purposes.

3.1 Criteria for vulnerability assessment

In this study, the cyclone-induced inter-village coastal vulnerability was assessed by integrating physical vulnerability, social vulnerability, and mitigation capacity. The detailed study was designed to derive a composite vulnerability index indicating the abbreviation of selected indicators and their functional relationship with vulnerability as shown in Fig. 2. The following subsections elaborate different criteria under each of the vulnerability subindices.

3.1.1 Criteria for physical vulnerability

Figure 3 shows different criteria selected to assess the physical vulnerability of the study area. Elevation and slope are one of the most important factors for physical vulnerability assessment. Those areas with high elevations and steep slopes are comparatively less vulnerable. In contrast, low elevations and gentle slopes are highly vulnerable (Ali et al. 2020; Sahana and Sajjad 2019). Drainage networks were extracted from Landsat 8 OLI data and validated using respective Google Earth images. The drainage density map was

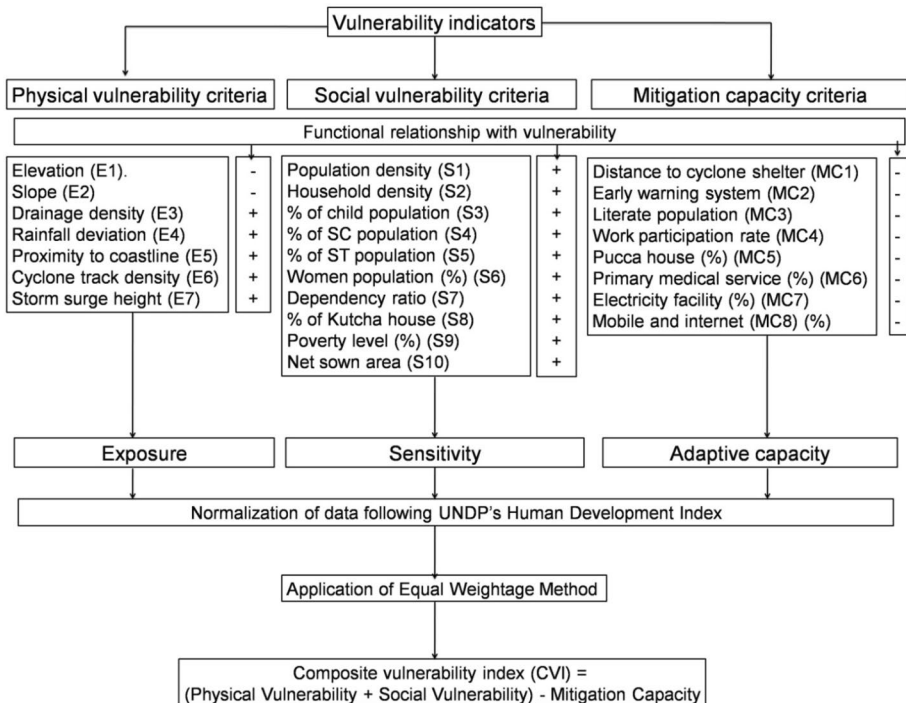


Fig. 2 The detailed study design of the present study

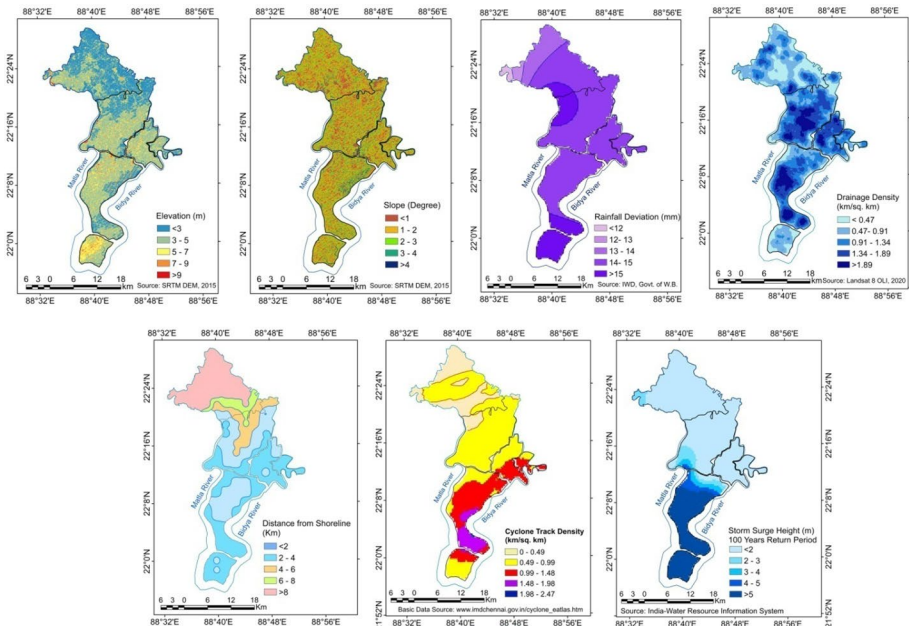


Fig. 3 Criteria selected for coastal exposures

then prepared using the line density tool in the ArcGIS environment and spatial data were extracted using the zonal statistics tool. The areas characterized by high drainage density are highly susceptible to flood risk during extreme weather events (Ghosh and Mistri 2021). Proximity to the coastline was measured using the multiple ring buffers with a 2 km interval distance. The rainfall deviation was calculated using the average and recorded rainfall data of five rain gauge stations, namely Uttarbhag, Canning, Nimpith, Kachuberia, and Raidighi. Thereafter, the IDW (inverse distance weighting) method was applied for spatial interpolation of rainfall deviation (Ali et al. 2020). The cyclone track data were downloaded from the cyclone e-atlas, IMD and incorporated into the GIS platform for spatial density analysis. The areas characterized by a high density of cyclone tracks denote more cyclonic activity and it is positively correlated with vulnerability (Islam et al. 2020). The highest storm surge in the 100-year return period was found in the southern part of the Basanti Block. The village-wise risk rating from 1 to 5 point scale was assigned for each of the villages, where 1 indicates the lowest risk and 5 indicates the highest risk caused by storm surge (Sahana and Sajjad 2019).

3.1.2 Criteria for social vulnerability

In this study, social vulnerability factors are considered that may contribute to cyclone vulnerability. The selected factors included in this study were population density, household density, percentage of the child population, percentage of women, SC, and ST population, dependency ratio, percentage of the kutchha house, poverty level (%), and net sown area. In India, the population and housing census is conducted every 10 years, and the most recent census data available to date are from 2011. The coastal region is densely populated in India. Therefore, population density spatially varies depending on local environmental

conditions and available resources. Tropical cyclones have a devastating impact on densely populated areas (Hoque et al. 2021). Therefore, densely populated areas have greater vulnerability to tropical cyclones. Additionally, children as well as the elderly population are highly exposed to tropical cyclones because they have limited ability to respond in emergencies without outside assistance during evacuation (Hoque et al. 2021). Similarly, the impact of cyclonic disasters is comparatively higher for the female population as compared to male counterparts as they have limited mobility and access to resources and most importantly safety and security measures prevail during disaster emergencies (Alam and Rahman 2014). The percentage of SC and ST populations is also an important determinant of social vulnerability. The higher the percentage of SC and ST population greater the vulnerability. This is because they are still a marginalized section of society due to low literacy rate, lack of skills, dependency on primary activities, and low standard of living. Kutcha houses are extremely vulnerable to tropical cyclones-induced gusting winds, heavy rains, and storm surges (Hoque et al. 2021). Therefore, the percentage of kutcha houses in a village was considered a criterion of social vulnerability. Farmers suffer the greatest economic losses from tropical cyclones due to massive crop damage (Hoque et al. 2016, 2016). The more farming-dependent an area is, the more vulnerable it is. Moreover, the percentage of the population living below the poverty line has faced the most destructive effects of cyclones even for years due to very low income, limited knowledge, and a lack of resources. The relationship between poverty and vulnerability is therefore positive (Ghosh and Mistri 2021).

3.1.3 Criteria for mitigation capacity

Mitigation capacity to tropical cyclones includes various measures such as distance from cyclone shelter, early warning system, literate population, work participation rate, percentage of pucca house, percentage of the population able to avail primary medical services, electricity facility, and mobile with internet connectivity to reduce the impact of the tropical cyclone. Cyclone shelter is a type of structural mitigation measure to provide temporary shelter to cyclone-affected communities. Local engineering departments and the Block Development Office provided information on cyclone shelters. However, this information was verified through a field visit during 2020–2021. In this study, the Euclidean distance technique was used for the measurement of the distance from the cyclone shelter. In an emergency, it is equally important that villagers have access to primary health centers. Early warning systems are essential for disaster preparedness (Akhand 2003). However, it depends on available infrastructure, connectivity, equipment, and personnel from local administrative offices to disseminate the accurate warning (Hoque et al. 2021). During the field survey, the aforesaid feasibility of the early warning system was checked and villages were categorized into highly effective, effective, moderate, and ineffective classes and accordingly given points from 1 to 4 scales where 1 denoted ineffective and 4 denoted highly effective class. Literate people play a crucial role to reduce the impact of the vulnerability. They are more aware of evacuation procedures and likely to be more efficient and prepared to tackle the disaster situation. Pucca houses are more resilient to natural disasters. Therefore, a higher percentage of pucca houses lessens the vulnerability. By analyzing field survey data, this study calculated how many people in villages have access to primary health care. Access to medical care is negatively correlated with vulnerability. Moreover, the work participation rate is helpful to understand the economic resilience of the people. When people are economically independent, they can afford to use various facilities such

as electricity, mobile phones, and the internet, which are very important to increase their coping capabilities.

3.2 Normalizations of data

After acquiring data for physical vulnerability, social vulnerability, and mitigation capacity, it is extremely important to normalize the datasets since they differ in units and scales. This study follows the UNDP’s Human Development Index method for data normalization. The functional relationship can be either positive or negative. An index value that significantly increases vulnerability is regarded as positive. Contrarily, the functional relationship is negative in the case of higher index value and lower vulnerability. The normalized score ranges between 0 and 1 where 0 denotes the lowest vulnerability and 1 denotes the highest vulnerability. Equation 2 shows the positive functional correlation.

$$X_{ij} = \frac{X_i - \text{Min}X_j}{\text{Max}X_j - \text{Min}X_j} \tag{2}$$

Equation 3 shows the negative functional correlation.

$$Y_{ij} = \frac{\text{Max}X_j - X_i}{\text{Max}X_j - \text{Min}X_j} \tag{3}$$

where X_{ij} is the normalized value of indicator (j) with respect to the specific region (i), X_i is the actual value of the indicator with respect to the region (i) and $\text{Max}X_j$ and $\text{Min}X_j$ are the minimum and maximum values, respectively, of indicator (j) among all the regions.

3.3 Vulnerability assessment

In the present study, the equal weightage method was applied to assess different vulnerability indices. Therefore, after the normalization of data, the following Eq. 4 was used to calculate the physical vulnerability index (P_V)

$$P_V = \frac{E_1 + E_2 + E_3 + E_4 + E_5 + E_6 + E_7}{7} \tag{4}$$

Social vulnerability (S_V) index can be expressed using the following the equation

$$S_V = \frac{S_1 + S_2 + S_3 + S_4 + S_5 + S_6 + S_7 + S_8 + S_9 + S_{10}}{10} \tag{5}$$

Mitigation capacity index (MC_i) was derived using the following Eq. X

$$MC_i = \frac{MC_1 + MC_2 + MC_3 + MC_4 + MC_5 + MC_6 + MC_7 + MC_8}{8} \tag{6}$$

The physical, social, and mitigation capacities ranged between 0 and 1 where 0 denoted low vulnerability and 1 denoted the highest vulnerability. Each index was classified into five equal classes such as lowest, low, moderate, high, and highest. In this study, the potential impact of vulnerability was also assessed by combining physical and social vulnerability and excluding mitigation capacity.

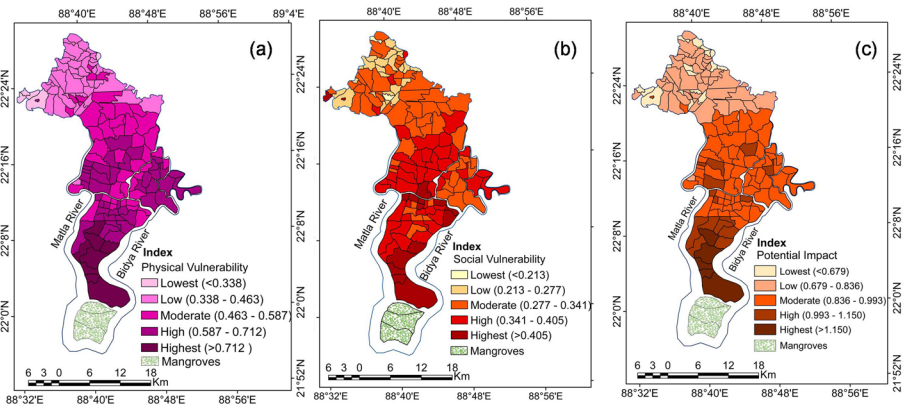


Fig. 4 Inter-village variations of physical vulnerability, social vulnerability, and potential impact

Thereafter, the composite vulnerability index (CVI) was derived by integrating afore-said three indices and the values range from 0 to 1 where 0 indicates the lowest vulnerability and 1 represents the highest vulnerability. After that, villages were categorized into five equal classes from lowest to highest.

$$CVI = (P_v + S_v) - MC_i$$

4 Results and discussion

4.1 Spatial variation of physical vulnerability criteria

The present study area is highly susceptible to tropical cyclones and resultant impacts on life and livelihood. The wide inter-village variation of physical vulnerability was found in the study area (Fig. 4a). Mostly, villages lie in the southern part of Basanti Block specifically Bharatgar (0.716), Radharanipur (0.733), Parbattipur (0.749), Nafarganj (0.764), Brinchi Bari (0.810), Lakspur (0.828), and Lot No. 126 (0.837) are extremely vulnerable to coastal exposures. As this part of the study area has reported the landfall of the most frequent and destructive cyclones over the years, these villages were found highly vulnerable. Besides, cyclone-induced storm surge flooding and high tidal current of the Matla and Bidya Rivers increase the severity of physical vulnerability mainly for those villages which are located close to these river banks. Near about 29% of villages of MBI that come under the Basanti and Gosaba Blocks were found highly vulnerable. As a result of the relatively high elevation, lesser impact of storm surges, and the resultant inundation in the middle part of MBI, there was moderate physical vulnerability affecting 48% of total villages. Contrarily, the physical vulnerability was considerably less in the upper part of MBI, particularly in hamlets under the Canning II Block. As per the analysis, 47% of villages were found very less to be less susceptible to tropical cyclones and their impacts due to their far location from the coastline.

4.2 Spatial variation of social vulnerability criteria

In the present study, an extreme to high social vulnerability was observed in the parts of southern, southwestern, and eastern parts (Fig. 4b). These sites are characterized by high population density, high dependency ratio, and higher parentage of illiterate population. Around 65% of houses are mud houses and semi-permanent structures with limited infrastructural facilities. Nearly 38% of villages both coastal as well as inland villages of Basanti and Gosaba Blocks were found in this category. However, the maximum number of villages (36%) of MBI were classified under the moderate social vulnerability class. Most of the villages of Canning II Block, some inland villages of Basanti Block, and the western part of Gosaba Block were found in this class due to high poverty levels and limited livelihood opportunities. Moreover, a very low to low social vulnerability was observed in some parts of the Canning II Block. Only 26% of villages belong to this category. Low population density, dispersed settlement patterns, less dependence on agriculture, and the use of wetlands for pisciculture are the main factors behind less sensitivity to natural disasters in these areas.

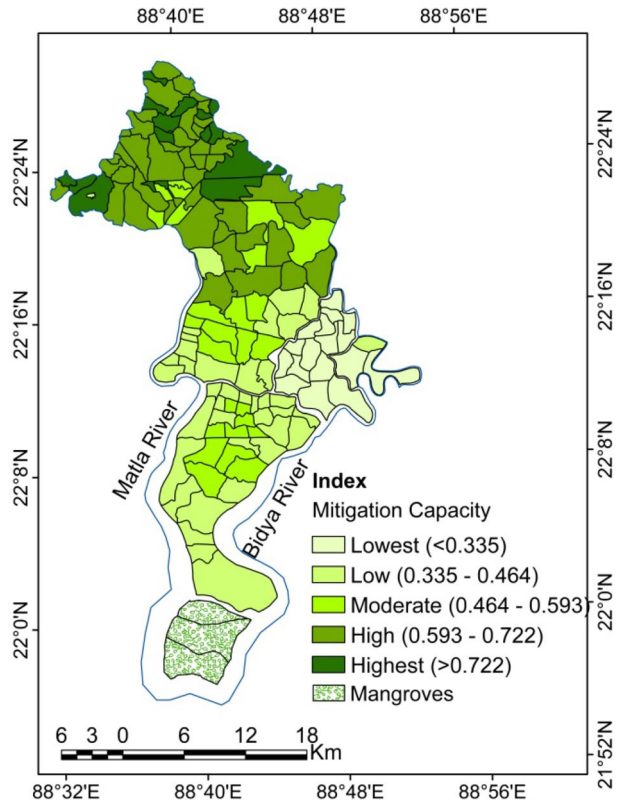
4.3 Spatial variation of the potential impact

The physical vulnerability and social vulnerability criteria combinedly determine the potential impacts of a particular place. The positive correlation between these two indices increases the intensity of vulnerability. The areas characterized by high potential impact are the most challenging because of physical constraints, climatic adversities, and socioeconomic backwardness. The villages located in the southern part of MBI, including Hiranmoypur (1.178), Brinchi Bari (1.23), Parbattipur (1.155), Laskarpur (1.238), and Lot No. 126 (1.307), would have very high impacts due to the low-lying coastal plain prone to intensive coastal erosion and flooding caused by storm surge and embankment breaches during high tide or natural calamities (Fig. 4c). Similarly, 10% villages of MBI experience high potential impact and most of them from Basanti Block. A few inland villages of Basanti and Gosaba Blocks also pose a high impact primarily because of various socioeconomic constraints. However, the maximum number of villages of Basanti Block and almost all the selected villages of Gosaba Block which constitute a combinedly 45% of MBI villages have been experiencing moderate potential impact. These villages are comparatively less susceptible to coastal exposures because of high elevation and low risk of storm surge-induced flood inundation. The embedded drainage system caused prolonged waterlogging in inland areas which impacted crop production, the only means of livelihood. Contrarily, low to lowest potential impact was observed in 40% of MBI villages, located in the upper part of the study area. There is less impact in the Canning II Block because it is less dependent on agriculture and pisciculture is an alternative method of livelihood.

4.4 Spatial variation of mitigation capacity criteria

In this study, very high to high mitigation capacity was found in the northern part of the study area which accounts for 11 to 42% of MBI villages (Fig. 5). Almost all the villages of Canning II C.D. Block and villages located in the northern part of Basanti Block have high resilience because of nearness to urban centers, well connectivity

Fig. 5 Inter-village variation of mitigation capacity to tropical cyclone

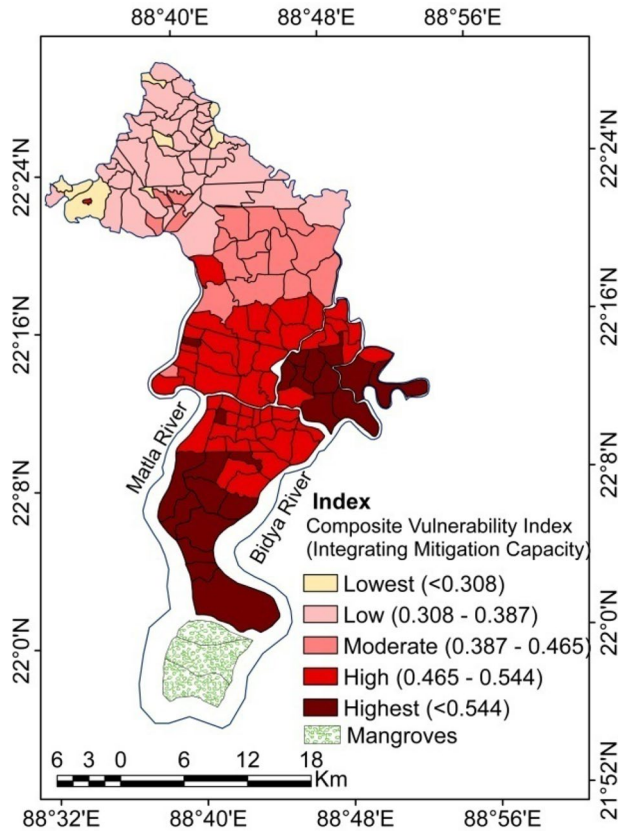


with the mainland, income opportunities, and availability of infrastructural facilities. Accordingly, moderate mitigation capacity was found mainly in inland villages of Basanti Block and a few villages of Canning II Block which represent 18% of MBI villages. Contrarily, very low mitigation capacity was observed in Gosaba Block as most of the houses are vulnerable. The intrinsic network of drainage channels has separated this island and confined people with limited livelihood opportunities. Moreover, high illiteracy and low work participation rate have been increasing the poverty level of these villages. The southern part of Basanti Block which constitutes 16% of MBI villages has also experienced low adaptation to tropical cyclones. Despite being highly populated, the inadequate number of cyclone shelters in comparison with the population density and less effective cyclone warning system, poor health services make these villages less resilient to tropical cyclones.

4.5 Spatial variation of cyclone vulnerability

The cyclone-induced coastal vulnerability was delineated in this study incorporating physical, social, and mitigation capacity criteria. The analysis revealed that 18% population of the study area inhabited in 14% of MBI villages were extremely vulnerable due to high exposure and sensitivity and less resilience. Most of these villages are located

Fig. 6 Inter-village spatial variation of vulnerability to tropical cyclones



in the southern and western parts of the study area (Fig. 6). Additionally, 30% of MBI’s population lives near extremely vulnerable villages, primarily in Basanti and Gosaba Blocks, which are highly vulnerable. These villages are highly susceptible not merely because of a cyclone but also to consequent impacts such as embankment breaching, flood inundation, and coastal erosion which are very impactful to sustaining life and livelihood. It is still challenging to implement mitigation measures in these areas due to the socioeconomic backwardness. However, the middle part of MBI constitutes 12% of MBI villages exposed to moderate vulnerability. Nearly 21% populations of the study area live in these villages. Many of these low-lying villages are protected by earthen embankments, but tides often overflow into adjacent villages, causing soil salinity to rise and resulting in lower agricultural productivity. Furthermore, the lowest to low vulnerability was observed in the northern part of the study area which accounts for almost 39% of MBI villages. Nearly 32% of the total MBI population lives in these villages. The entire Canning II Block comes under this category because of high resilience but low potential impacts. Since these villages are located relatively far from the coast, there is less cyclonic activity and less storm surge flooding. Disaster preparedness, emergency response, and the speedy reemergence of these villages are made easier

with direct connectivity to the mainland, medical facilities, and a range of livelihood opportunities.

4.6 Livelihood challenges to tropical cyclones

A tropical cyclone is one of the most destructive disasters in Sundarban. It is very essential to understand the inter-village variation of cyclone vulnerability for disaster management. Climate change causes a rapid increase in sea surface temperature (SST). The rate of increase of SST over the Bay of Bengal is recorded at $0.019\text{ }^{\circ}\text{C}/\text{Yr}$ (Peduzzi et al. 2012). As a result, ISD has been experiencing severe and frequent cyclones in recent years. The average elevation of this region is 3 m from the mean sea level and most of the parts are protected by an earthen embankment (Ghosh and Mistri 2020b). However, these embankments frequently breach due to cyclone-induced storm surges. The average height of the storm surge ($< 6\text{ m}$) is much higher than the embankment height ($\sim 3.6\text{--}5.0\text{ m}$) (Hossain et al. 2015; Islam et al. 2021). Therefore, saline water intruded into the agricultural land and increased salinity. It affected the cropping pattern as well as crop production. The situation becomes quite worrisome for farmers when tropical cyclones coincide with a spring tide. A similar impact was observed after cyclone Aila in 2009. The soil salinity in Gosaba Island was reported to significantly increase and physiological properties were changed rapidly immediately after the cyclone (Halder and Debnath 2014). It caused a rapid decrease in the production of rice. As 70% of the households in the study area are still agriculture-dependent, therefore their livelihood is remarkably threatened due to cyclones (Ghosh and Mistri 2020c). A huge number of people from the Basanti and Gosaba Blocks migrated outside mainly to metro cities to sustain their livelihood. As a nationwide lockdown was imposed due to the COVID-19 pandemic in 2020, these migrated workers come back to their homeland to sustain their daily livelihood based on agriculture, fishing, and forestry. However, one of the most destructive supercyclones Amphan in 2020 again strikes this region and completely devastated life and livelihood. Immediately after one year of that, Cyclone Yaas caused a massive flood in the entire Sundarban and completely ruined the farming and fishing activities. A household survey was conducted (2020–2021) in this study to understand the impact of these cyclones on their livelihood. Most of the coastal dwellers urge the impact of the storm surge caused by the cyclone and resultant flood inundation. Nearly, 65% of the coastal villagers indicated storm surge as a serious threat which is 34% in the case of inland villages. Next to storm surges, coastal villages are highly susceptible to embankment breaching and consequent saline water intrusion. In coastal villages, almost 77% of households reported high threats due to embankment breaching and consequent exposure to flooding. Most of the respondents (67%) in coastal villages are severely affected by coastal erosion (Fig. 7a). Moreover, inland villages have also been affected due to increasing soil salinity and waterlogging problem caused by the embedded drainage system. The perception survey of households confirmed that the aftermath effects of the cyclone most severely affected agriculture, fishing, and shrimp culture accordingly (Fig. 7b). In coastal villages, 67% of households reported a massive decrease in agricultural production due to recent cyclonic activity. However, the inland villages are comparatively less impacted as 55% of households reported a very high decrease in agricultural production. Therefore, per capita income, poverty and unemployment rate are significantly high in coastal villages. So, the livelihood challenges are more acute for coastal villagers as compared to inland dwellers (Fig. 7c).

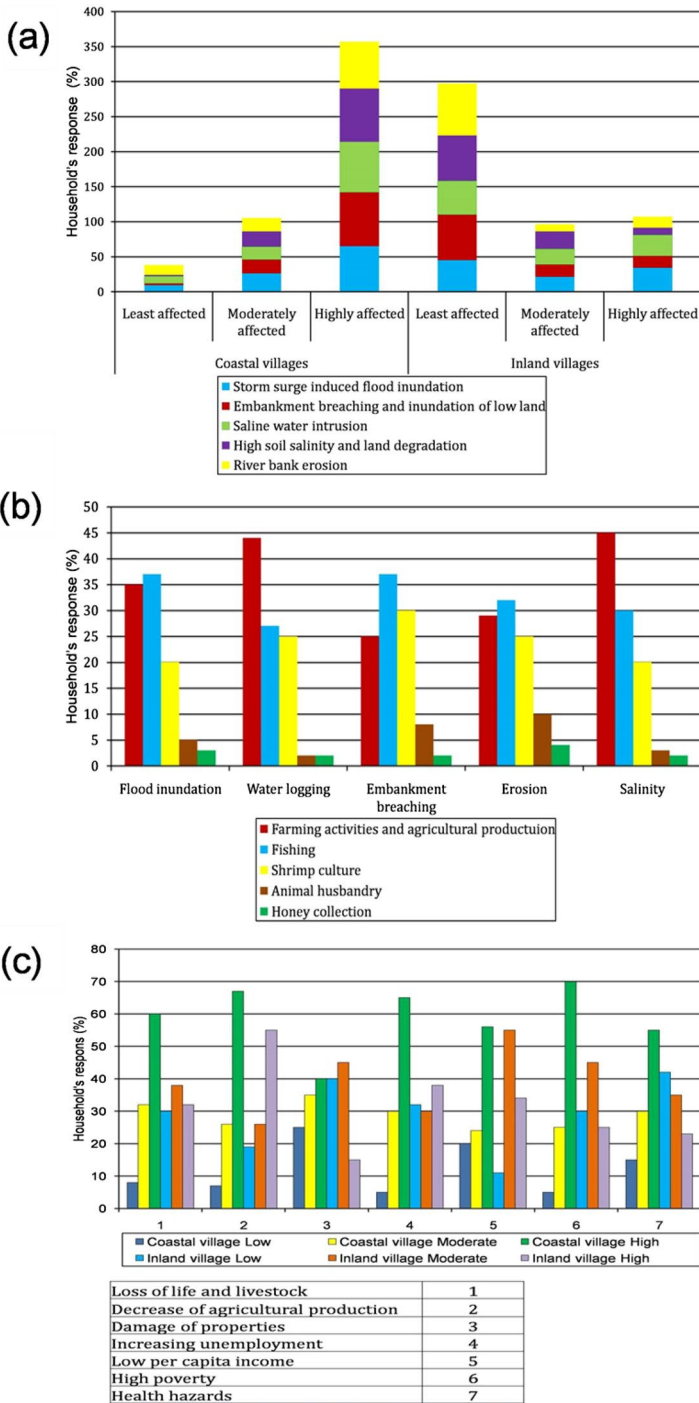


Fig. 7 Perception surveys of local people about cyclone and its aftermath effects on livelihood

4.7 Mitigation capacity

To reduce the impact of the disaster, the implementation of mitigation capacity is very important. Before policy implication and allocation of funds for structural and non-structural measures, it needs to know the degree of vulnerability of a place. Thus, micro-level hazard and vulnerability maps can be used to take preventive measures before disasters strike. As a result, an inter-village cyclone vulnerability map has been prepared. A detailed survey of vulnerable villages has also been conducted to gain insight into their strategies for dealing with cyclones. To mitigate cyclones and their effects, it would be effective to improve the early warning systems and to disseminate timely information even in remote areas. Continual improvement is needed in digital monitoring systems to track cyclones and predict landfall, wind speed, amount of downpours, and storm surge height. These data will need to be communicated among villagers. Sometimes the dissemination of cyclone warnings has been hindered by the inaccessibility of the place due to its remoteness. Because of poor economic conditions, almost 60% of villagers in such remote villages cannot use electronic gadgets such as mobile phones, TVs, and radios. As a result, it is quite difficult to provide timely updates about a cyclone. In comparison with the total population, the study area has less number of cyclone shelters. During the field survey, some villagers expressed their reluctance to move these cyclone shelters, especially women and elderly people mainly for their safety and security. Therefore, the local authorities must take effective measures to ensure the welfare and safety of the sheltered population, as well as provide primary medical services in the event of an emergency. Further, some temporary mud houses and huts have been observed to be unwisely constructed very close to the riverbank and surprisingly even on the active floodplain. These mud houses were often flooded due to embankment breaching and sometimes displaced by floodwaters and tidal waters. The winds of cyclones hastened mud house destruction. Therefore, the local administrative authority must enforce strict restrictions on them. However, some local villagers are very much aware of the consequences of cyclone-induced flooding. Based on their own experience, they have raised the base height of their houses to prevent cyclone water intrusion (Fig. 8). It should be a lesson to rethink building planning and structure in vulnerable coastal areas. As these people live for years in such a hostile environment, their experience and strategy of adaptation must be studied at the ground level before framing any policy measures. Local geo-environmental conditions must be considered in all planning and strategic policy. As well, the creation of mangrove bio-shields around embankments through social forestry could be very effective in protecting against direct impact from cyclones. It may also prove to be beneficial to reduce coastal erosion, increase the longevity of the embankment, and most importantly, increasing greenery to protect the environment.

5 Conclusions

The present research study illustrated the cyclone vulnerability of MBI integrating physical vulnerability, social vulnerability, and mitigation capacity criteria. A total of 22 indicators were considered for assessing cyclone vulnerability following the IPCC framework approach of vulnerability assessment. This study also includes a field survey to highlight livelihood challenges and adaptation measures. The present analysis revealed that physical vulnerability and social vulnerability together pose a potential impact on the



Fig. 8 Impacts of cyclone Yaas in 2021, challenges and adaptations **a, b** embankment breaching **c, d,** and **e** vulnerable houses along river bank **f** multi-purpose cyclone shelter **g** the villager pointing out the flood height after cyclone Yaas, 2021 **h** base height of the house increases to prevent flood water intrusion

southern coastal villages of MBI. Nearly 15% of MBI villages are experiencing high potential impacts at the interface of natural hazards. Contrarily, most of the villages located in the northern part of the study area are comparatively more resilient. The composite vulnerability index (CVI) that incorporates mitigation capacity indicates wide inter-village variations in the degree of spatial vulnerability. Near about 14% of villages of MBI are extremely vulnerable because of high exposure, high sensitivity, and low resilience. Tropical cyclone poses threat to the low-lying southern part of the Basanti Block and the western part of the Gosaba Block because of proximity to the coastline, low elevation, high cyclonic activity, and resultant storm surge. Near about 32% of MBI villages are categorized into the high vulnerability class. Most of these villages come under Basanti Block adjacent to extremely vulnerable villages. Most of these villages lying along the active creeks are protected by earthen embankments and are highly susceptible to coastal erosion hazards and saline water intrusion. Besides, socioeconomic backwardness potentially increases the degree of vulnerability. As estimated, almost 48% of the total MBI population lives in these highly vulnerable villages. However, the northern parts of the study area

mainly the villages under the Canning II Block are less vulnerable due to less cyclonic activity in these parts. Besides, a range of livelihood opportunities because of nearness to urban centers, high accessibility, and infrastructural as well as institutional facilities make these villages more resilient at the interface of the natural disaster. As a result of the cyclonic disaster, the life and livelihood of coastal villages are more challenging as compared to inland villages. These villages are not only exposed to cyclonic activity but the resultant impacts like storm surge-induced flood inundation, waterlogging, embankment breaching, and saline water intrusion cause severe impacts in those villages. As 70% of the population depends on primary activities particularly fishing and farming, the saline water intrusion adversely affected the production even for the years. However, the assessment of spatial economic loss would be more insightful to comprehend the economic vulnerability of residents which might be considered as the future scope of the research. A proper mitigation strategy is therefore very important to tackle such adverse conditions. The improvement of the digital warning system, regular dissemination of cyclonic updates, increasing the number of cyclone shelters with safety and security measures, especially for females, the elderly, and child population, and creation of mangrove bio-shield along the embankments through a social forestry program can reduce the impact of cyclone for a considerable extent in future.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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