



Natural hazards-induced vulnerabilities (1988–2024) and community-coping methods: A mixed-method study in the exposed coastal regions of Bangladesh

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Abstract

Bangladesh's exposed coasts are becoming extremely vulnerable to multiple climate change-induced natural hazards, which are exacerbated by socio-economic fragility. This study, the first of its kind in Bangladesh's twelve exposed coastal districts, analyzes trends in the most frequent natural hazards from 1988 to 2024, examines their underlying causes and consequences, and explores local communities' diverse perceptions of coping mechanisms and adaptation strategies. A mixed-method approach was employed, integrating qualitative and quantitative methods, including household questionnaire surveys, Focus Group Discussions (FGDs), Key Informant Interviews (KIIs), and field observations conducted from December 2024 to February 2025. The study's findings reveal that synergistically, environmental, physical, as well as socio-economic factors influence coastal multi-hazard vulnerability. Lack of awareness, limited institutional capacity, poor infrastructure, and fragile housing significantly aggravate these risks. Disaster-related mortality and injury ratios are higher among disproportionately affected children, women, and the elderly, compared to men. Major consequences include disease outbreaks like diarrhea and cholera, severe livelihood losses accounting for BDT 1,050,000 (approximately USD 8,500), and extensive environmental degradation in fisheries, agriculture, and mangrove ecosystems. In response, coastal communities have adopted several coping strategies, including community-based early warning systems, livelihood diversification, mangrove plantation, and cultivation of specific salt-tolerant rice varieties. Improving early warning systems, upgrading infrastructure, promoting sustainable livelihood practices, and expanding community training are all crucial to strengthening resilience throughout coastal Bangladesh. A lack of long-term recovery planning and inadequate policy implementation limit such resilience. This study will provide policymakers of relevant ministries with critical insights for ecosystem-based, gender-sensitive, and integrated coastal management policies to enhance the community's adaptive capability and resilience.

Keywords: Exposed coastal regions, Multi-hazard vulnerability, Community coping strategies, Climate change adaptation, Coastal hazard resilience

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1 Introduction

Climate change impacts are a major concern for underdeveloped and developing countries, resulting in various disasters (Ahmed and Atiqul Haq, 2019). Bangladesh,

one of the largest deltas globally, is extremely vulnerable to natural disasters owing to its geographical location, low-lying and flat terrain, dense population, illiteracy, poverty, inadequate institutional setup, and other factors (Cell, 2007). The nation ranked 7th on the long-term (1999–2018)

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Climate Risk Index (CRI), indicating its high susceptibility to disasters brought on by climate change (Eckstein et al., 2018). The frequency of natural disasters, particularly cyclones, is rising. Between 1990 and 2004, Bangladesh's coastal regions experienced ten major cyclones (Uzzaman, 2014). Another estimation projected a 5-mm sea level rise (SLR) annually in Bangladesh over the past 30 years (Uzzaman, 2014). The locality is at risk from the climate change-induced issues, including environmental, social, cultural, economic, and technological innovation (Islam and Nursey-Bray, 2017; Rakib et al., 2019; Hossen et al., 2019). Thus, adaptation and mitigation technologies, skills, and expertise are utmost necessary to get rid of disasters triggered by climate change (Hussain and Hoq, 2008).

In Bangladesh, the agriculture sector is impacted by floods and cyclones throughout the pre- and post-monsoon and the rainy seasons (Rahman, 2009). Rice is the primary crop, and the production rate is declining because of freshwater shortages and decreased soil fertility due to saline water in the southwestern region of Bangladesh, notably in Satkhira, Khulna, and Bagherhat districts (Ali, 2000). According to Islam and Hossain (2014), different climatic disasters have an impact on the livelihood of people residing in coastal areas and char lands. For example, in Bangladesh's southwestern coastal area, Cyclone Aila destroyed around 82% of shrimp cultivation farms. The unemployment rate is also increasing significantly due to climate change-related disasters, sea level rise, cyclones, tidal surges, and flooding with salinity, causing the land to become unfertile, and the loss of fishing (Uzzaman, 2014). The southern part of Bangladesh is substantially displaced by disaster-induced migration, with the majority of those (78%) displaced relocating to neighboring cities, specifically Bagerhat, Khulna, and Satkhira (Mallick and Vogt, 2014; Alam and Miller, 2019). The severity of disasters attributed to climate change is predicted to reach 2.5% of gross domestic product (GDP) after 2030, up from the prior losses of 1.81% (MoEFCC, 2022).

The southwestern portion of the coast, mostly the Sundarbans, provides ten million individuals with earning sources, but they are likewise the most vulnerable to climate change, mainly erosion and salinity (Uzzaman, 2014). Approximately 26% of Bangladesh's landmass is flooded each year, leading to several problems (Mirza, 2000). Furthermore, the prevalence of diseases is increasing, especially diarrhea, cholera, and viral diseases, along coastal regions for extreme temperatures and salinity (World Bank, 2000). Numerous studies have demonstrated that vulnerable groups, such as children and women, are more affected than males by catastrophic disasters, primarily cyclones and floods, which is exacerbated by the fact that women have less access to resources as well as opportunities (Fatema et al., 2019; Guha-Sapir et al., 2004). Although cyclone shelters and other disaster-risk reduction measures have reduced casualties in southern Bangladesh, economic and livelihood losses continue to rise due to frequent disasters and limited sustainable livelihood options (Quader et al., 2017).

Coastal people cope with multiple hazards and disasters and persevere through them with relentless struggles, with their traditional knowledge and perceptions, despite

their extreme poverty as well as vulnerability to different sorts of coastal hazards and disasters (Parvin et al., 2008). However, it is anticipated that climate change and its consequent hazards will affect people's adaptive capacities, which are already overburdened by recurring natural disasters, extreme poverty, and governance-linked issues. Hence, designing effective capacity-building interventions requires a comprehension of the ongoing community-based coping approaches regarding various coastal hazards, along with climate-related disasters. Empirical studies that focus on local-level coastal communities and their diversified perceptions relating to distinct natural hazards over a longer period are rare in Bangladesh. Therefore, addressing this critical research gap, this study aims, for the first time, to provide a comprehensive analysis of the trends of the most frequent climate change-induced hazards (1988–2024) in the exposed coastal regions of Bangladesh, including their underlying causes, consequences, and current attempts to minimize the adverse effects of multi-hazards on the coastal population's lives and livelihood as well as explores the extents of their adaptation strategies and institutional measures to manage the coastal zone sustainably. In addition to providing an overview of climate change-induced hazards, this research aims to investigate coastal communities' perceptions of multiple hazards, their vulnerabilities, and the coping strategies they employ. Specifically, the study seeks to: (1) identify the most frequent hazards affecting Bangladesh's coastal regions, (2) examine the underlying causes and consequences of these hazards, and (3) assess community-level responses and adaptive measures. The findings are intended to assist coastal managers, development organizations, policymakers, and local communities in designing sustainable, cost-effective strategies to manage coastal hazards, protect livelihoods and resources, and enhance community resilience in the context of a changing climate.

2 Study Area

Bangladesh's exposed coastal region, which lies between 20.74° to 22.82° north latitudes and 89.04° to 92.35° east longitudes, is divided into three separate zones (). These zones include the slightly steeper eastern zones, the central coast with its numerous offshore islands which are geomorphologically active, and the southwestern coastal part with mangrove forests (Quader et al., 2017). Due to the alluvial deposits of three main rivers, namely the Ganges, Brahmaputra, and Meghna, the coastal area has low topography, except for the elevated eastern portion (Khan et al., 2005; Singh, 2002). Based on tidal fluctuations, cyclone-affected areas, soil, underground, and surface water salinity, 19 districts are designated as coastal areas under the Integrated Coastal Zone Management Plan (ICZMP) of Bangladesh (Quader et al., 2017). However, for this study, twelve exposed coastal districts have been selected. The districts of Khagrachari, Rangamati, and Bandarban in the east; West Bengal, India, in the west; Jashore, Narail, Gopalganj, Barisal, Jhalokathi, Chandpur, and Kumilla in the north; and the Bay of Bengal in the south encircle the entire exposed coastal zone. Bangladesh's coastal area covers

Table 1. Sample size and socio-demographic characteristics of the study's participants.

Variables	Categories	Frequency (n)	Percentage (%)
Gender	Male	249	83
	Female	51	17
	Total	300	100
Age (years)	18-25	04	1.3
	25-35	16	5.3
	35-45	125	41.7
	45-55	92	30.7
	55-65	53	17.7
	>65	10	3.3
	Total	300	100
Educational Status	Uneducated	105	35
	Primary	95	31.7
	Secondary	70	23.3
	Higher Secondary	20	6.7
	Graduate	06	2
	Post-graduate	04	1.3
	Total	300	100
Occupational Status	Agriculture	83	27.7
	Fishing	43	14.3
	Laborer	71	23.7
	Businessman	58	19.3
	Govt. employee	23	7.7
	Others	22	7.3
	Total	300	100
Household Income (BDT)	< 10,000	84	28
	10,000-20,000	122	40.7
	20,000-30,000	71	23.7
	30,000-40,000	19	6.3
	>40,000	04	1.3
	Total	300	100
Family Status	Nuclear	141	47
	Joint	159	53
	Total	300	100

(Source: Field Survey, Dec. 2024–Feb. 2025).

an area of $40 \times 10^3 \text{ km}^2$, along with 710 km of shoreline, extensive river channels, and numerous islands, from the east coast of Teknaf Upazila, Cox's Bazar district, to the western section of Shyamnagar Upazila, Satkhira are the exclusive economic zones for multiple economic sources (Saha, 2015; Hussain and Hoq, 2008; Roy, 2018).

3 Methods

This study utilized a mixed approach, qualitative and quantitative, to determine vulnerabilities faced by coastal communities during natural disasters. Primary data were obtained through structured questionnaire surveys, which included socio-demographic characteristics (Table 1) as well as open-ended questions, a total of 15 Focus Group Discussions (FGDs), 6 Key Informant Interviews (KIIs), and physical observations of this study area between December 2024 and February 2025. The majority of face-to-face interviews were for 30 to 45 minutes. Due to varying literacy levels, consent was primarily obtained orally. To keep data collection manageable, convenient, and cost-effective, a moderate sampling size of 300 was finalized (100 for each of the exposed coastal zones of Bangladesh, e.g., eastern, central, and western, respectively). A cluster-based random sampling technique was employed, where each coastal zone was divided into clusters based on administrative units (e.g., districts, upazilas, and unions). The clusters were

selected to ensure geographic diversity and representativeness of local coastal conditions. Households within each cluster were randomly selected, with inclusion criteria: residence in the cluster for at least five years, primary livelihood linked to coastal resources (e.g., fishing, agriculture, aquaculture), and willingness to participate. 'Others' occupational status involves politicians, freelancers, boatmen, and housewives in Table 1. Households with temporary residence, non-coastal livelihoods, or unwillingness to participate were excluded. This cluster-based approach ensured equivalent representation from each region and captured a thorough understanding of the factors influencing overall coastal vulnerability and sustainable coastal management. The ground control points (GCPs) were also collected to ensure consistent geospatial positioning throughout the most vulnerable locations where the majority of natural hazards and disasters strike. Google Maps was utilized to gather these GCPs, and handheld GPS devices were employed to measure precise coordinates (Apparao et al., 2013). Furthermore, secondary data were gathered from a variety of published sources, like literature reviews, books, census reports, online journals, recently published thesis papers, well-known and reliable newspapers, and government and non-government projects. All sorts of descriptive data, including figures and tables, were analyzed and visualized using Microsoft Excel 2021.

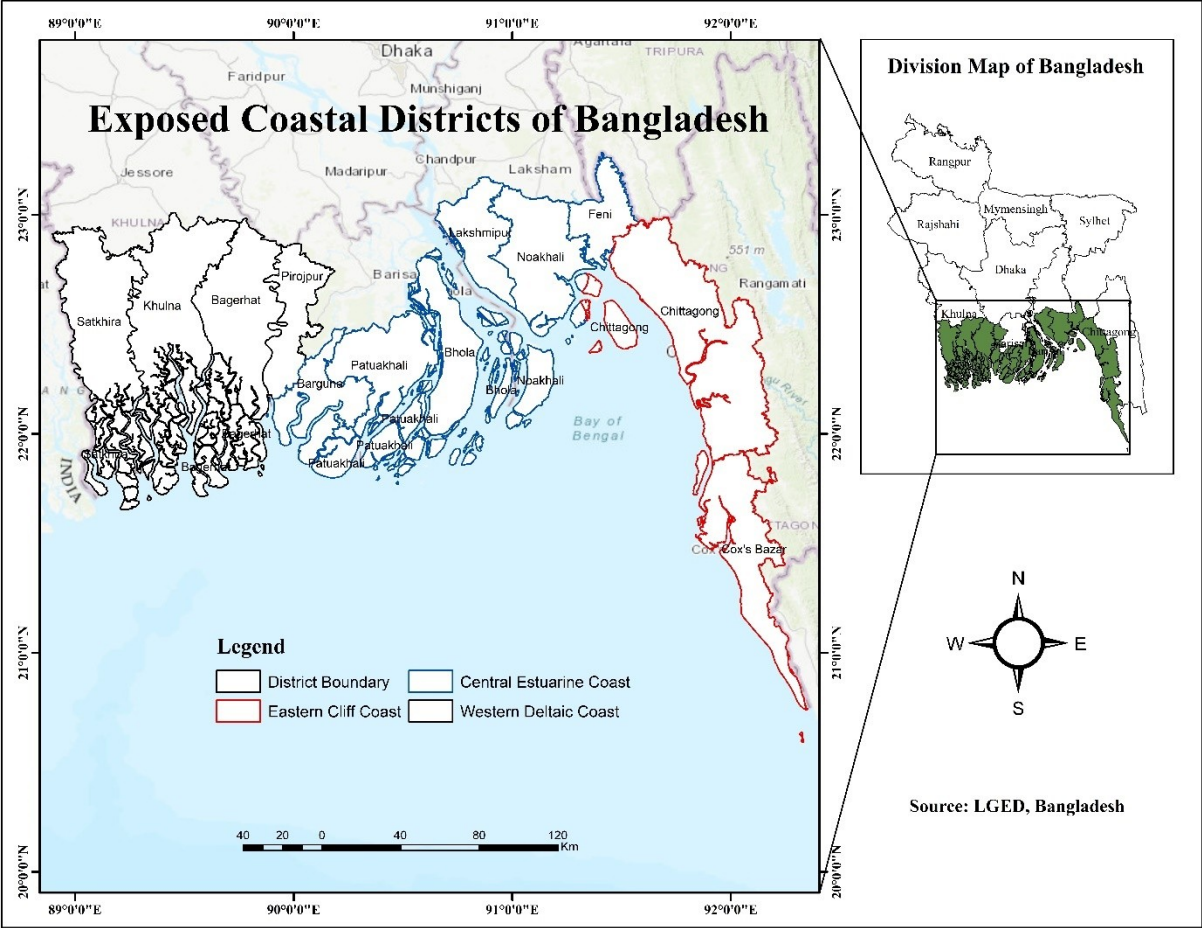


Fig. 1. Study area - exposed coastal districts of Bangladesh, which are directly connected to the sea.

4 Results

4.1 Factors Related to Coastal Multi-Hazard Vulnerability

4.1.1 Environmental Factors

The most prevalent hazards of the present study area are cyclones, followed by floods, coastal erosion, storm surges, salinity intrusion, earthquakes, and tsunamis (Fig. 2). Located in Bangladesh’s most southern region, the exposed coastal districts are highly vulnerable to cyclones and storm surges, which cause massive flooding. Additionally, the central portion of the study area is prone to severe riverbank erosion due to its location in the Meghna estuary, one of Bangladesh’s largest river systems. However, salinity becomes a catastrophic issue in many coastal areas, especially in the western coastal region.

The trend in coastal hazards across the study region is shown in Fig. 3. Cyclone and flooding frequencies exhibit an upward trend among all other hazards in this study area. On the contrary, approximately 80% of respondents have observed shoreline changes along the coast in their lifetimes, with around 38.33% of rapid, 58.67% of moderate, and only 3% of slow rates (Table 2). Regarding the shoreline changes, 31.33% of respondents gave their opinions on rapid changes for 10–15 years, adding that these changes have fallen between roughly 500 meters and 5 kilometers over the recent years.

Table 2. People’s perception of shoreline changes (erosion and accretion).

Category		n	(%)
Experience of coastal erosion	Yes	288	96
	No	12	4
Observed any shoreline changes	Yes	238	79.33
	No	57	19
	Not sure	5	1.67
Rate of shoreline changes	Rapid	115	38.33
	Moderate	176	58.67
	Slow	9	3
Observed rapid shoreline changes (years)	1–5	78	26
	5–10	73	24.34
	10–15	94	31.33
	15–20	30	10
	>20	25	8.33

Source: Field Survey, Dec. 2024–Feb. 2025.

4.1.2 Socio-Economic Factors

Several socio-economic factors are associated with vulnerability to coastal multi-hazards in this study, illustrated in Table 3. Almost all respondents interviewed were local (95%) residents, with only 5% representing non-local residents. A substantial proportion of those respondents (59.67%) stated that they owned agricultural lands and had livestock (79%). In the context of overall hazard risk perception, most respondents (62.33%) perceive it as moderate, with notable percentages viewing it as high (21%) and very

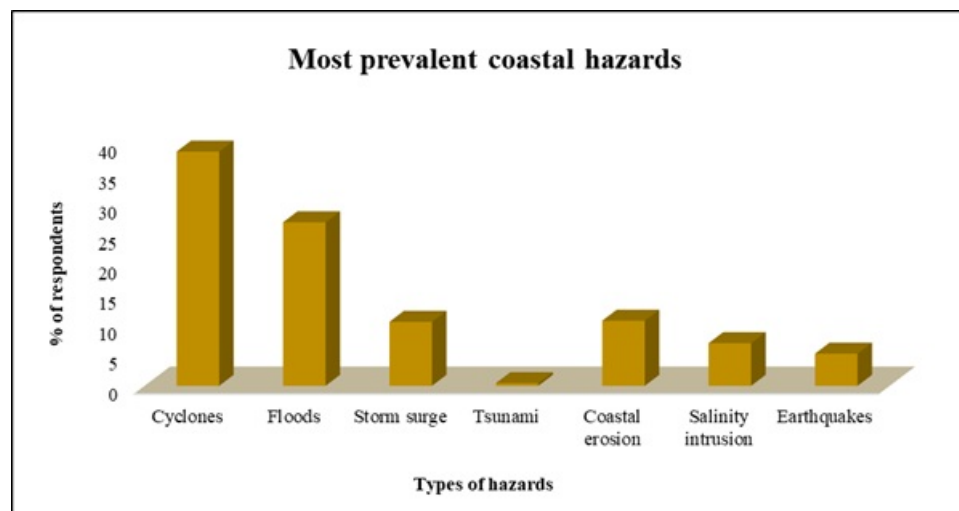


Fig. 2. People's perceptions of the most prevalent hazards based on substantial threats.

high (11.67%), respectively. In addition, 69.33% of all respondents have no insurance for hazard-related damages, and 78.33% had not participated in community training.

Table 3. Socio-economic factors related to coastal multi-hazard vulnerability.

Category		n	(%)
Types of residents	Local	285	95
	Non-local	15	5
Agricultural lands	Yes	179	59.67
	No	121	40.33
Livestock	Yes	237	79
	No	63	21
Perception of the hazard's risk	Very high	35	11.67
	High	63	21
	Moderate	187	62.33
	Low	9	3
	Very low	6	2
Household insurance for hazard-related damages	Yes	65	21.67
	No	208	69.33
	Not available	27	9
Attended any community training	Yes	65	21.67
	No	235	78.33

(Source: Field Survey, Dec. 2024–Feb. 2025).

Table 4. Existing conditions of the cyclone shelters.

Criteria		n	(%)
Building types	School	60	85.71
	Community center	2	2.86
	Others (NGO)	8	11.43
Construction materials	Brick	68	64.15
	Concrete	34	32.08
	Tin	4	3.77
Number of floors	Two	52	74.29
	Three	14	20
	Four	4	5.71
State of the building	Good	38	54.29
	Fair	26	37.14
	Bad	6	8.57
Capacity (number of people)	200	12	17.15
	300	18	25.71
	400	18	25.71
	500	15	21.43
	600	5	7.14
	1000	1	1.43
	1200	1	1.43

(Source: Field Survey, Dec.2024–Feb. 2025).

4.1.3 Physical Factors

In the present study, 70 cyclone shelters have been surveyed to examine the existing characteristics and conditions of these cyclone shelters along the whole coast (Table 4), highlighting that most of them (85.71%) are school buildings, constructed mainly of brick (64.15%), and have two stories (74.29%). 54.29% of the buildings are in good condition, and most shelters can accommodate 400 people (25.71%), with a similar percentage for 300 people (5.71%). However, overall circumstances indicate that if severe cyclones resembling those that hit in 1991 and 2007 were to strike again, there wouldn't be enough capacity to accommodate all individuals who could be evacuating to their closest shelters, regardless of how well warnings were disseminated.

The physical factors triggering the increased vulnerability to the coastal multi-hazards are presented in Table 5. In land use, residential areas comprise 72% of the surveyed locations, followed by mixed-use zones (22%) in this study. Gentle slopes are mostly predominant (45.33%) across the study region, although 23.67% of the surveyed sites are steep slopes, mainly in the eastern coastal zone due to the hilly regions. The semi-pucca houses, partially built with durable materials, are now the most common (77%), exhibiting an array of vulnerabilities and resilience. In contrast, kutchra houses that are typically made of mud and bamboo totaled 17.33% and pucca houses (comprising brick and cement) just 5.67%. The road surface structure is also characterized by semi-pucca roads (61.67%), with pucca roads accounting for 25.33% and kutchra roads for 13%, implying evacuation and transit constraints during hazards. However, 60% of bridges are in good condition, but a significant percentage are bad (26.67%) and under repair (13.33%), posing potential risks to connectivity. Likewise,

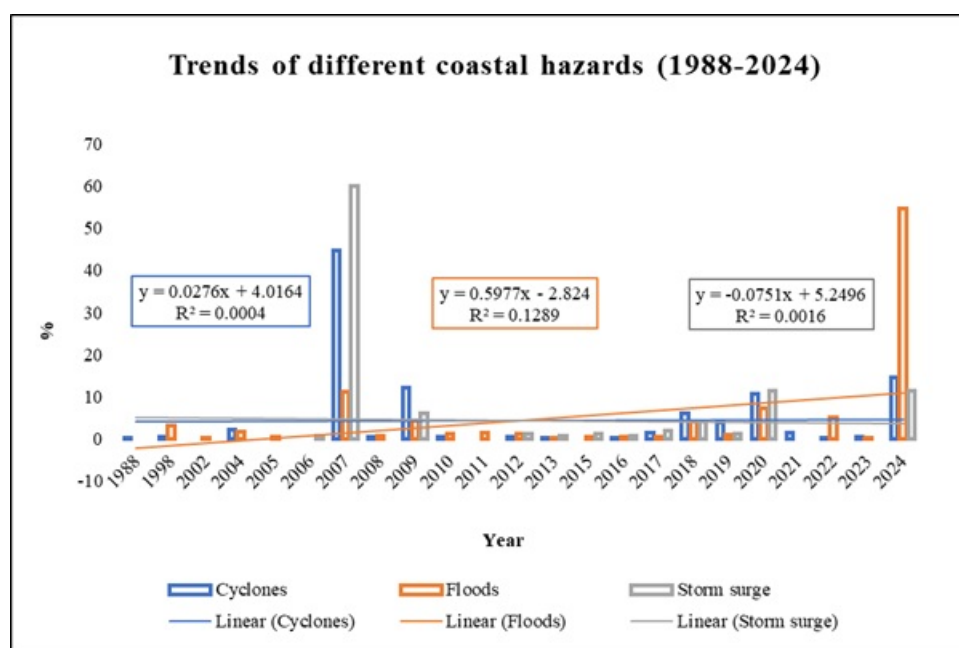


Fig. 3. People's perceptions of the trends of the most frequent and devastating coastal hazards (1988–2024).

embankments, critical for coastal protection, are generally in good condition (53%), although a substantial percentage are bad (32%) and under repair (15%), exposing possible shortcomings in defense against coastal multi-hazards.

Table 5. Physical factors behind the increased vulnerability of coastal hazards.

Category		n	(%)
Land use	Residential	216	72
	Commercial	16	5.33
	Industrial	2	0.67
	Mixed use	66	22
Slope of the ground	Flat terrain	73	24.33
	Gentle slope	136	45.33
	Steep slope	71	23.67
	Terraced land	20	6.67
Housing structure	Kutcha	52	17.33
	Semi-pucca	231	77
	Pucca	17	5.67
Road surface structure	Kutcha	39	13
	Semi-pucca	185	61.67
	Pucca	76	25.33
Bridges	Good	180	60
	Bad	80	26.67
	Under repair	40	13.33
Embankments	Good	159	53
	Bad	96	32
	Under repair	45	15

(Source: Field Survey, Dec. 2024–Feb. 2025).

4.1.4 Emergency Responses during Coastal Hazards

The support received from the government and the non-government organizations (NGOs) during any hazard or disaster's emergency responses is illustrated in Fig. 4, with food representing the most prominent form of aid (41.47%). Medicine constitutes the second largest percentage at 30.3%, followed by pure drinking water (10.85%) and clothes (6.38%). However, loans for land provide the least support (1.59%), with employment opportunities (0.32%).

Additionally, most respondents assert that the roles of NGOs are more appreciable than government support, for instance, the Bangladesh Red Crescent Society (BDRCS), HEED Bangladesh (Health, Education, and Economic Development), BRAC, Grameen Bank, ASA, and Padakhep are highly mentionable NGOs in Bangladesh that play a significant role in aiding coastal communities during emergency responses.

4.1.5 Recovery Options from Multi-Hazard Vulnerability

People's perceptions regarding recovery options from coastal multi-hazard vulnerability are demonstrated in Fig. 5. Improved infrastructure becomes the most critical recovery option (19.21%), followed by the next highest percentage of better early warning systems (19.91%) and expanded community training (17.25%). Additionally, fixing roads and embankments is deemed necessary, according to 13.77% of respondents. More financial aid from the government is regarded by 11.46% of responses, while adequate street lights are considered a recovery solution by 7.87%. Upgrading the existing cyclone shelters and ensuring sufficient food accounts for 4.75% and 2.55%, respectively. The least prioritized recovery options are installing well enough water treatment plants (1.27%) and providing fundamental health services (1.96%).

4.1.6 Mitigation Approaches for Coastal Multi-Hazards

People's perceptions to mitigate coastal multi-hazards are presented in Table 6, where, in the changing environmental circumstances, changing livelihood practices are the most adopted strategy, accounting for 46.05%. BRRI dhan99, BRRI dhan97, and BRRI dhan47, along with BINA dhan10, are reported as the most prominent rice varieties cultivated across the study region to combat the ongoing effects of salinity. According to the implemented measures

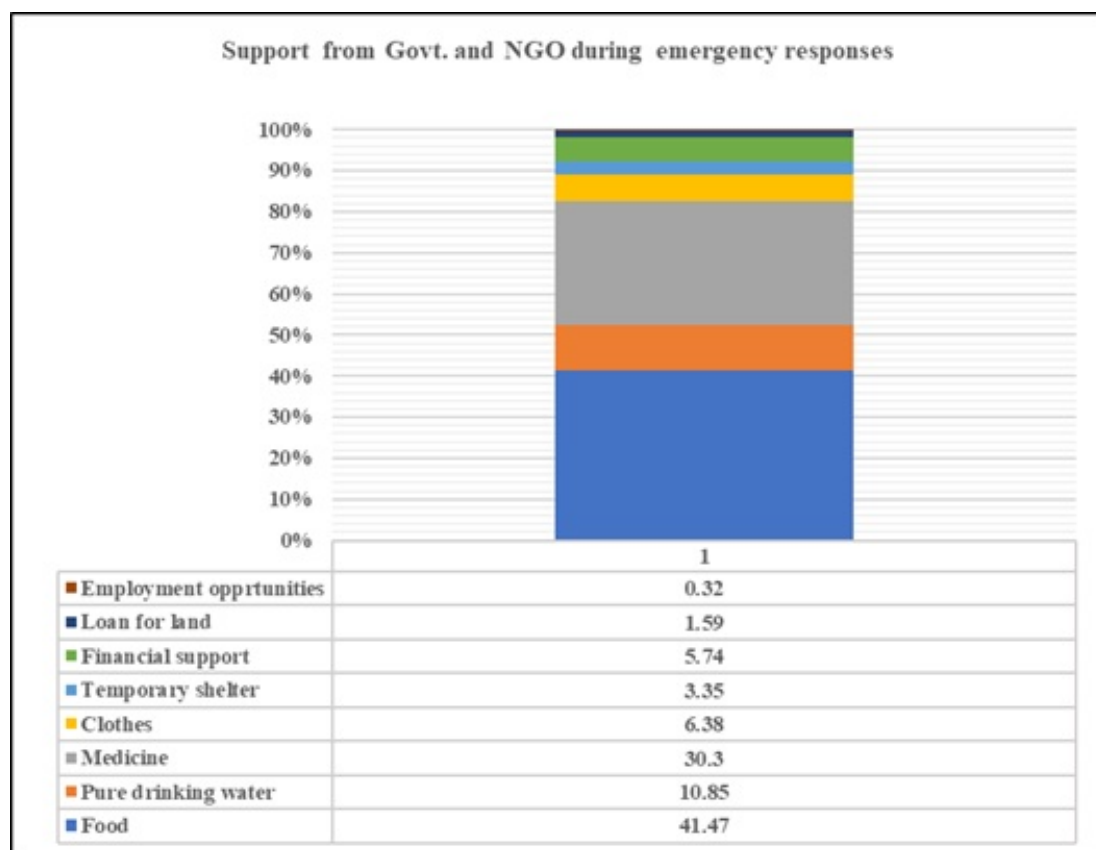


Fig. 4. Types and extent of assistance received from the Government and NGOs during emergency responses.

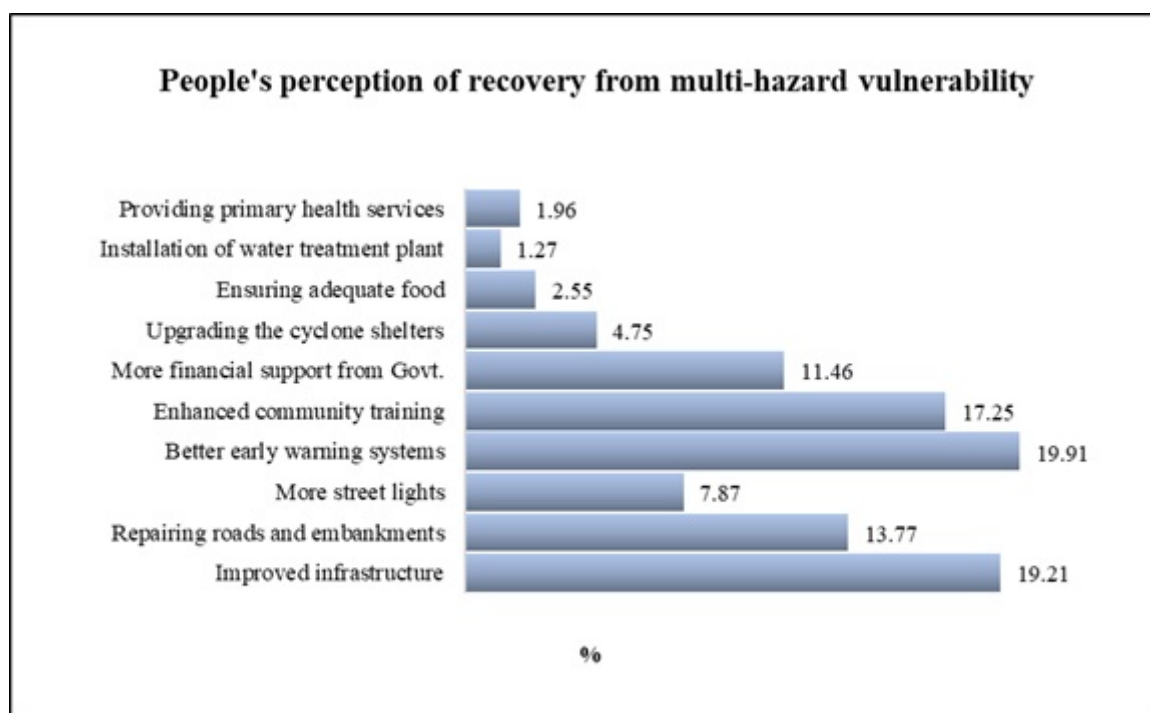


Fig. 5. People's perception of recovery from coastal multi-hazards following both experiences and needs.

within the community, early warning systems are highly notable (30.45%). A vast majority (74.33%) responded that the existing policies need to be amended. Regarding government investments, community training and awareness, and infrastructure development are highly prioritized at 44.62%

and 35.38%, respectively. In addition, research and relevant data acquisition are identified as the least significant expenditure area (2.2%), which is also regrettable for any long-term initiatives in the vulnerable regions. Nevertheless, workshops are the most popular training modality (85.98%).

Table 6. People's perception of mitigating coastal multi-hazards.

Coping method		n	(%)
Strategies adopted for changing environmental conditions	Relocation	53	12.33
	Change in livelihood practices	198	46.05
	Use of salt-resistant crops	115	26.74
	Diversification of income sources	64	14.88
Measures implemented within the community	Constructing embankments	145	27.26
	Mangrove plantation	153	28.76
	Early Warning Systems	162	30.45
	Community training programs	72	13.53
Need for existing policy changes	Yes	223	74.33
	No	77	25.67
Prioritization of government investments	Infrastructure	161	35.38
	Environmental conservation	81	17.8
	Community training and awareness	203	44.62
	Research and data collection	10	2.2
Preferred training methods	Workshops	276	85.98
	Online courses	21	6.54
	On-the-job training	24	7.48

(Source: Field Survey, Dec. 2024–Feb. 2025).

4.1.7 Preparedness for Coastal Multi-Hazards

The people's perception of preparedness before encountering coastal hazards is presented in Table 7. 76.34% of respondents are somewhat knowledgeable about coping strategies. Similarly, regarding emergency kits, 74% reported having them. A significant proportion (71.34%) lacks an evacuation plan, and 79.94% (at the community level) were somewhat prepared. Communication effectiveness within these communities was perceived as partially effective by 84.34%, and support from the govt. and NGOs seemed somewhat supportive (60.67%).

Public awareness of multiple coastal hazards is depicted in Fig. 6. The highest levels of awareness are found for cyclones (97%) and floods (96.33%), respectively, indicating that while the people is usually aware of the more frequently occurred hazards such as cyclones and floods, awareness regarding less frequent but possibly devastating catastrophic like tsunamis is substantially lower, emphasizing the needs for specific awareness campaigns concerning these less frequent hazards.

However, the most common ways in which people generally get informed about potential hazards are displayed in Fig. 7, where the primary source is television (35.94%), and radio is considered the next notable source (19.07%). According to Fig. 8, storing emergency supplies remains the most common preparatory measure for different coastal hazards, based on 36% of the respondents. Shelter reinforcement or construction is also important, accounting for 33%. Around 28% of the respondents stated about prepared evacuation plans, with only 2% attending disaster preparedness training.

Table 7. People's perception of preparedness before striking coastal hazards.

Coping method		n	(%)
Individual knowledge base	Very knowledgeable	22	7.33
	Somewhat knowledgeable	229	76.34
	Not knowledgeable	49	16.33
Availability of emergency kits	Yes	46	15.33
	No	222	74
	Partially	32	10.67
Plan for evacuation	Yes	43	14.33
	No	214	71.34
	Not sure	43	14.33
Community preparedness level	Very Prepared	16	5.33
	Somewhat Prepared	238	79.34
	Not Prepared	46	15.33
Effectiveness of communication within the community	Very effective	22	7.33
	Somewhat effective	253	84.34
	Not effective	25	8.33
Support from the Govt. and NGOs	Very supportive	68	22.66
	Somewhat supportive	182	60.67
	Not supportive	50	16.67

(Source: Field Survey, Dec. 2024–Feb. 2025).

4.2 Consequences of Coastal Multi-Hazard Vulnerability

4.2.1 Death and Injury Related to Coastal Multi-Hazards

Deaths and injuries within the study area resulting from different hazards are included in Table 8, where children had the highest percentage of deaths (29.41%), closely followed by females (30.25%) and aged people (21.85%), including both males and females, respectively. Again, females accounted for a significant percentage of injuries (30.95%), while children and the aged populace had 24.29% and 14.14%. Although males had the lowest percentage (18.49%) of deaths, they accounted for the second-highest rate (30.62%) of injuries.

Table 8. Death and injury related to coastal multi-hazards.

Category		n	(%)
Death	Male	22	18.49
	Female	35	29.41
	Children	36	30.25
	Aged	26	21.85
Injury	Male	184	30.62
	Female	186	30.95
	Children	146	24.29
	Aged	85	14.14

(Source: Field Survey, December 2024–February 2025).

4.2.2 Diseases Related to Coastal Multi-Hazards

The prevalence of several diseases associated with coastal hazards, for instance Cyclone Sidr (2007) and Remal (2024), Flood 1998 and 2024 during the lifetime of this study's respondents, and the related medical costs, a total of BDT 1,050,000 (approximately USD 8,500), are illustrated in Table 9. Diarrhea exhibits the most prevalent incidence (30.69% of the cases reported) and incurs the high-

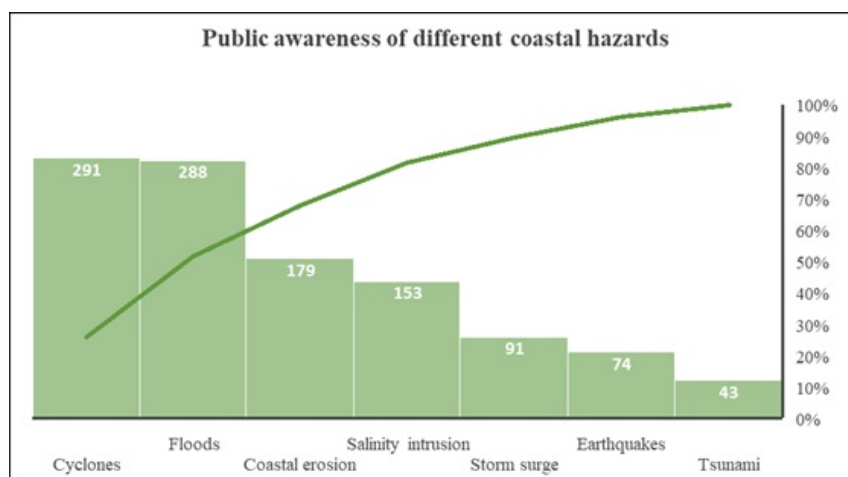


Fig. 6. Level of awareness among coastal communities regarding various coastal hazards.

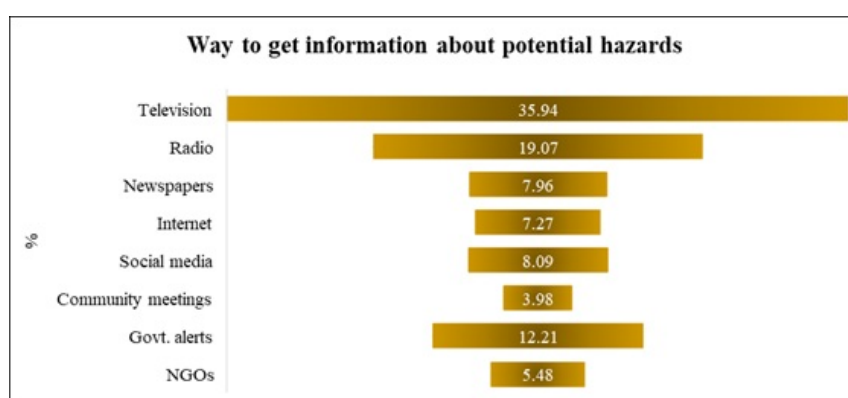


Fig. 7. Ways to get information about potential hazards.

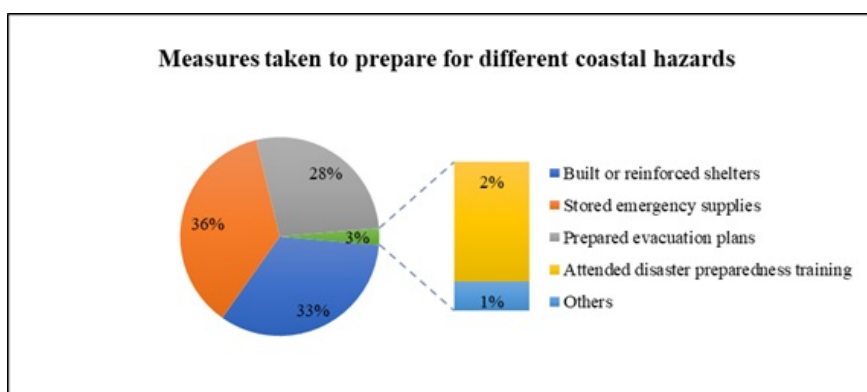


Fig. 8. Measures taken to prepare for different coastal hazards.

est medical cost, totaling Tk 348,000, indicating the significant consequences of waterborne diseases after such circumstances. The ‘Others’ category, particularly injuries, comprises 17.46% of cases, with the next-highest medical cost being Tk 330,000, signifying that injuries also contribute notably to health stress and financial hardship. Mental disorders have the lowest prevalence, with only 0.79% (medical costing Tk 15,000), although this could be unreported because of challenges in recognition during survey time, as well as their temporary and permanent medical cost issues for remedies due to the uncertainties.

Table 9. Diseases related to coastal multi-hazards along with medical costs.

Category	n	(%)	Medical costs (BDT)
Fever	99	26.19	100,000
Diarrhea	116	30.69	348,000
Cholera	65	17.2	162,000
Asthma	11	2.91	40,000
Skin diseases	18	4.76	45,000
Mental disorders	3	0.79	15,000
Others (injuries)	66	17.46	330,000
Total	378	100	1,050,000

(Source: Field Survey, Dec. 2024–Feb. 2025).

4.2.3 Livelihood Impacts

Coastal multi-hazards have a significant impact on the communities’ livelihood patterns (Table 10), resulting in total economic losses of BDT 108,500,000 (approximately USD 8700), assessing the damaged properties across the surveyed locations primarily based on the major cyclones and floods experienced in their lifetime, e.g., Cyclone Sidr 2007 and Remal 2024, along with Flood 1998 and 2024. Homestead land and houses incurred the greatest loss, accounting for Tk 34,200,000. Similarly, agricultural products, primarily varieties of crops (rice, maize, and root crops, such as carrots, radishes, and beets), endured substantial damage, including losses totaling Tk 10,000,000, indicating the notable vulnerability in the agricultural sector. On the contrary, the estimated livestock losses, specifically cattle, including cows, followed by goats, hens, ducks, and sheep, made up the second-largest percentage (30.67%), with losses of Tk 38,010,000, reflecting the severe impact on livestock. Other assets, comprising arable land, trees, mainly fruit and nut trees in the eastern coastal region, ponds, fish enclosures, shrimp cultivation in the western zone, boats, and businesses, further contributed to the economic damages, totaling Tk 25,090,000.

Table 10. Assessment of damaged properties.

Category	n	(%)	Amount of losses (BDT)
Homestead land and house	228	27.64	34,200,000
Arable land (633 Bigha)	102	12.36	20,400,000
Agricultural products	200	24.24	10,000,000
Trees	11	1.33	770,000
Farm	15	1.82	1,200,000
Cattle	253	30.67	38,010,000
Pond	2	0.24	600,000
Fish enclosure	5	0.61	500,000
Boat	4	0.48	320,000
Business (store)	5	0.61	2,500,000
Total	825	100	108,500,000

(Source: Field Survey, Dec. 2024–Feb. 2025).

4.2.4 Coastal Multi-Hazard Induced Migration

From Table 11, it can be seen that a considerable percentage of respondents (29.67%) in the study region lost their livelihood due to multiple coastal hazards; however, the vast majority (70.33%) did not face such a loss. Nevertheless, despite the substantial impact on some people’s livelihoods, the overall migration rate caused by these multi-hazards remains comparatively low (12.67% of respondents). According to the respondents’ viewpoints, several factors, like strong ties to society, a shortage of migration resources, available options for alternative livelihood, or dependency on aid and assistance within the afflicted region, might all lead to a slower migration rate, regardless of the property losses.

Table 11. Coastal multi-hazard induced migration.

Criteria	n	(%)
Loss of livelihood	Yes	89 29.67
	No	221 70.33
Migration	Yes	38 12.67
	No	262 87.33

(Source: Field Survey, December 2024–February 2025).

4.2.5 Structural and Non-structural Damages of Institutions

Multiple coastal hazards trigger both structural and non-structural damage to different institutions within the study area, and the impacts vary enormously between various educational institutions. Schools are the most affected, followed by madrasas, colleges, and universities. According to Table 12, institutional structural damages were primarily related to the foundation, with 12.33% of responses for broken condition, and 2.33% severely damaged. The walls experienced significant damage, accounting for 51.33% regarded as broken and 6% as severely damaged. However, the roof showed a lower damage rate in the broken category (24%), yet a relatively higher rate for severely damaged (10.67%). Doors and windows also suffered considerable structural damage amongst the reported properties, with 12.67% severely damaged and 61% broken. In the context of non-structural damages, functional damage in water supply was notably high, with 45.34% of responses and 2.33% non-functional. Subsequently, sanitation facilities encountered issues, with 58.67% partially functional and only 17.33% non-functional. Electricity had a similar pattern, with the highest percentage (41%) for partially functional and the second-highest (22.33%) for nonfunctional. Backup power supplies, such as generators, showed a substantial rate of functional damage (32%), whereas solar-powered systems had a far greater partial functionality of 66.67%.

Table 12. Structural and non-structural damages of institutions.

Damaged properties		n	(%)
Structural	Foundation		
	Intact	256	85.34
	Broken	37	12.33
	Severe Damage	7	2.33
	Walls		
	Intact	128	42.67
	Broken	154	51.33
	Severe Damage	18	6
	Roof		
	Intact	196	65.33
	Broken	72	24
	Severe Damage	32	10.67
	Doors and windows		
Non-structural	Intact	79	26.33
	Broken	183	61
	Severe Damage	38	12.67
	Water supply		
	Functional	157	52.33
	Partially Functional	136	45.34
	Non-functional	7	2.33
	Sanitation		
	Functional	72	24
	Partially Functional	176	58.67
	Non-functional	52	17.33
	Electricity		
	Functional	110	36.67
	Partially Functional	123	41
	Non-functional	67	22.33
	Backup power supply		
	Functional (Generators)	96	32
	Partially Functional (Solar)	200	66.67
	Non-functional (Fire)	4	1.33

(Source: Field Survey, Dec. 2024–Feb. 2025).

4.2.6 Environmental and Socioeconomic Impacts

Table 13 presents the overall environmental and socioeconomic repercussions of multiple hazards across the study region. Marine life and fisheries had significant to moderately negative impacts, with a small percentage having no impacts in most cases. Similarly, the agricultural sector experienced significant negative impacts (46.33%). Subsequently, vegetation and forest, particularly mangroves, showed significant negative impacts, with 21.67% and 34.67% of responses. The infrastructure and communication systems were likewise significantly impacted.

Table 13. Environmental and socioeconomic impacts of coastal multi-hazards.

Category		n	(%)
Marine life	Significant negative impact	129	43
	Moderate negative impact	130	43.33
	No impact	41	13.67
Fisheries	Significant negative impact	130	43.33
	Moderate negative impact	165	55
	No impact	5	1.67
Agriculture	Significant negative impact	139	46.33
	Moderate negative impact	155	51.67
	No impact	6	2
Vegetation	Significant negative impact	65	21.67
	Moderate negative impact	231	77
	No impact	4	1.33
Forest (Mangroves)	Significant negative impact	104	34.67
	Moderate negative impact	162	54
	No impact	34	11.33
Infrastructure	Significant negative impact	129	43
	Moderate negative impact	165	55
	No impact	6	2
Communication	Significant negative impact	56	18.67
	Moderate negative impact	240	80
	No impact	4	1.33

(Source: Field Survey, Dec. 2024–Feb. 2025).

5 Discussion

5.1 Trends and Responsible Factors Analysis of Coastal Multi-Hazard Vulnerability

Bangladesh's exposed coastal districts' multi-hazard vulnerability is intricately linked to environmental, physical, and socio-economic factors, concerning pre- and post-disaster phases such as preparedness, mitigation, emergency response, and recovery, as demonstrated in this study's findings. Cyclones and flooding are the prevalent coastal hazards mentioned by local respondents, which is consistent with other contemporary national disaster trends (World Bank, 2024; Ashrafuzzaman, 2023). The majority of respondents experienced coastal erosion, with approximately 38% noting rapid shoreline changes over the last decade, which aligns with satellite-derived data of coastal land loss within Bangladesh's southwestern part (Saddam et al., 2025). Low elevation, proximity to tidal rivers, and soft alluvial soils are some of the physical factors of the coastal area that exacerbate exposure, especially in the Meghna estuary, along with the districts adjacent to the Sundarbans, like Satkhira, Khulna, and Bagerhat. According to Rahman (2024), these regions are vulnerable to both anthropogenic and hydrodynamic stresses, such as expansion of shrimp aquaculture, land subsidence, and embankment

breaches. Socio-economic evidence reinforces this physical vulnerability, e.g., lack of insurance coverage, reliance on climate-sensitive sectors, including fishing, agriculture, or labor, and most of them have never received community training, implying that livelihood dependency on natural resources and limited institutional readiness are perpetuating cycles of vulnerability (Hauque et al., 2022). Furthermore, gender dynamics aggravate these risks; children and women are more constrained in accessing resources, mobility, and information, which aligns with regional trends of gendered disaster consequences across South Asia (Md et al., 2022). Poor housing quality, with mostly semi-pucca, as well as underdeveloped infrastructure, such as damaged bridges and embankments, semi-pucca roads, additionally limits evacuation and resilience capacities.

The findings on post-disaster (emergency response and recovery) and pre-disaster (mitigation and preparedness) phases in Bangladesh's exposed coastal regions indicate that disaster management is primarily still relief-oriented compared to resilience-focused, alongside both government and NGO attempts to prioritize short-term needs like temporary shelter, food, and medicine instead of long-term recovery plans. This disparity reflects infrastructural constraints, institutional weaknesses, and inadequate coordination that restrict timely evacuation and efficient communication during disasters, in line with previous investigations highlighting gaps in Bangladesh's catastrophe governance and communication mechanisms (Rahman, 2024; Ashrafuzzaman, 2023). Respondents perceived NGOs, including the Bangladesh Red Crescent Society and BRAC, as more effective at distributing emergency relief, aligning with earlier research that civil society organizations are crucial to humanitarian response at the community level (Al-Mueed et al., 2021; Uddin et al., 2022). However, insufficient infrastructure investment, inadequate sanitation and health services, and limited funding to restore livelihoods remain obstacles to post-disaster recovery, which supports the World Bank's (2024) report that recovery is often inconsistent and delayed in coastal Bangladesh. The National Adaptation Plan (NAP) of Bangladesh (2023–2050) supports community-based initiatives that align with adaptation and mitigation responses, which signify emerging local innovations such as livelihood diversification, the use of salt-tolerant crop varieties, and mangrove restoration (MoEFCC, 2022). Nevertheless, exposure to hazards continues to increase due to the persistence of poor maintenance of embankments, minimal institutional accountability, and inadequate policy enforcement (Sarker et al., 2023; Chowdhury et al., 2025). While community awareness regarding frequent hazards such as cyclones and flooding is high, comprehension of less common but devastating hazards like earthquakes and tsunamis stays limited, underscoring the necessity for early warning system advancement, inclusive disaster literacy, and localized training (Md et al., 2022; UN Women, 2022). Integrated disaster governance, which incorporates gender-sensitive preventive education, ecosystem-based mitigation, rapid emergency response, and equitable recovery financing, therefore, is necessary to foster anticipatory resilience (MoEFCC, 2022; World Bank, 2024; Hauque et al., 2022).

5.2 Consequences of Coastal Multi-Hazard Vulnerability

Empirical data support the notion that the consequences of these multi-hazard vulnerabilities manifest in substantial harm to the environment, the economy, and the people. According to the field investigation, death and injury patterns reveal that children as well as women suffer the highest rates of disaster-associated deaths, while males and females account for roughly equivalent rates of injuries (~31%). These findings align with global studies revealing that in low-income coastal regions, disasters disproportionately undermine child survival and shorten the life expectancies of women (Sarker et al., 2023; Fatouros and Capetola, 2021). Health implications further emerged as a notable outcome in the current study, with diarrheal disease and cholera, respectively, being among the most prevalent, mostly because of post-flood contamination, with salinity intrusion into the drinking water sources. Recent World Health Organization (2024) statistics confirm similar outbreaks after Cyclone Remal (2024), emphasizing inadequate water and sanitation infrastructures throughout coastal Bangladesh. The surveyed communities' Tk 1.05 million linked health-care expenditure illustrates the financial impact of health issues brought on by climate change. Livelihood disruption was found to be another significant consequence, as evidenced by losses exceeding Tk 108.5 million, with livestock losses and housing damages being the most prominent. These outcomes are consistent with national trends indicating that natural disasters result in average annual losses equal to GDP's 1.5–2% (World Bank, 2024). Additionally, recurrent flooding and salinity intrusion have decreased soil fertility and lower agricultural productivity, especially in the southwestern delta, leading many households toward seasonal migration or non-agricultural wage labor (Chumky et al., 2023). However, even with 29.67% reporting the loss of livelihood, only 12.67% migrated, implying limited mobility resources and strong social attachment, as Alam and Miller (2019) also pointed out. On the contrary, structural damages to mostly schools, with walls (51%), exhibit the public infrastructures' fragility that disrupts emergency shelter capacities and education continuation. Environmental repercussions were similarly severe, where 55% of respondents experienced moderate to severe impairment to fisheries, 54% to mangroves, and approximately 46% to agriculture, which coincides with other ecological research relating increased erosion to the frequent cyclonic activity and reduced mangrove cover (Chowdhury et al., 2025).

5.3 Adaptive Measures at the Community-Level to Increase Resilience

Adaptive and preventive measures, therefore, have become crucial to mitigate the impacts of coastal multi-hazards, based on this study's findings regarding policy needs and community practices. About half of the respondents (Table 6) mentioned changes in livelihood practices as their adaptation strategies. According to MoEFCC (2022), these micro-level strategies align with national adaptation goals outlined in the Bangladesh NAP (2023–2050), which prioritizes resilient communities and sustain-

able livelihoods. However, the least preferred policy was relocation, often suggested in international adaptation frameworks, indicating that attachment to one's ancestral land as well as cultural identity goes beyond the perceived safety advantages (Sarker et al., 2023). Effective community-level interventions encompassed early warning systems, embankment strengthening, and mangrove plantations; nevertheless, 74% of respondents emphasized that current policies needed to be revised to ensure enforcement and equity. In addition, nearly 45% of participants consider government expenditures on community training and awareness, following infrastructure, signifying that non-structural measures of resilience are becoming progressively recognized. Improved early warning dissemination via digital tools, such as SMS, radio, television, and social media, along with participatory training initiatives, could substantially improve preparedness. Furthermore, coastal afforestation endeavors and the adoption of specific salt-resistant rice cultivars can locally sustain productivity and mitigate the effects of cyclones (Al-Mueed et al., 2021). Women's active involvement in community-driven disaster management has also proven beneficial in various other South Asian contexts, for reduced asset loss and mortality rates (UN Women, 2022). Thus, a multifaceted preventive approach, combining capacity building, technological interventions, gender-responsive governance, and ecological restoration, is still crucial. The study's findings unambiguously suggest that building resilience throughout Bangladesh's exposed coasts necessitates not only investments in infrastructure but also institutional accountability and social empowerment. In the coming decades, sustainable coastal management will demand the integration of local knowledge, policy coherence, and scientific forecasting to safeguard ecosystems, human well-being, and livelihoods against the escalating hazards posed by climate change.

6 Conclusion

This study comprehensively evaluated the nature, causes, and adverse consequences of natural hazard-induced vulnerabilities in Bangladesh's exposed coastal regions as well as the coping mechanisms of coastal communities to enhance resilience. The findings show that physical, environmental, and socio-economic factors, considering pre- and post-disaster phases, interplay to exacerbate the effects of coastal multi-hazards. Inadequate infrastructure, specifically a limited number of cyclone shelters, a lack of institutional preparedness, poor housing, and poverty further intensify these vulnerabilities. Children, women, and the elderly appear to be the most impacted individuals, highlighting a persistent social and gender disparity regarding disaster resilience. The study also revealed that such recurrent hazards substantially damage livelihoods, resulting in economic losses of over BDT 108,500,000 (approximately USD 8700), along with triggering disease outbreaks and, in some regions, migration pressures. Despite these challenges, local communities continue to exhibit remarkable adaptability through their traditional knowledge, including livelihood diversification, mangrove plantations initiatives, and salt-tolerant crop cultivation. Better early warning systems

(19.91%), improved critical infrastructures (19.21%), more financial support from the government (11.46%), and adequate and upgraded cyclone shelters (4.75%) have become the utmost necessity among coastal communities. However, the research concludes that in coastal Bangladesh, disaster management remains primarily relief-oriented, lacking long-term and comprehensive resilience-building strategies. Policymakers should prioritize increasing community-based training, strengthening early warning systems, supporting sustainable livelihood diversification, maintaining existing cyclone shelters, and safeguarding embankments. Furthermore, institutional collaborative relationships between local communities, governmental organizations, and NGOs must be developed to ensure impartial resource allocation and effective post-disaster recovery. To promote preparedness and lessen long-term vulnerability, investments in raising public awareness, quality education, and communication infrastructure are equally crucial.

Due to budget limitations and time shortage, a relatively small sample size may not fully represent the socio-economic diversity and vulnerability of all exposed coastal districts. The cross-sectional design of the study limits its capability to assess temporal variations of hazard impacts as well as adaptation outcomes. Self-reported perceptions were utilized to collect data, which might introduce respondent bias. Additionally, Chi-square tests were not applied because several variables did not meet the required assumptions (e.g., expected cell frequencies and categorical independence) for reliable statistical inference. Nevertheless, future studies should focus on longitudinal analysis to evaluate the feasibility of long-term adaptation, the application of emerging technologies like remote sensing and GIS in hazard forecasting, and the integration of social and ecological models towards sustainable coastal management. Comparative research in various deltaic settings may also provide additional insights for transboundary climate resilience practices. Expanding youth-inclusive and gender-focused research would further improve the understanding of adaptive capacity at the community level.

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The authors declare no conflict of interest.

CRedit Statement

Most. Suria Khatun: Conceptualization, Methodology, Data curation, Software, Visualization, Formal analysis, Validation, Writing - original draft, Writing - review & editing. **Md. Anisul Kabir:** Conceptualization, Method-

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AI-Assistance Disclosure

No AI tool was used for data analysis, interpretation, or drawing of conclusions. All responsibility for the content rests with the authors.

Data Availability

Data as well as the survey questionnaire will be made available on request.

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