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An Assessment of Tropical Cyclone Frequency in the Bay of Bengal and Its Impact on Coastal Bangladesh

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Abstract: This study examines the frequency of tropical cyclones in the Bay of Bengal and their impact on Bangladesh. The extent of environmental harm led to the selection of two specific areas: the Panpatty Union and Galachipa Upzilla in the Patuakhali district, and the Sariakat Union and Swandip Upzilla in the Chittagong district. The results indicate that cyclonic storms are more common in May and November. The results also demonstrate that the studied regions are vulnerable to the effects of tropical cyclones and suffer significant consequences. The differences in influence between the two locations are statistically significant with a confidence level of 90%. The findings have significant ramifications for policymaking decisions.

Keywords: tropical cyclones; observation; Bay of Bengal; Bangladesh

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1. Introduction

The tropical monsoon zone encompasses the Bay of Bengal. The area described is a northern extension of the Indian Ocean, located between latitudes 5° N to 22° N and longitudes 80° E to 100° E (Figure 1). The eastern coasts of Sri Lanka and India form the region's western boundary. The deltaic region of the Ganges–Brahmaputra–Meghna River system surrounds the region to the north. On the eastern side, the boundary extends up to the Myanmar peninsula and the Andaman–Nicobar ridge. The southern limit of the Bay is approximately defined by the imaginary line from Dondra Head in the southern part of Sri Lanka to the northern tip of Sumatra. The bay covers around 2.172 million square kilometers and contains a total volume of about 5.616 million cubic kilometers of water. It has an average depth of 2600 m. Bangladesh is located in the northernmost part of the Bay of Bengal.

Bangladesh is a natural hazard prone country, and the country experiences a number of natural hazard events like tropical cyclones, storm surges, coastal erosion floods and drought that cause heavy losses of life and jeopardize development activities every year [1–7]. Climate change is the greatest environmental challenge facing the world today. Rising global temperatures will bring changes in weather patterns, rising sea levels, and an increase in the frequency and intensity of extreme weather events. Researchers have identified Bangladesh as one of the twenty-seven most vulnerable countries to the impact of climate change [4]. The extreme weather patterns in the coastal zone which include the variability and trend of surface air temperature, sea surface temperature, rainfall, wind speed during the monsoon season and, most importantly, tropical disturbances (tropical depressions and cyclones) have adverse impacts not only on resources, the environment and infrastructure but also on the livelihoods of coastal inhabitants.

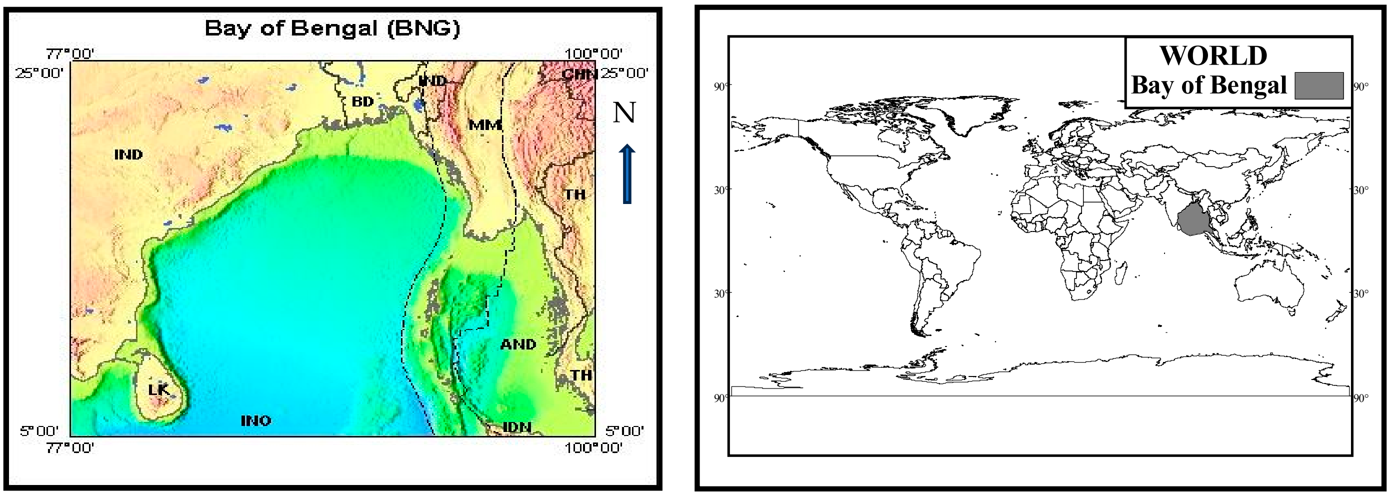

Figure 1. Location of the Bay of Bengal.

The coastal zone of Bangladesh is mainly affected by tropical cyclones and storm surges which lead to flooding and have an adverse impact on the agriculture sector and fisheries [8,9]. The situation is going from bad to worse, because of the increasing frequency of natural hazards and declining land and productivity [8]. Under the climate change situation, extreme events are likely to inundate much larger areas of the coastal zone, causing enormous loss of life, property, and a decline in the economy of coastal Bangladesh [9].

The increased frequency of more intensive tropical cyclones and shorter return periods is a significant warning for the coastal zone and the nation as a whole [10–21]. This clearly indicates that there will be more damage to agriculture, fisheries, and infrastructure. It has been found that most of the tropical cyclones have their landfall in the months of April–May and October–November [15], which are the maturing periods of Boro and Amon rice, respectively. Thus, the losses are very high and adversely impact productivity and food security [15].

Problems on the coast are many; however, with great diversity in wealth and untapped resources, the coastal zone could be a major area of economic activity. Several studies [15–19] have pointed out a number of steps and policy options for coping with change and sustaining livelihood activities using scientific, technological and institutional measures. The substantial population residing in the coastal region is highly vulnerable and has experienced significant land or property displacement, necessitating their relocation from one location to another.

The southern coastal areas have distinct geographical, physical, and economic characteristics compared to the rest of the country [22]. These regions are extremely susceptible to a range of natural hazards, including tropical cyclones, flooding caused by storm surges, coastal erosion, and the entrance of saline water. Approximately 32% of the nation's land is classified as coastal and is home to a population of around 35 million people. Patuakhali and Chittagong (Figure 2) are coastal districts characterised by a lack of significant topographical features. The area referred to is the central coastal region of Bangladesh, as depicted in Figure 2c. Tropical cyclones are the predominant natural disaster in this region, resulting in significant loss of human life and property [23].

Chowdhury [5] explained that cyclonic storms have always been a major concern for the coastal plains and offshore islands of Bangladesh. A tropical cyclone accompanied by torrential rain and a devastating tidal surge causes havoc to lives and property in the cyclone path and the environment in the affected area. The damage due to a cyclone is colossal and around a decade is needed to repair the economic, infrastructure and social damages. Some vivid examples include the tropical cyclones of 12 November 1970, 29 April 1991, 15 November 2007 and 25 May 2009 [22,23]. Detailed investigation of tropical cyclones, their vulnerability and their impacts is needed for mitigation of their disastrous impacts. From this point of view, this study will contribute to national development and formulate an effective long-term disaster management program [24–28]. The study will help to investigate the vulnerability of the coastal zone due to tropical cyclones, generate a database of coastal resources and demographic parameters, analyse the impacts on livelihoods, including population, the ecosystem, the environment and biodiversity, infrastructure, fisheries and agriculture and other elements, and recommend mitigation and adaptation strategies.

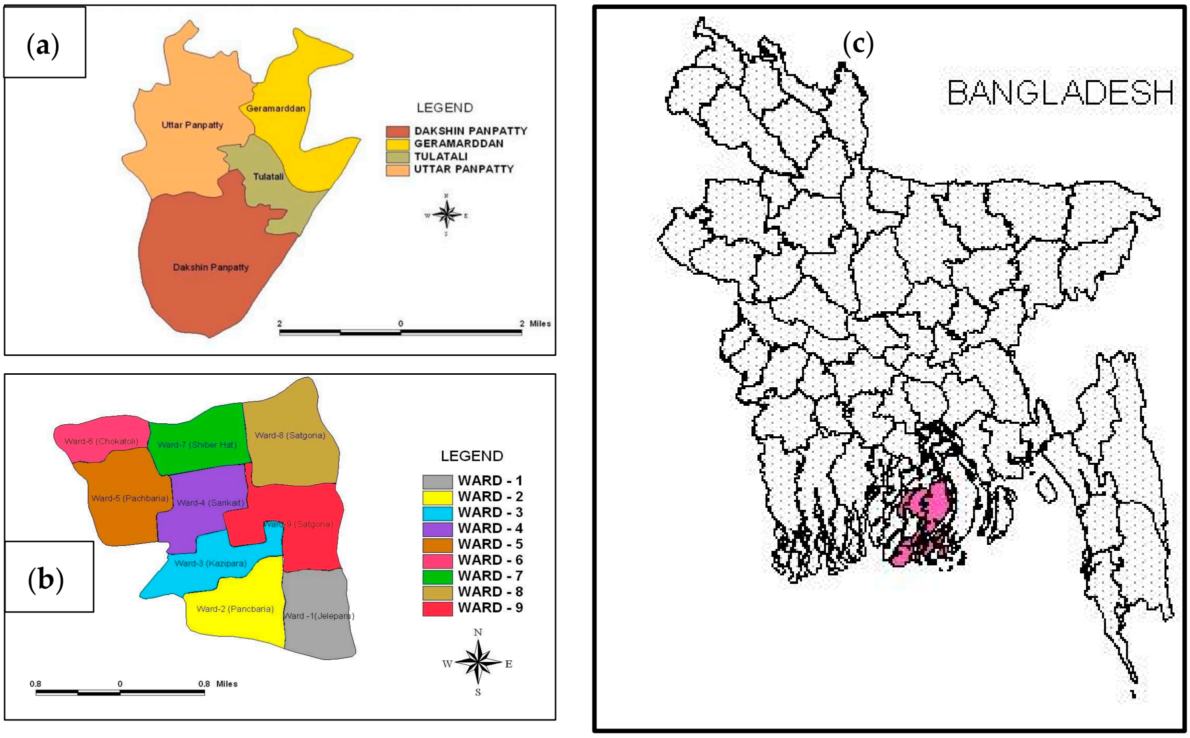

Figure 2. Study area (**a**) Panpatty Union, Galachipa Upazilla in Patuakhali District, (**b**) Saraikat Union, Sandwip Upazilla in Chittangong District and (**c**) Bangladesh.

2. Data and Methods

2.1. Data

According to the definition, tropical cyclones are warm-cored, non-frontal synoptic cyclones that form over tropical or subtropical waters. They are characterised by organised atmospheric convection and a distinct cyclonic surface wind circulation. The World Meteorological Organization's Regional Specialised Meteorological Centres rank them on one of five tropical cyclone scales based on the wind velocities located around the circulation centre. The scale employed to evaluate a specific tropical cyclone is contingent upon the basin in which it is situated. For instance, the Saffir–Simpson hurricane wind scale and the Australian tropical cyclone intensity scale are both employed in the Western Hemisphere. The maximal sustained winds of tropical cyclones are ranked on all scales based on a period from one to ten minutes. These winds are either observed, measured, or estimated using a variety of techniques [29].

The intensity of tropical cyclones is determined by the maximal sustained winds and the tropical cyclone basins in which they are situated, and they are ranked on one of five levels. Officially, meteorological agencies monitor tropical cyclones using only a limited number of classification scales. However, other scales exist, including the integrated kinetic energy index, the power dissipation index, the hurricane severity index, and the accumulated cyclone energy index. The warning centres unofficially classify tropical cyclones that form in the Northern Hemisphere according to one of three intensity scales. Tropical depressions and tropical storms are the two classifications for tropical cyclones or subtropical cyclones that are located in the North Atlantic Ocean or the north-eastern Pacific Ocean. The Saffir–Simpson hurricane wind scale will be used to classify a system if it intensifies further and becomes a hurricane. This scale is based on the estimated maximal sustained winds over a 1 min period. The ESCAP/WMO Typhoon Committee employs four distinct classifications for tropical cyclones that are within the Western Pacific basin. These classifications are determined by the estimated maximal sustained winds over a 10 min period [29].

The India Meteorological Department's scale is based on the anticipated 3 min maximum sustained winds of systems within the North Indian Ocean and employs seven distinct classifications. Tropical cyclones that form in the Southern Hemisphere are officially classified by the warning centres on one of two scales, both of which are based on a 10 min period of sustained wind speeds: Systems within the Australian or South Pacific tropical cyclone domain are classified using the Australian tropical cyclone intensity scale. Météo-France establishes the scale for the classification of systems in the South-West Indian Ocean for the purpose of use in a variety of French territories, such as French Polynesia and New Caledonia. The definition of sustained winds, as recommended by the World Meteorological Organisation (WMO) and implemented by the majority of weather agencies, is a 10 min average at a height of 10 metres (33 feet) above the sea level. Conversely, the Saffir–Simpson cyclone scale is predicated on wind speed measurements that are averaged over a one-minute period at a height of 10 metres (33 feet). The Australian scale is based on the average of maximum sustained winds and 3 s wind gusts over a 10 min interval, whereas the scale employed by the Regional Specialised Meteorological Centre (RSMC) New Delhi implements a 3 min averaging period. Direct comparisons between basins are rendered challenging by these distinctions. When the sustained winds exceed 35 kn (40 mph; 65 km/h) in all basins, tropical cyclones are assigned such names [29].

The India Meteorological Department (IMD, RSMC New Delhi) monitors all tropical cyclones that form in the North Indian Ocean between 100° E and 45° E. In this area, a tropical cyclone is described as a large-scale cyclone that does not have a front and forms over warm waters in the tropics or subtropics. It has organised thunderstorms and a clear circular pattern of surface winds that rotate in a cyclonic direction. In the North Indian Ocean, the lowest official classification for a weather system is called a depression. A depression is characterised by sustained wind speeds from 17 to 27 knots (20–31 miles per hour; 31–50 kilometres per hour) during a period of three minutes. If the depression continues to worsen, it will develop into a deep depression, characterised by winds ranging from 28 to 33 knots (32–38 miles per hour; 52–61 km per hour). In our study, we only considered one term depression and deep depression where the intensity is considered as less than 34 knots. If the system becomes stronger, it will be categorised as a cyclonic storm and given a name by the IMD only if it reaches wind speeds of 34–47 knots (39–54 mph; 63–87 km/h). Severe cyclonic storms are characterised by wind speeds ranging from 48 to 63 knots (55–72 miles per hour; 89–117 kilometres per hour), whereas very severe cyclonic storms feature winds of hurricane power, ranging from 64 to 89 knots (74–102 miles per hour; 119–165 kilometres per hour). Extremely severe cyclonic storms are characterised by winds with a velocity of 90–119 kn (104–137 mph; 167–220 km/h), which are equivalent to hurricane-force winds. In the North Indian Ocean, the most severe categorisation is a super cyclonic storm, characterised by winds with a minimum speed of 120 knots (140 mph; 220 km/h), equivalent to hurricane-force winds [29]. Here, we have considered, again, a severe cyclonic storm as the merging of a severe cyclonic storm, very severe cyclonic storm, extremely servere cyclonic storms and super cyclonic storms.

In the course of this investigation, both survey-type data and cyclone frequency data were utilised. Information on cyclone impact on coastal livelihoods was gathered using different methods, including questionnaire surveys, observations, and interviews with local authorities. Data were gathered from a number of different government agencies, such as the Comprehensive Disaster Management Programme (CDMP), the Comprehensive Disaster Management Bureau (CDMB), the Department of Environment (DoE), the Bangladesh

Bureau of Statistics (BBS), the Upazila Local Government Education Department (LGED) office, the Union office, the Space Research and Remote Sensing Organisation (SPARRSO), and the Bangladesh Meteorological Department (BMD). More specifically, the cyclone storm data (from 1924 to 2023) were obtained from BMD, Upazilla map information from LGED, information about pouplation from BBS, historical cyclone data from CDMB, BMD and SPARRSO, and questionnaires were given to experts from CDMP, CDMB, DoE, BBS, LGED, and SPARRSO, as well as to the inhabitants in those study areas.

2.2. Methods

For the purpose of gaining a better understanding of the vulnerability pattern and impact of tropical cyclones that cause catastrophic damage, we developed a questionnaire. A total of one hundred respondents were interviewed, and the findings were then averaged. The sampling method used was systematic random sampling. We also utilised a t-test to determine whether or not the difference was statistically significant. To summarise, the steps that were taken are as follows:

- The use of a systematic random sample;
- Open contacts with all of the interested parties, the content analysis, as well as the collection, extraction, and processing of long-term meteorological parameters;
- Examination of the attitude of local residents towards cyclonic impacts and adaptation and development of the probable methods for future adaptation;
- The statistics on the landfall of tropical storms that have made landfall in Bangladesh have been analysed in order to determine how vulnerable the coastal zone is. For the purpose of generating risk and vulnerability, the maps and data obtained from land use, demographic data, and data on resources have been utilised;
- Based on the questionnaire survey and in-depth analysis of the severity of severe cyclonic storms and hurricanes of super cyclone intensity, the effects on residents' ability to make a living have been analysed;
- The solutions for adaptation and mitigation have been examined through the use of a questionnaire survey, a focused group discussion (FGD), a community risk assessment (CRA), and interviews with social leaders.

3. Results

3.1. Monthly Frequency

The monthly peak occurrence rate of depression and deep depression in the Bay of Bengal ranges from 12% to 18% between June and October. The highest rate of 18% is observed in August from 1924 to 2023. In contrast, the lowest rate of depression formation in the Bay of Bengal occurs in March (Figure 3). In November, the highest frequency of cyclonic storms observed was 18.72%, whereas in October it was 15.27%. The frequency of cyclonic storms is rather high in December, accounting for 12.32%. No cyclonic storm formed in February (Figure 4). The months of May, and from October to December experienced the highest number of severe cyclonic storms, with November having the highest frequency at 25.19% and May having the second highest frequency at 23.66%. The lowest frequency of severe cyclonic storms was seen in January (Figure 5).

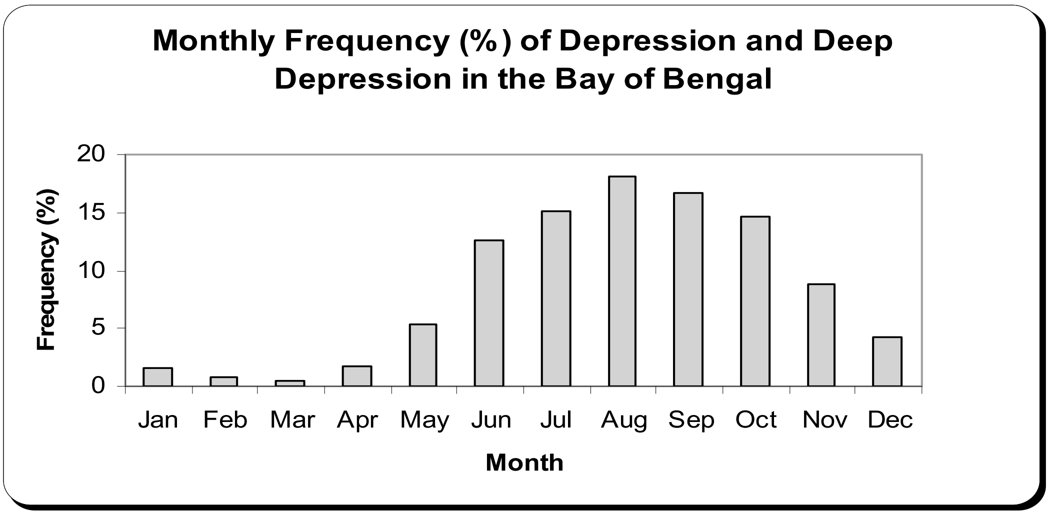

Figure 3. Monthly frequency of depression and deep depression.

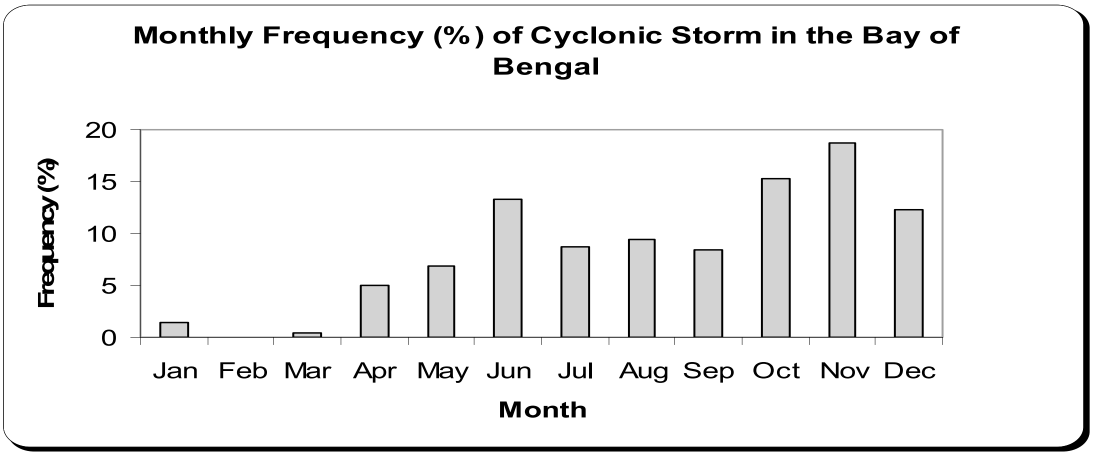

Figure 4. Monthly distribution of cyclonic storm.

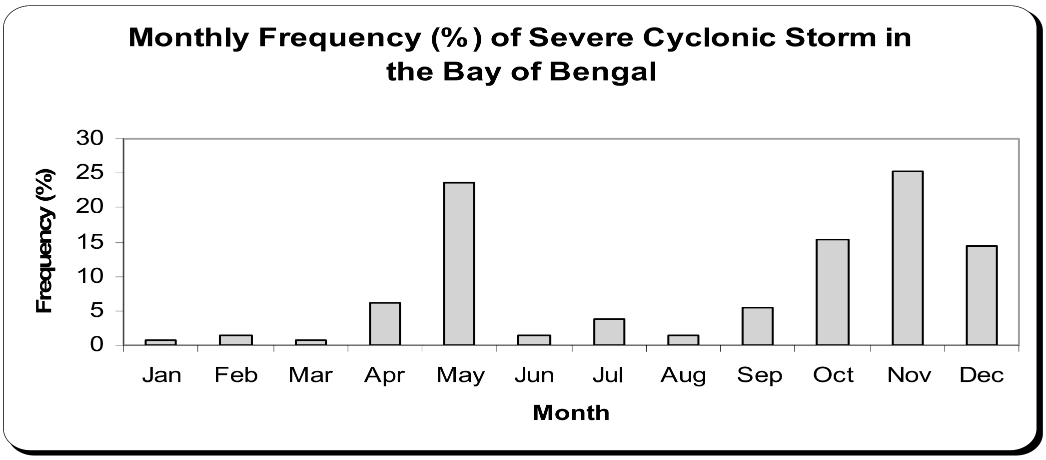

Figure 5. Monthly distribution of severe cyclonic storm (SCS).

3.2. Vulnerability Assessment

Vulnerability assessments are methodical evaluations of building elements, facilities, population groups, or components of the economy to identify characteristics that are prone to damage from the impacts of natural hazards. Vulnerability is determined by the combination of existing dangers and the specific qualities and quality of the resources or population that are exposed to those hazards. Vulnerability can be assessed for individual structures, specific sectors, or selected geographic areas, such as places with high development potential or previously built areas in hazardous zones. The findings of a vulnerability assessment can be utilised to prioritise efforts in mitigating risks and can provide valuable insights for disaster recovery, mitigation, and response planning. The relief map depicts the topography of the research area, including different elevations relative to sea level. It is evident that the southern regions consist of low-lying areas, whereas the northern regions are characterised by higher elevations in both unions (Figure 6).

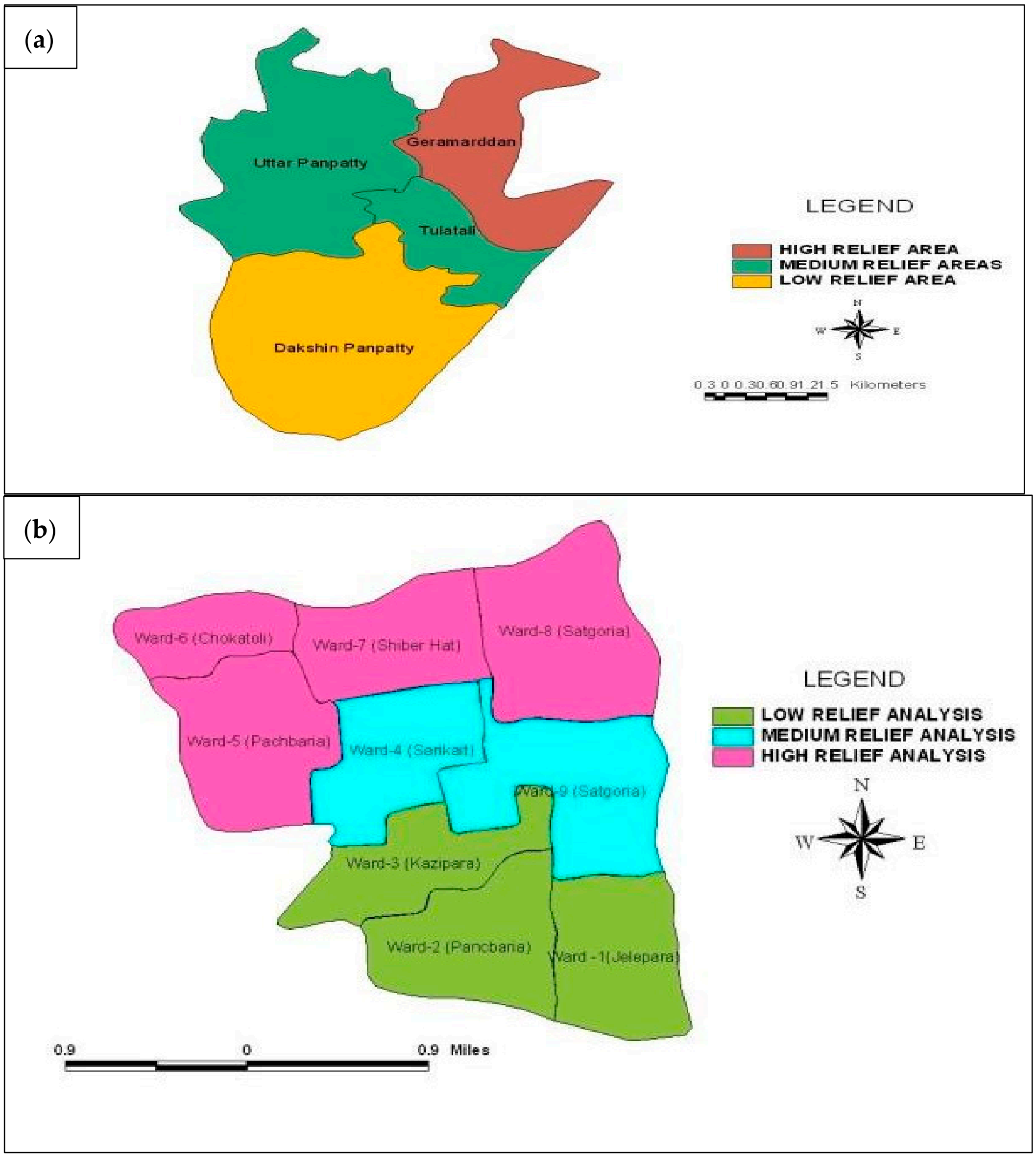

Figure 6. Relief analysis between (**a**) Panpatty and (**b**) Sariakat union.

It can be seen that the north-eastern parts of Panpatty Union are more suitable for agricultural production, whereas in Sariakat Union, it is observed that agricultural production is suitable in the central part (Figure 7). In Panpatty Union, the Geramarddan and Tulatali villages are more favourable for agricultural production compared to Uttar and Dakshin Panpaaty. Ward 3 (Kazipara), Ward 4 (Sarikait), and Ward 9 (Satgoria) are more suitable for agricultural production, whereas in low-land areas, production is less (Figure 3). In both unions, the southern parts are more appropriate for fishing (Figure 8). Dakshin Panpaaty is more favourable for fishing compared to other areas. Geramarddan shows an opposite scenario (Figure 8). The southern part, namely, Ward 1 (Jelepara), Ward 2 (Pancbaria), and Ward 3 (Kazipara) is a more appropriate zone for fishing, whereas Ward 4 (Sarikait) and Ward 9 (Satgoria) represent a moderate fishing zone. On the other hand, Ward 5 (Panchbaria), Ward 6 (Chokatali), Ward 7 (Shiber Hat), and Ward 8 (Satgoria) are less favourable for fishing (Figure 8).

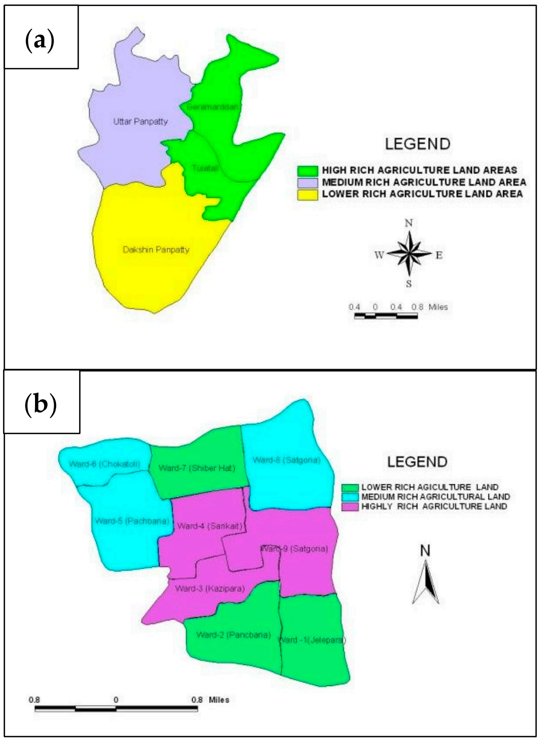

Figure 7. Agriculture land analysis between (**a**) Panpatty and (**b**) Sariakat union. There are three types of land identified—highly rich/fertile, medium rich/fertile and lower rich/fertile land.

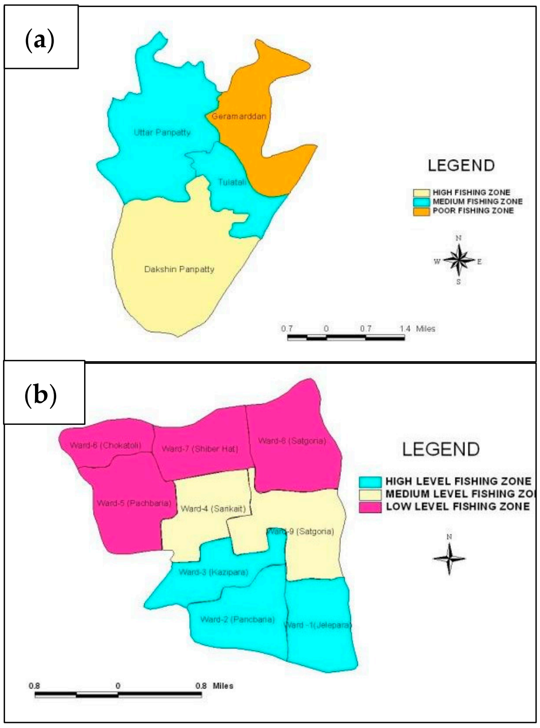

Figure 8. Fishing zone comparison between (**a**) Panpatty and (**b**) Sariakat union.

It was found that the south-western parts are more hazard prone in Panpatty Union (Table 1) whereas in Sariakat union, the south-eastern parts are more hazard prone (Figure 9). The southern part of the study area (Uttar and Dakshin Panpatty) is considered a high hazard-prone zone. Three types of hazard zones are described as follows in Sariakat Union:

Table 1. Hazard matrix in Panpatty union (1 = present; 2 = not present).

Name of Disaster Name of Village	Cyclone	Flood	Storm Surge	Riverbank Erosion	Salinity Intrusion	Heavy Rainfall
Geramarddan	1	1	1	1	1	1
Tulatali	1	1	1	1	1	1
Uttar	1	1	1	2	1	1
Dakshin	1	1	1	1	2	1

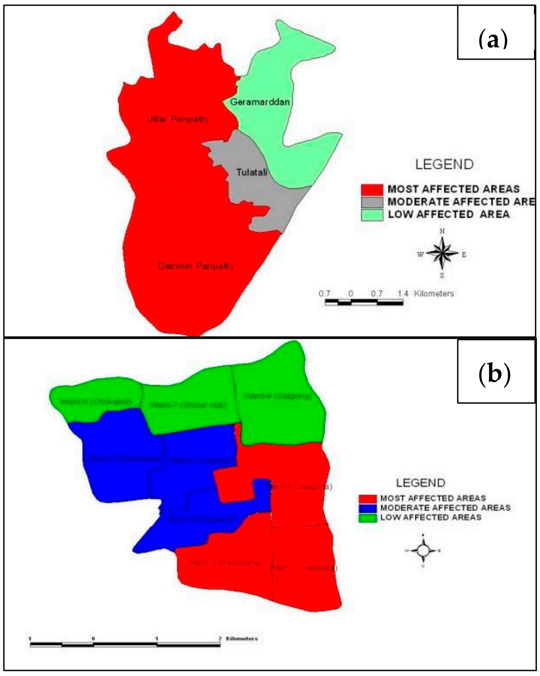

Figure 9. Hazard zone comparison between (**a**) Panpatty and (**b**) Sariakat union.

Hazard Zone—High: Ward 1 (Jelepara), Ward 2 (Pancbaria), and Ward 9 (Satgoria).

Hazard Zone—Moderate: Ward 3 (Kazipara), Ward 4 (Sarikait), and Ward 5 (Panchbaria).

Hazard Zone—Low: Ward 6 (Chokatali), Ward 7 (Shiber Hat), and Ward 8 (Satgoria).

In both Unions, it is observed that the southern part is more vulnerable compared to other parts due to cyclones (Figure 10). Dakshin Panpatty is more vulnerable to cyclones whereas Geramarddan is less vulnerable. The southern part faces more food crises compared to other parts due to cyclones in both Unions (Figure 11).

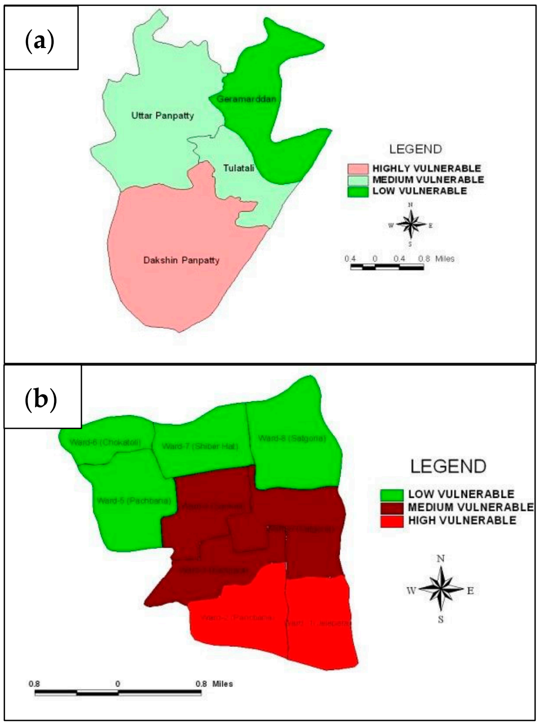

Figure 10. Cyclone vulnerability comparison between (**a**) Panpatty and (**b**) Sariakat union.

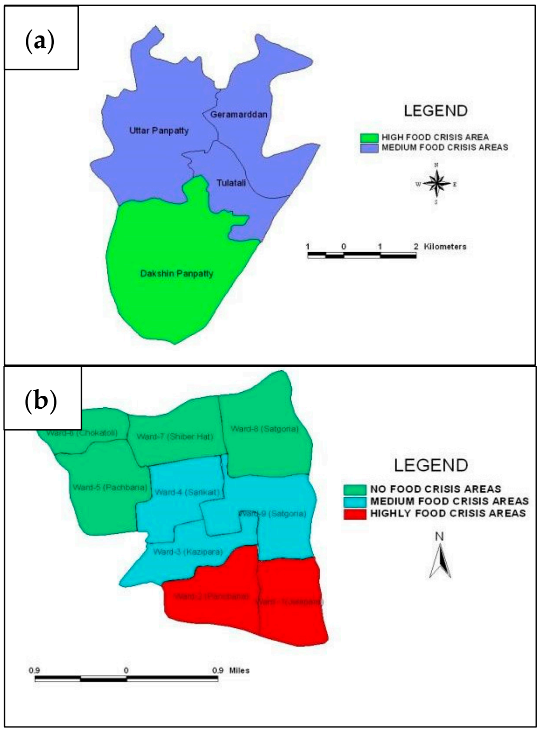

Figure 11. Food crisis comparison between (**a**) Panpatty and (**b**) Sariakat union.

3.3. Tropical Cyclone Impact on Coastal Livelihoods

The residents of this area use different materials for making houses. In Panpatty Union (Figure 12a), 65% of the houses are constructed of tin, wood and mud. A total of 20% of houses are made of rod, cement and tin and 15% are made of straw and clay (Figure 12). Most of the houses are built using tin shed (62.50%) and others are built using bricks (categorised as Pacca), bricks and tin (categorised as semi-pacca) and mud (categorised as katcha) in Saraikat Union (Figure 12b).

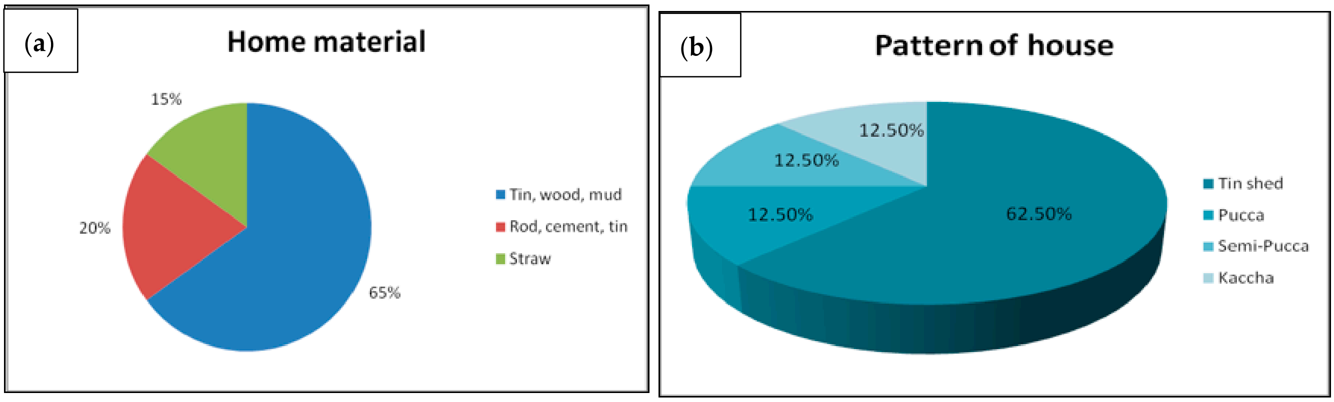

Figure 12. Home materials in Panpatty Union, Galachipa Upazilla in Patuakhali District (**a**) and Saraikat Union, Sandwip Upazilla in Chittangong District (**b**).

In Panpatty Union, we observed that 40% of houses were fully damaged whereas 10% of houses were bent (their position was displaced). Furthermore, 30% were partially damaged and 20% of houses were without a roof (Figure 13a). In Saraikat, a significant portion (40%) of the houses have suffered extensive damage and are currently covered by temporary flying sheds (due to disappearance of the roof) (Figure 13b).

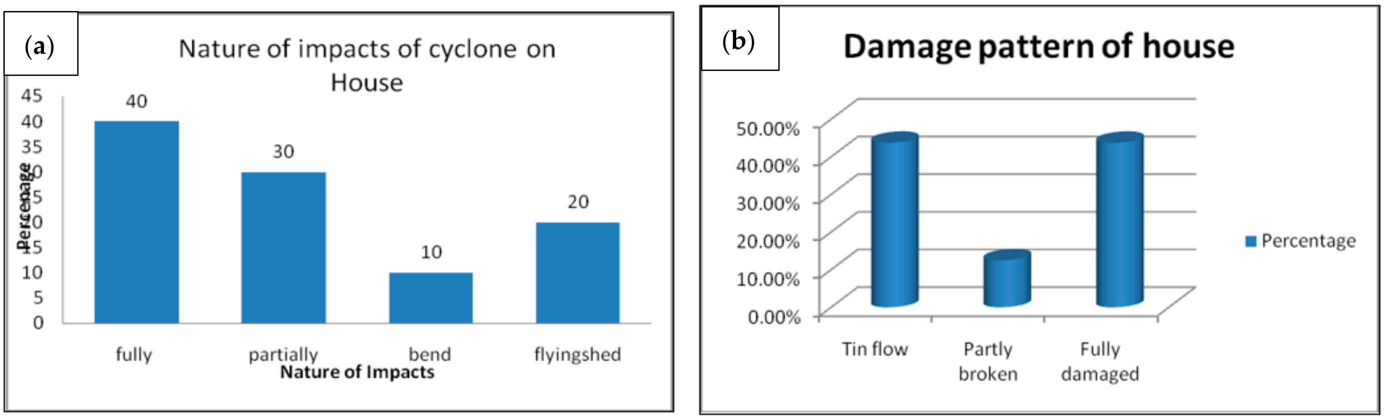

Figure 13. Nature of impacts of cyclone on house in Panpatty Union (**a**) and Saraikat Union (**b**).

In Panpatty, 60% of the agricultural productions are dropping (not stable to stand), 20% are rotating (position displaced) and 10% are both floating (moving with water) and under clay (under the mud) (Figure 14a). About 80% of agricultural production is affected by an increase in salinity and fertility loss due to cyclones (Figure 14b). Approximately 40% of fisheries are in a floating state and 30% are deceased. Another 20% of fisheries have experienced a reduction and the other 10% have been influenced by external factors (Figure 15a).

The highest frequency was observed (45%) in educational settings which were damaged by cyclones along with 25% in markets, 20% in cultural institutions and 10% in others (Figure 16a). Approximately 50% of institutions, markets, roads and bridges are partly broken due to cyclone disaster (Figure 16b). In Panpatty, we can see that due to the cyclone, 30% of people are affected by diarrhoea, 20% are affected by fever and 10% are affected by dysentery, typhoid and skin disease, respectively. The greatest impacts of cyclonic disasters are observed on plants and animals (Figure 17).

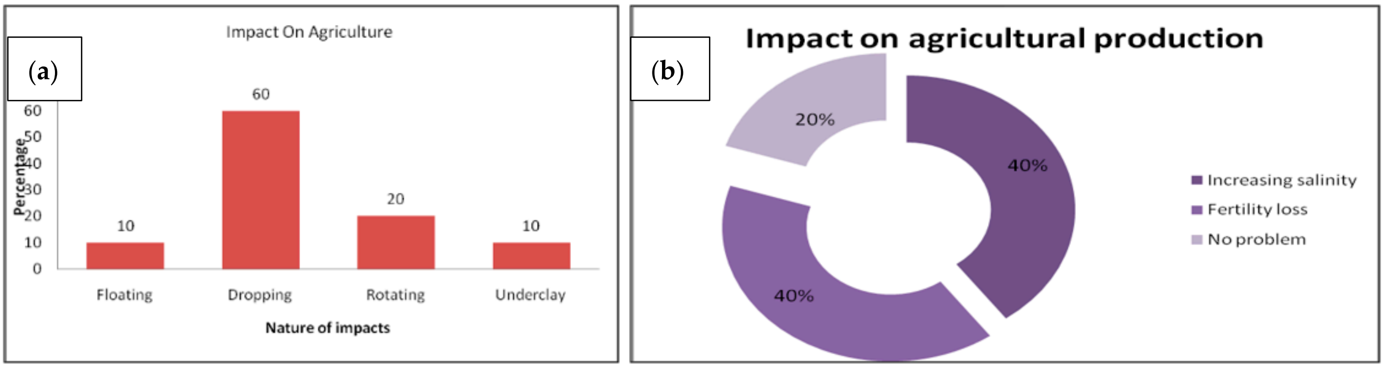

Figure 14. Impacts of cyclone on agriculture in (**a**) Panpatty Union and (**b**) Saraikat Union.

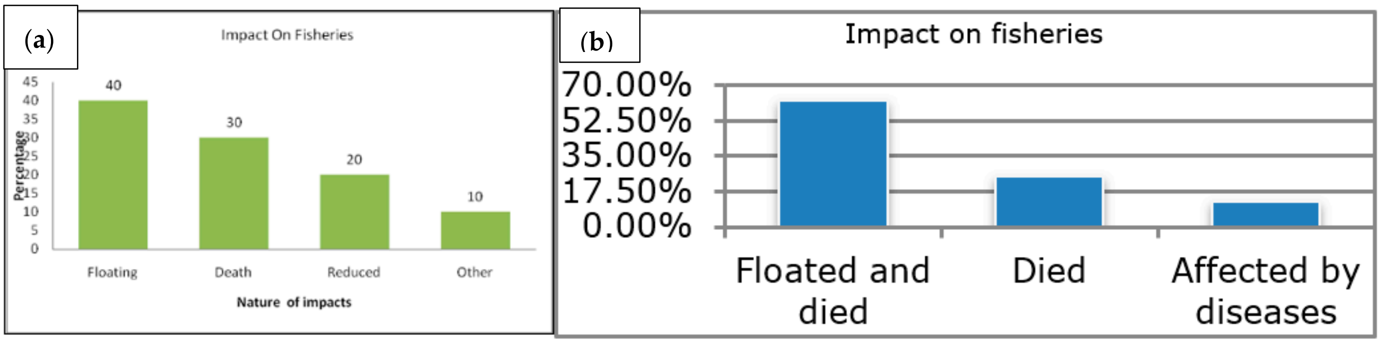

Figure 15. Impacts on fisheries in Panpatty Union (**a**) and Saraikat Union (**b**).

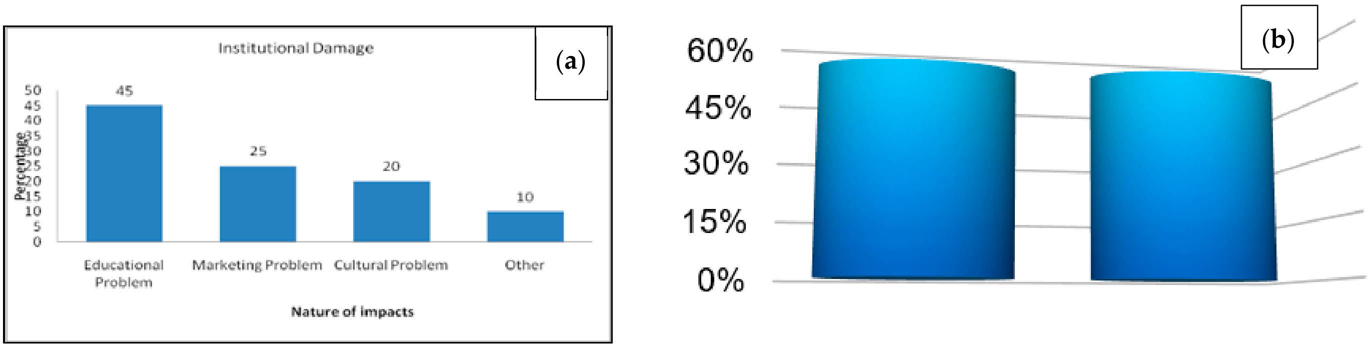

Figure 16. Institutional damage in Panpatty Union (**a**) and Saraikat Union (**b**).

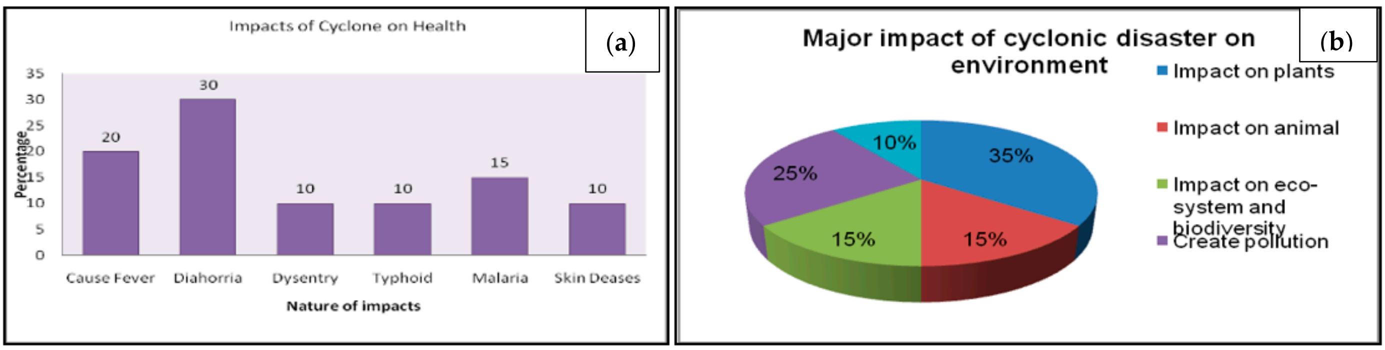

Figure 17. Impacts of cyclone on (**a**) health and (**b**) environment.

4. Physical Mechanisms

Tropical cyclone formation can occur when certain atmospheric and oceanic conditions are optimal. Gray [30] outlined environmental factors that he deemed relevant to tropical cyclone formation and these are sea surface temperature (SST), conditional instability in the lower-to-mid troposphere, absolute vorticity in the lower troposphere, mid-troposphere relative humidity, divergence in the upper troposphere, and low vertical shear of the horizontal winds between the lower and upper troposphere. Later studies (for example, Gray [31]) demonstrated the climatological aspects of the seasonal frequency of tropical cyclone formation at any location by six seasonally averaged parameters, three of which are dynamic potential and the remaining three are thermal potential. Gray [30] defined seasonal genesis as the multiplication of dynamic factors (the Coriolis parameter, low-level relative vorticity, and the inverse of tropospheric vertical wind shear) and thermal potential factors (ocean thermal energy from ocean temperatures greater than 26 degrees to a depth of 60 m, the equivalent potential temperature gradient as the difference in equivalent potential temperature between the surface and 500 hPa, and mid-tropospheric relative humidity). Gray [31] also explained the following background requirements for a possible tropical cyclone formation: (1) correct climatology (for example, region, season, SST, etc.), (2) correct synoptic flow pattern (for example, a monsoon trough, or high vorticity with small vertical wind shear, etc.) and (3) an active mesoscale convention system within a cloud cluster system. He also mentioned if these three requirements are met then there is still a doubt unless the presence or lack of concentrated wind convergence at the centre of a tropical convergence is examined. It is commonly accepted that tropical cyclones occur in wet, unstable conditions with low-level tropical disturbances like easterly waves, tropical cloud clusters and warm sea surface temperatures. Tropical cyclone creation demands a background understanding of tropical convection. Tropical cyclones can originate from various factors, including an African easterly wave, broad-scale vorticity convergence, upper tropospheric troughs, the Inter Tropical Convergence Zone, typical cold fronts, monsoon troughs, and a baroclinic–barotropic instability of the African region (Camargo et al. [32]).

Human-induced global warming, as indicated by both theoretical understanding and numerical simulations, is anticipated to heighten the intensity of tropical cyclones globally. Although recent historical data suggests a potential increase in severe tropical cyclones, various complicating factors hinder the clear detection of anthropogenic influence on tropical cyclone trends in observational records. Factors such as anthropogenic aerosol cooling, which counteracts greenhouse warming, and the presence of substantial natural climate variability pose challenges for conducting reliable trend analyses, obscuring any discernible patterns. Tropical cyclones are prevalent in Bangladesh and have the potential for devastating impacts. This research aims to address the existing gap in understanding the quantifiable effects of climate change and natural climatic variability at the regional level, building upon prior studies that have made valuable contributions [32].

The Earth's climate undergoes fluctuations and transformations for diverse reasons across extensive time periods. Significant climate variations often stem from changes in the strength and frequency of phenomena like the El Niño Southern Oscillation (ENSO), as exemplified by research such as Wahiduzzaman et al. [12] Human activities are also acknowledged as contributors to climate change, with increasing levels of greenhouse gases altering the physical responses of ocean and atmospheric variables. Natural indicators, such as coral bleaching and shifts in the distribution of plants and animals, provide additional evidence of global climate changes. Despite accounting for natural variability, a noticeable rising trend is observed in current observational records and reconstructed paleoclimate data over the past 2000 years from sources like tree rings, ice cores, and corals. The last decade has witnessed unprecedented meteorological and climatic changes, including storm surges, coastal erosion, saltwater contamination, altered precipitation patterns, increased TC frequency, intense rainfall, hotter days, more fires, and prolonged droughts, contributing to the widespread belief that climate change is already causing significant disruptions [32].

Over the twentieth century, mean surface air temperatures have risen, affecting both wet and dry seasons and daily temperature ranges. This warming aligns with the overall trend attributed to human-caused global warming since the mid-twentieth century. Infrastructures in North Indian Ocean rim countries, often situated in low-lying coastal areas, are particularly susceptible to the impacts of sea-level rise. Variations in ocean levels are influenced by factors like tides and climatic changes on Earth, emphasising the non-uniform nature of sea-level rise across space and time. Given the prominence of ENSO in causing interannual variability, it significantly affects yearly variations in sea levels [32].

5. Summary

This study investigated the vulnerability of tropical cyclones and their impact on coastal livelihoods in the Bay of Bengal coastal counties of Bangladesh. The results indicate that both Panpatty Union, Galachipa Upazilla in Patuakhali district and Sariakat Union, Sandwip Upazilla in Chittagong district are vulnerable to cyclones, with Panpatty Union, Galachipa Upazilla being more vulnerable compared to Sariakat Union, Sandwip Upazilla. The impacts of cyclones on human lives, livestock, fish, agricultural properties, and production are significant in both regions, with Panpatty Union, Galachipa Upazilla facing more severe impacts than Sariakat Union, Sandwip Upazilla. These differences in vulnerability and impact are statistically significant at a 90% confidence level. These findings are consistent with other studies by Saha et al. [25,26], Subhani et al. [27] and Al-Maruf et al. [28].

The findings recommend proactive measures by the government and relevant authorities to enhance the resilience of these coastal areas to cyclones. This includes investing in infrastructure development, early warning systems, and community-based adaptation strategies. Additionally, there is a need for comprehensive disaster management programs that focus on reducing vulnerability and building the adaptive capacity of the coastal communities.

Overall, this study contributes valuable insights into the vulnerability of coastal areas to tropical cyclones, which can inform policy decisions and actions to mitigate the impact of cyclones on livelihoods in Bangladesh. The findings underscore the importance of a holistic and integrated approach to disaster management that considers the unique challenges of coastal regions and addresses the multiple dimensions of vulnerability.

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