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Highlights:

1. Relative cyclone risk was assessed at two spatial scales in southeastern Bangladesh.
2. Conceptual structure of general risk model was brought to practice for the assessment.
3. Diverse data representing the cyclone hazard, exposure, and vulnerability was analyzed and integrated.
4. Complementary use of AHP and GIS has been valuable for projecting the cyclone risk.
5. A reasonable consistency was noticed between the simulated risk and experiential impacts.

Cyclone risk assessment of the Cox's Bazar district and Rohingya refugee camps in southeast Bangladesh

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Abstract

Bangladesh has a long history of devastating tropical cyclones. In view of the effects of the storms on the country, risk assessment is essential for devising the mitigation strategies at various levels.

By way of bringing the conceptual structure of general risk model in practice, this work aims to examine the spatial patterns of cyclone risk in the Cox's Bazar district (I) and Rohingya refugee camps (II) located on the southeastern coast of Bangladesh. We use 14 parameters representing the hazard, exposure, and vulnerability as the components of risk. The selected parameters were analyzed and integrated though the complementary use of Analytic Hierarchy Process (AHP) and Geographic Information System (GIS) for depicting the cyclone risk situation comprehensively at both the spatial scales. The status of the cyclone risk was identified and quantified as very high (6.84%, 3.43%), high (45.78%, 27.82%), moderate (5.97%, 39.42%), low (40.62%, 28.70%), and very low (0.81%, 0.61%) for the spatial scale I and II respectively. In general, northwestern and southern peripheral areas exhibited higher risk than the central and northeastern parts of the Cox's Bazar district; and in the refugee settlements, camp number 1E, 1W, 7, and 13 revealed relatively higher levels of the risk. The results of the assessment (I) were correlated with experiential damage from the 1991 cyclone; a reasonable consistency was noticed between the simulated scenario and the observed impacts. We assume that the deliverables of this spatial analysis could be useful to stakeholders while formulating the cyclone risk mitigation policies for the region. Furthermore, this work demonstrates that the applied method would deliver reliable results if tested in other coastal environments.

Keywords: Bangladesh; Cyclone risk; General risk model; AHP and GIS; Cox's Bazar; Rohingya refugees

1. Introduction

Tropical cyclones are characterized by high speed winds, extreme rainfall, and storm surge. These attributes often make them violent, resulting in colossal loss of life, widespread destruction of infrastructure, and emergence of diseases along the coastal areas of the world (Shultz et al., 2005; Hong and Möller, 2012; Krapivin et al., 2012; Mori and Takemi, 2016). Last 30–40 years have particularly seen an increase in strong cyclones around the world (Varotsos et al., 2015). The storms like Bhola (1970), Tracy (1974), Andrew (1992), BOB 06 (1999), Katrina (2005), Sidr (2007), Nargis 2008, Sandy (2012), Haiyan (2013), Hudhud (2014) Patricia (2015) and Idai (2019) are the recent examples of the tropical cyclones which caused enormous human causalities and economic loss (Willoughby and Black, 1996; Emanuel, 2005; Brunkard et al., 2008; Lin et al., 2009; Paul, 2009; Lagmay et al., 2015; Huang et al., 2017). Among the historical extreme storm events, the Bhola (1970) that killed 0.3-0.5 million people is considered as deadliest ever recorded cyclone and the hurricane Katrina that destroyed more than 200,000 homes and other infrastructure is the costliest with an economic loss of US$125 billion (Vigdor, 2008; Fritz et al., 2009; Peduzzi et al., 2012; Deryugina et al., 2014). However, the nature of risks posed and the magnitude of impacts varies considerably form one region to another (Resio and Irish, 2015). Between 1980 and 2009 cyclones affected 466 million people, resulting in death of 412,644 and injury to 290,654 with less developed nations in Asia experiencing the maximum mortality and injury (Doocy et al., 2013). On an average, a tropical storm landfall in the north Indian Ocean results in death of about 2000 persons which is much higher compared to average fatalities per landfall in any other ocean basin of the world (Seo and Bakkensen, 2016).

Bangladesh is locus of hydrometeorological hazards. The country has been facing the brunt of the tropical cyclones mainly because of its location and lowland topography (Khalil, 1992; Ali, 1996; Alam et al., 2003; Shamsuddoha and Chowdhury, 2007; Alam and Collins, 2010; Haque and Jahan, 2016). Bangladesh experiences cyclones almost each year during early summer and retreating rainy season; as a result, cyclone related deaths have been recorded as more than one million since 1877 (Paul and Dutt, 2010; Dasgupta et al., 2014). In fact, most of the world's catastrophic cyclones have been those hitting Bangladesh e.g., the episodes of 1584, 1737, 1942, 1876, 1897 and 1970. The event of 29 April 1991 is one of the deadliest in the series; the storm struck the eastern coast of the country with wind speeds exceeding 240 km/h, generating storm surge of more than 9 meters above mean sea level, killing 138,000-145,000 people and resulting in economic loss of $2.07 billion (Ministry of Health and Family Welfare, 1992; Bern et al., 1993; Khalil, 1993; Ikeda, 1995). Another cyclone in 2007 (Sidr) caused death of 3,406 people (Paul, 2009) and economic loss of $1.67 billion (Dasgupta et al., 2010). The economically deprived and marginalized populations living along the densely populated coastal areas are the most affected and compelled to remain under the continuing threat of the storms because of landlessness (UNICEF, 1993). Not only is the large number of deaths a concern, the magnitude of the economic loss from the storms is also too high for an economy like Bangladesh. The economic burden is further aggravated by the rehabilitation costs, taking substantial share of the Gross Domestic Product (GDP) after every catastrophic cyclone event in the country. Moreover, succeeding the primary effects, the cyclones have also been causing sanitation issues and disease epidemics owing to scarcity of fresh water in the storm hit areas (Hoque et al., 1993).

Although, Bangladesh is frequently effected by the tropical cyclones, the risk levels of different areas remain largely unknown. Periodic evaluation of the hazard severity, exposure and vulnerability conditions at varied spatial scales is imperative for recognizing the risk of coastal areas and alleviating the impact of future cyclones in the country. Recently, many Geographic Information System (GIS) based attempts have been made for assessing the cyclone hazard, vulnerabilities, and mitigation capacities in Bangladesh (e.g., Rana et al., 2010; Hoque et al., 2016; Hoque et al., 2017; Hossain and Paul, 2017; Quader et al., 2017; Hoque et al., 2018; Hossain et al., 2019). The investigation by Hoque et al. (2019) that performs the cyclone risk assessment of eastern coast seems most relevant to the present work because of some spatial overlap in the area of interest (Cox's Bazar district) and identical methods adopted (AHP and GIS). Even though there is variation among the choice of parameters and the interpretations thereof between the two studies, the present one provides an opportunity to make comparisons for understanding how the selection of parameters, weightage of the parameters and human bias can influence the results of multiple criteria decision making studies even with the similar objectives. Moreover, focus on the Rohingya refugees is also a uniqueness of the present analysis because the Rohingya humanitarian crisis gained global attention exclusively from the perspective of conflict and the risk posed by various natural hazards to about 1 million people as a result of 2017 exodus remains absolutely unspecified.

Risk assessment has been recognized as a priority action for building the resilience of the communities and preventing the disasters (Sendai Framework, 2015). By combining the possible role of a hazard, exposure, and vulnerability, the risk assessment illustrates how a system is expected to be affected in future. Therefore, pre-event assessment is an opportunity to comprehend the status of risk in a particular area, initiate mitigation measures and reduce the anticipated losses. As a component of risk, hazard implies the nature, intensity, location, and frequency of a process (natural hazard); whereas exposure is spatial in context and describes the people and assets at a particular location with likelihood of being effected by the prevailing hazards (UNDP, 2010). Vulnerability on the other hand considers the physical, social, economic, political, and environmental characteristics of a community or a system as the fundamental features for the risk assessment (Martine and Guzman, 2002; Turner et al., 2003; Adger 2006; Dwyer, 2004; Douglas, 2007). Vulnerability is vital for understanding the conditions that enables a hazard to become a disaster (Tapsell et al., 2010). Although vulnerability may seem to be an intuitively simple notion, it is complex to define and even more difficult to quantify and apply in practice (UNEP, 2002). Comprehensive vulnerability analysis considers the totality of the system; however, real world constrictions necessitate a 'reduced' vulnerability assessment (Turner et al., 2003).

Geographic Information System (GIS) coupled with different statistical techniques provides an effective decision support environment for the multiple criteria based assessment of risks related to various natural hazards (e.g., Zerger and Smith, 2003; Gillespie et al., 2007; Rana et al., 2010; Alam et al., 2018; Bhat et al., 2018) including cyclones (Taramelli et al., 2008; Klemas, 2009; Ozcelik et al., 2012; Mahapatra et al., 2015, Hoque et al., 2018; Mansour, 2019; Nguyen et al., 2019). With a robust spatial data management structure, GIS exhibits exceptional capabilities to analyze and integrate varied datasets in a flexible manner for assessing and integrating the different elements of the risk. Moreover, the complexities associated with the variation in spatial scales, resolutions, and the subjectivity concerns of the qualitative data are resolved efficiently.

In this study, we attempt to assess the relative cyclone risk of the Cox's Bazar district (Spatial Scale-I) and the Rohingya refugee camps (Spatial Scale-II) for understanding how or to what extent any part or spatial unit of the selected sites might be harmed by the future tropical cyclones? The assessment has been performed though a sequence of steps that include: selection of parameters that may contribute to the risk, development of corresponding GIS layers, prioritization and ranking of the parameters using Analytic Hierarchy Process (AHP), integration of the GIS layers for weighted overlay analysis, development of risk scenarios and correlation of the simulated risk with experiential effects.

2. Materials and methods

Risk is typically a function of hazard, exposure, and vulnerability (Blaikie et al., 1994; Crichton, 1999; Kron, 2002; Tomlinson et al., 2011; Cavan and Kingston, 2012; Oven et al, 2012; Espada et al., 2015; Murnane et al., 2016; Hagenlocher et al., 2018; GAR, 2019). So, the risk assessment studies need to understand how the components of risk i.e., hazard, exposure and vulnerability interact or overlap with each other (UNDP, 2010). In order to put the connection and the effects of intersection between the components into perspective, risk is classically expressed as Eq.1. And risk assessment is thus described as "a qualitative or quantitative approach to determine the nature and extent of disaster risk by analyzing potential *hazards* and evaluating existing conditions of *exposure* and *vulnerability* that together could harm people, property, services, livelihoods and the environment on which they depend" (UNISDR, 2017).

$$\text{Risk} = \text{Hazard (H)} \times \text{Exposure (E)} \times \text{Vulnerability (V)} \quad (1)$$

In light of the conceptual expression of the risk (Eq.1) and explanation for the risk assessment provided by the UNISDR (2017), this study evaluates and combines all the parameters representing the cyclone hazard, exposure, and vulnerability to obtain the cyclone risk scenario of the pilot sites.

2.1 Study area

Cox's Bazar is a southeastern coastal district in Chittagong division of Bangladesh (Fig.1). The district has eight administrative units (*Upazilas)* i.e., Chakaria, Cox's Bazar–S, Kutubdia, Pekua, Moheshkhali, Ramu, Ukhia, and Teknaf spread over an area of ~2200 km² (in this study). The

Cox's Bazar district (CBD) shares some part of the border with Rakhine state of Myanmar from the southeast and from the west the district is encompassed by the mighty Bay of Bengal (India Ocean). As per 2011 census the total population of the district is 2,289,990, with a density of 920 persons per km². In addition to the native population, there are 209,847 Rohingya refugee families with a population of 909,774 (UNHCR, 2019) temporarily settled in the district since 2017. The refugees are living in makeshift bamboo and tarpaulin shelters spread over the multiple clusters in the Ukhia and Teknaf Upazilas of the CBD (Fig.1b). The refugee shelters are so fragile that they cannot withstand a weakest cyclone storm and given the demographic construction (Fig. S1), the community seems to be extremely vulnerable. The gravity of the problem is further aggravated by the physical environment they are settled in, where the possibility of various natural hazards such as cyclones, floods, and landslides is very high (e.g., Ahmed et al., 2018).

2.2 Analytic Hierarchy Process (AHP) and Geographic Information System (GIS)

Each extreme event creates a unique damage and loss scenario, determined by various factors such as hazard severity, physical environment, social construction, capacity elements and many other real-time conditions. All these factors are dynamic in nature; consequently, predicting the role of contributing factors and forecasting the expected loss precisely is a complex task. However, multiple criteria decision making (MCDM) may provide an ideal and flexible environment to speculate the role of various contributing factors for simulating the disaster risk. Number of methods with respective merits and demerits are available for such decision making processes e.g., Multiplicative Exponential Weighting, Simple Additive Weighting, and Analytic Hierarchy Process (Zanakis et al., 1998; Özcan et al., 2011). Proposed by Saaty (2008), the Analytic Hierarchy process (AHP) is considered as one of the efficient MCDM procedures in operation (Whitaker, 2007). The harmonizing use of the AHP and Geographic Information System (GIS) has emerged as a formal methodology to support environmental decision making (Huang et al., 2011). Moreover, the combined used of AHP and GIS has been specifically recommended for the cyclone risk assessment (Hoque et al., 2017).

Considering the wide usage and the endorsements, we relied on the AHP and GIS as a decision support system for the cyclone risk assessment of the selected sites (I and II). The AHP primarily aims to derive ratio scales, starting with the selection and comparison of the criterions for deciding their relative importance (for details see Saaty, 2008). We selected 14 relevant criterions that determine the cyclone risk scenario of a particular location. A matrix was developed for the pairwise comparison of the selected parameters on a scale ranging from 1 to 9, where 1 represents 'equal importance' and 9 'extreme importance' (Table S1 and S2). The comparative weights of the selected parameters were determined on the basis of expert opinion—local knowledge of the authors, and past experiences as documented in the peer reviewed literature (e.g., Emanuel, 2005; Lin et al., 2009; Paul, 2009; Peduzzi et al., 2009; Dasgupta et al., 2014; CRED, 2016; Huang et al., 2017; Xiao et al., 2017). Since the decisions made about the priorities of the criterions may not be perfect, the AHP requires a consistency check of the pairwise comparison matrix, which was done by calculating the consistency ratio (CR), Eq. 2:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

where CI is the consistency index (CI), calculated using Eq. 3:

$$\mathrm{CI} = \frac{(\lambda_{\max} - \mathrm{n})}{\mathrm{n} - 1} \tag{3}$$

where $\lambda_{\max}$ is the highest eigenvalue of the matrix and *n* represents the size of the matrix; RI is the random index representing the consistency of a randomly generated pairwise comparison matrix (Stefanidis and Stathis, 2013). The matrix is considered as consistent if the CR≤10%

(Roszkowska, 2013). The consistency ratio of the pairwise comparison matrix developed in this analysis (Table S2) was calculated as 8.7%. The relative importance of each criterion derived through AHP (Table 3) was subsequently assigned to the corresponding GIS layers. The ranking of the alternative classes within each criterion was done according to the scheme presented in Table S3. The study involved the conversion of all the data layers into raster format, with consistent projection (WGS 1984, UTM Zone 46) and cell size (30mx30m) for weighted overlay analysis in ArcMap10.2 software. Finally, the cyclone risk was projected by spatially categorizing the study sites (I and II) into different zones with varying risk potential i.e., very high, high, moderate, low and very low. The complete outline of the methodology adopted in this study is illustrated in Fig. S2.

2.3 Data sets

In context of the cyclones, wind speed, surge height and frequency are the three main attributes representing the hazard (e.g., Khalil, 1992; Terry, 2007; Paul, 2009; Peduzzi, 2012; Dasgupta et al., 2014; Zachry et al., 2015; Mori and Takemi, 2016; Hoque et al., 2018; Klotzbach et al., 2018). Whereas, proximity to coast, elevation, amount of rainfall, type of land cover, and population and assets in a particular area are some of the most relevant parameters of the exposure as demonstrated by various studies (e.g., Shultz et al., 2005; Wu et al., 2007; Díaz et al., 2008; Konrad and Perry, 2010; Doocy, et al., 2013; IPCC, 2013; Woodruff et al., 2013; Hoque et al., 2016; Mansour, 2019). And factors such as population density, size of female population, percentage of population with disability, literacy rate and number of cyclone shelters and healthcare facilities available may be considered as few of the important indicators of the vulnerability to cyclones (e.g., Bern et al., 1993; Chowdhury et al., 1993; Cutter et al., 2003; Cutter and Finch, 2008; Tapsell et al., 2010;

Flanagan et al., 2011; Bethel et al., 2011; Mahmood et al., 2014; Ronoh, et al., 2015; Tenerelli el al., 2015; Alam et al., 2018; Ahmad and Kelman, 2018; Faruk et al., 2018; Fussell et al., 2018). The following section provides the risk connotations of all the criterions (Table 1) used in the present work:

2.3.1 Cyclone intensity

Maximum sustained wind speed defines the intensity of a cyclone (Paul, 2009; Peduzzi, 2012; Dasgupta et al., 2014; Zachry et al., 2015; Mori and Takemi, 2016). This analysis used National Oceanic and Atmospheric Administration (NOAA) storm data to understand the historical pattern of the cyclone intensity in the CBD. Storm records spanning over a period of more than 110 years (1904-2016) from the NOAA archive were filtered to retrieve the cyclones with track over the Cox's Bazar district (Fig. 2 and Table 2). The data reveals that 22 cyclones have hit the district during this period and the storm that remained active from 26 April to 03 May 1994 has been highest intensity cyclone directly experienced in the district with track over Teknaf Upazila of the CBD (Fig. 3). This storm (1994) actually, attained category-4 intensity; however, it struck the CBD as category-3. Another category-2 cyclone (18 - 25 November, 1995) had track over the Ukhia Upazila, followed by a category-1 storm (AKASH, 12 – 15 May, 2007) with track over the Cox's Bazar-S and Chakaria Upazilas. All the remaining storms with tracks over the Ramu, Moheshkhali, Kutubdia, and Pekua Upazilas have been low intensity events (TS and TD). There is not much information available about the affects; the obvious reasons for that seems to be the generally low intensity of these storms except few (e.g., that of 1994, 1995, 2007).

2.3.2 Cyclone frequency

Frequency is described as the number of tropical cyclones in a given period or it may be illustrated as the return period of a storm of specific intensity. Our analysis reveals that on an average the

Cox's Bazar district is directly hit by a cyclone storm of varying intensities after every 5 years. There is a noticeable temporal pattern in the frequency of the events during the period from 1904-2016; most of the cyclones have occurred in the months of May and November (Fig. S3). The frequency of direct cyclone strikes has been relative very high in Ukhia, followed by Cox's Bazar-S and Chakaria (Fig. 3). The cyclone frequency was noticed minimum in Kutubdia; however, the small number of the cyclone track over the Kutubdia Upazila can be attributed to its smallest size as well. In general cyclone activity— both intensity and frequency has been maximum on the central segment (Ukhia and northern part of Teknaf) of the Cox's bazar district.

2.3.3 Storm surge

Storm surge is a phenomenon of rising water height of the waves because of high speed winds and low pressure associated with the cyclones resulting in coastal floods. Previous experiences reveal that most of cyclone related deaths in Bangladesh were due to surges associated with the storms (Khalil, 1992; Zachry et al., 2015; Seo and Bakkensen, 2016). UNICEF (1993) cyclone evaluation team during their post cyclone (1991) survey observed that almost all deaths have been as a result of drowning from the tidal wave that accompanied the cyclone. With continuous sea level rise in the wake of climate change, the cyclone storm surges are likely to enter deep into land and effect populated areas (Paul, 2009; Dasgupta et al., 2010; Peduzzi, 2012). In general, the frequency of 7m and 10m surge is 5 years and 20 years respectively during high tide along the coast of Bangladesh (Dasgupta et al., 2014). The surge height of the 1991 cyclone has also been reported more than 9m (Khalil, 1993). We use the projected storm surge height and observed surge height during 1991 cyclone as a reference to identify the areas of Cox's Bazar district that are likely to get effected by a surge of this height (10m). The scenario has been developed using Advanced

Land Observing Satellite (ALOS) Digital Surface Model (DSM) (Fig. 3), which reveals that substantial areas of Kutubdia (~95%), Pekua (~95%); Moheshkhali (~55%), Cox's Bazar (~50%), Chakaria (~45%) and Teknaf (~45%) are expected to get effected by the 10m high storm surge. The remaining Upazilas (Ukhia and Ramu) would be impacted less with the surge of such size. Owing to the low resolution of the DSM, the variability in the storm water depth could not be established in this analysis.

2.3.4 Rainfall

Many studies suggest positive correlation between the amount of rainfall and cyclone frequency i.e., the total amount of rainfall has been observed to be more in areas where the frequency of cyclones is high (e.g., Wu et al., 2007; Díaz et al., 2008; Cerveny and Newman, 2010; Konrad and Perry, 2010). In general, rainfall in Cox's Bazar district exhibits a specific spatial pattern; the average annual rainfall decreases from 3001-3500mm in south to 2400-2800mm in north with Teknaf, Ukhia, southern parts of Ramu and Cox's Bazar-S receiving the maximum, followed by Moheshkhali and southern part of Chakaria receiving 2801-3000mm. Kutubdia, Pekua, and northern Chakaria receive comparatively minimum rainfall of 2400-2800mm (Fig. 3).

2.3.5 Proximity to coast

The coastal areas of the CBD are at the forefront to face the force of high speed winds and storm surges associated with the cyclones originating from the Bay of Bengal. This in general includes the coastline on the western side of the district with an aerial length of ~155 km. All the Upazilas share some extent of the coastline. We developed multiple spatial zones (Fig. 3) on the basis of distance from the coastline with different intervals (5, 10, 15,….40 km). The zonation implies that closer the area to the coastline more is the probability being effected and vice versa.

2.3.6 Elevation

Elevation is important feature of the exposure that explains propensity of a location to suffer damage especially from the storm surge (IPCC, 2013; Doocy, et al., 2013; Woodruff et al., 2013; Mahapatra et al., 2015). However, not all low-lying areas are subject to the effect of storm surge; this is specifically the case with such areas nearer to the coast. We divided the area of interest into various elevation zones using the ALOS DSM (Fig. 3). The northwestern areas especially Kutubdia, Pekua and western parts of Moheshkhali, Chakaria, and Cox's Bazar-S are the most low-lying. In addition, scattered linear segments along the coast of Teknaf Upazila are also low elevation areas (Fig. 3). The Ukhia and Ramu Upazilas are mostly highlands and are bordered by an elevated coastline.

2.3.7 Land cover

Another input parameter to assess the exposure of the CBD in this analysis has been land cover (e.g., Shultz et al., 2005; Hoque et al., 2016; Hoque et al., 2018). We make a decision on the exposure of any land cover category on the basis of its sensitivity to the effects of a cyclone. Maximum likelihood classifier (MLC) was used to identify various land cover categories from the Landsat-8 Operational Land Imager (OLI) scene (date of acquisition: 2019/02/01). Three broad land cover classes i.e., water, vegetation, and bare soil and built-up (BB) were identified in the area of interest (for details see Table S4). The BB class has been stated as the most sensitive, because the land cover hosts most of the population, settlements, and commercial activities, thus the likelihood of cyclone impacts are relatively higher than the other categories. Given the probability of impact vegetation was considered as second sensitive land cover class as the chances of human casualties are minimum compared to BB, followed by water as least sensitive category in the prioritization. Kutubdia, Pekua, Chakaria, and Cox's Bazar-S share maximum concentration of BB class (Fig. 3). Moreover, some scattered patches in Ukhia and Teknaf including Rohingya refugee camps are also part of the BB landcover.

2. 3.8 Population size

Among myriad factors contributing to the vulnerability of a community, demographic composition is one of the fundamental factors. The characteristics like population size and population density are important for the vulnerability assessment (Ikeda, 1995; UNEP, 2002; Cutter and Finch, 2008; Flanagan et al., 2011; Peduzzi, 2012; Tenerelli el al., 2015; Chakraborty and Joshi, 2016; Fussell et al., 2018). A rapidly increasing population has led to landlessness in Bangladesh, which in turn forced the people to settle in available areas with high risk of severe cyclonic storms (UNICEF, 1993). According to 2011 census Chakaria hosts largest size of the population (0.47 million) followed by Cox's Bazar-S with 0.45 million. The size of the population is smallest (0.12 million) in the Kutubdia Upazila of the CBD (Fig. 3).

2. 3.9 Population density

The population density has long been viewed as one of the main contributing factors to the vulnerability of communities both in developed and underdeveloped nations (Alam et al, 2018). Larger death toll caused by extreme events in Asia is mainly ascribed to the high population density (UNEP, 2002). In the CBD, Cox's Bazar-S is having a relative very high population density of 2011 persons per km², followed by Pekua with 1229 persons per Km². The population density is lowest (581 persons per Km²) in the Kutubdia Upazila (Fig. 3).

2. 3.10 Female population size

Women and children are 14 times more likely to die than men in a disaster (Habtezion, 2013), especially in the economically deprived communities. Women may also have mobility constraints and less physical flexibility under certain circumstances (Cutter et al., 2003). In the devastating cyclone of April 1991 that resulted in death of ~145 thousand people in Bangladesh, most who lost life were women (Ikeda, 1995). Similar is the example of 2004 Asian Tsunami in which women accounted for over 70 percent of the causalities (Habtezion, 2013). The demographic data of the CBD reveals that the Chakaria Upazila has the largest size of the female population (0.23 million) and Kutubdia lowest (0.06 million).

2. 3.11 Population with disability

Persons with disabilities are potentially vulnerable (Bethel et al., 2011; Ronoh et al., 2015). In this analysis we use data on disability related to speech, vision, hearing, mental health, autistic behavior and physical flexibility as one of the dimensions of the vulnerability. Any of these defects can cause impediments to understand an emergency situation, avoiding a harmful situation, and getting access to the resources. Kutubdia is having highest percentage of disabled population (2%), and least is that of Cox's Bazar-S (Fig. 3).

2. 3.12 Literacy

Literacy or level of education can play an important role in responding to an emergency situation that in turn would determine the degree of impacts (Cutter et al, 2003, Flanagan et al., 2011). People in Bangladesh often do not vacate the area to avoid a life threatening situation from the cyclones owing to fear of theft and willingness to protect their household belongings (Ahmad and Kelman, 2018). Moreover, sometimes people face difficulties in understanding the message of warning propagated by government agencies. During the post cyclone (1991) evaluation, 16% of the respondents revealed that even if they got cyclone warning at least four hours before, they did not respond to it because of not understanding the meaning of the warning (UNICEF, 1993). This behavior or situation may be attributed to illiteracy or low level of education. Average literacy rate of the Cox's Bazar district is very low (37.1%), with maximum of 49.2% and 47.6% in Cox's Bazar-S and Chakaria respectively and minimum of 26.7% in Teknaf.

2. 3.13 Cyclone shelters

There are about 2500 cyclone shelters along the coast of Bangladesh constructed as a safety facility for the coastal population following the deadliest cyclone of 1970 (Faruk et al., 2018). These shelters have proved to be an effective mitigation strategy against the high speed winds, extreme rainfall and storm surges; however, the distribution of these shelters is not uniform and about nine percent of these facilities are not usable (Mahmood et al., 2014). As of 2011 there are 443 cyclone shelters in the Cox's Bazar district with maximum number in Chakaria (130) and least in Pekua and Ramu with 13 in each (Fig. 3).

2. 3.14 Healthcare Facilities

Healthcare facilities are important especially for managing the aftermath of extreme events. World Health organization (WHO) in their health situation and trend assessment report stated that Bangladesh is having less than 11 beds per 10 thousand people compared to world average 30 between 2005-2012; and density of doctors, nurses and midwives is 6 compared to critical threshold of 23 per 10,000 (www.searo.who.int). For understanding the status of healthcare facilities in the district we use the number of beds and staff (doctors, nurses, and technicians available in the government and private hospitals) as a gauge. The assessment was made on the basis of the ratio between the healthcare facilities and the population (000) in each Upazila of the district (Fig. 3). The availability of the healthcare services was found to be relatively better in Cox's Bazar-S (1:0.6) and minimum in Moheshkhali (1:5).

3 Results and discussion

3.1 Hazard, exposure and vulnerability

This analysis developed respective scenarios of hazard, exposure and vulnerability. The spatial scenario of the cyclone hazard was projected by superimposing the data layers of the intensity, storm surge, frequency and rainfall. In general, the status of the hazard was quantified as 30.76%, 8.93%, 16.37%, 15.03%, and 28.88% falling in very high, high, moderate, low and very low hazard categories respectively (Fig. S4 and S5). Maximum parts of the Cox's Bazar-S, Chakaria, coastal Teknaf and central Ukhia Upazilas reveal very high levels of the cyclone hazard. The areas including central Ramu, southern Pekua and some parts in northern Chakaria exhibit high hazard ranks. Kutubdia, northern Pekua, and coastal areas of Moheshkhali fall in moderate hazard zone. The hazard levels are low in the elevated western and eastern segments of Ukhia and central N-S stretch of Teknaf, and very low in northeastern Chakaria, eastern and western parts of Ramu and central Moheshkhali (Fig. S4 and S5).

The spatial pattern of the exposure has been developed by overlaying the GIS layers of proximity to coast, elevation, land cover, and population size. Overall scenario of the exposure to cyclone has been observed as 5.85%, 24.79%, 28.80%, 32.20% and 8.33% under very high, high, moderate, low and very low categories respectively (Fig. S4 and S5). Western Moheshkhali and western Cox's Bazar-S reveal very high exposure levels, followed by western Chakaria and scattered parts in Moheshkhali, eastern Cox's Bazar-S, central Ramu, central Ukhia and southern

Teknaf with high exposure levels. Kutubdia and Pekua are largely in moderate exposure category; whereas, the remaining parts of the district are either low or very low exposure zones.

The outline of the vulnerability derived here is a function of the parameters that include population density, size of the female population, percentage of population with disabilities, levels of literacy, and availability of the cyclone shelters and healthcare facilities in each Upazila of the Cox's Bazar district. Vulnerability has also been found expressing substantial variations in relation to the Upazila boundaries. Overall the spatial distribution pattern of the vulnerability is 15.45%, 38.74%, 42.75%, 3.18% under very high, high, moderate, and low classes correspondingly (Fig. S4 and S5). Vulnerability has been observed very high in Cox's Bazar-S and Pekua; and high in Moheshkhali, Ukhia and Teknaf. The Upazilas including Chakaria and Ramu fall in moderate vulnerability class, whereas the Kutubdia is relatively a low vulnerability Upazila The criterions like population density, size of the total population, and size of the female population have played major role in shaping the overall vulnerability status of the Upazilas in this study.

3.2 Risk simulation of the Cox's Bazar district (Spatial Scale-I)

With the weighted overlay analysis of all the parameters representing hazard, exposure, and vulnerability, we simulated the cyclone risk in the Cox's Bazar district. This analysis reveals that on the whole 6.84%, 45.78%, 5.97%, 40.62%, and 0.81% of the area is at very high, high, moderate, low and very low cyclone risk correspondingly (Fig. 4 and Fig. S6). The influence of few parameters such as intensity and frequency of the storms, inundation from the surge, population density, and availability of the cyclone shelters has been dominant in determining the overall risk of a particular location.

Most of the very high risk area is contributed by Cox's Bazar-S (70.91%), followed by Teknaf with 28.96%. Remaining Upazilas share negligible percentage of the very high risk area in the CBD. As far as high risk areas are concerned, the Chakaria Upazila tops the list with 32.13%. The scenario of the high risk category in other Upazilas is 18.85% (Moheshkhali), 12.47% (Pekua), 11.47% (Teknaf), 11.42% (Ramu), 8.62% (Ukhia) and 5.01% (Cox's Bazar-S). The moderate risk class is dominant in the Kutubdia with a share of 51.28%, followed by the Cox's Bazar-S and Teknaf Upazilas contributing 23.49% and 12.09% respectively. Moheshkhali and Ukhia contribute almost equally to the moderate risk class (5.88% and 5.89%) and rest of the Upazilas (Pekua and Ramu) with less than 1%. Another risk category identified in this analysis is the low cyclone risk zone; Ramu with 29.66% shares the maximum part of this risk category and the scenario in other Upazilas of the district is 24.49% (Chakaria), 19.3% (Ukhia), 15.1% (Teknaf), 8.46% (Moheshkhali), and 2.65% (Cox's Bazar-S). The last category of this classification is very low risk zone; Ramu contributes 55.79% of the total area under this class; whereas, Chakaria and Moheshkhali are next with 28.95% and 14.62% respectively (Fig. 4). Other Upazilas of the district that include Kutubdia, Pekua, Cox's Bazar-S, Ukhia and Teknaf are not contributing to the very low risk zone.

It is important to note that the fundamental principle behind the depiction of the risk scenario in this study is based on the spatial overlap of the causative factors i.e., higher the spatial intersection of the positively correlated contributing factors, higher would be the level of cyclone risk. In general, the overlap of the factors that drive the risk was relatively high in the northwestern and southern coastal areas than the central and northeastern parts of the Cox's Bazar district. For example, this assessment revealed that the probability of loss from the future cyclones is relatively very high in Cox's Bazar-S than the other Upazilas (Fig. 4). The reason is that Cox's Bazar-S scores high in almost all the selected criterions of the hazard, exposure and vulnerability that have a positive relationship with the cyclone risk; such as cyclone frequency, probable effects of storm surge, proximity to coast, elevation, population density, total population size, and female population size. On the other hand, the criterions which are in favor of Cox's Bazar-S (e.g., healthcare facilities and literacy) have been assigned lesser weight during the ranking process; consequently, the Upazila reveals relatively higher risk. In the similar manner, depending on the number and weight of the contributing parameters, the relative risk levels change for the other locations in the study area.

3.3 *Risk simulation of the Rohingya refugee camps (Spatial scale-II)*

Rohingya expatriates are living in eight clusters comprising of 34 camps with a population density of more than 33047 persons per km². In addition to predetermined hazard and exposure scenarios (spatial scale-I), we used data on six demographic parameters representing the vulnerability of Rohingya refugees for assessing the relative cyclone risk at the camp scale (spatial scale-II). The parameters include size of child population (below 11), size of female population, and total population (Fig. 5). Moreover, critical demographic characteristics such as number of families with a person with disability, families with people with special needs, and number of elderly (60+) people in each camp were also considered (Fig. 5). Our analysis reveals that camp number 1E, 1W, 7, and 13 exhibit very high to high cyclone risk levels. The risk conditions of camps that include 2W, 2E, 4, 5, 6, 8W, 8E, 9, 10, 11, 12, 14, 15, 16, 18, 19, 22, 24, 26 and Nayapara-RC are high to moderate. Kutupalong-RC and camp number 27 reveal largely moderate to low risk status, whereas risk has been found low to very low in the remaining camps such as 4-extension, 17, 20, 20-extension, Choukali, 21, 23, and 25 (Fig. 6). In general, the area under very high, high, moderate, low, and very low risk classes has been quantified as 3.43%, 27.82%, 39.42%, 28.70%, and 0.61% respectively. Given the smaller areal extent of the Rohingya refugees camps (spatial scale –II), the hazard scenarios have been downscaled from the spatial scale-I. The hazard situation is more or less constant for all the Rohingya refugee camps (Fig. 6); thus the portrayed cyclone risk levels of the camps are predominantly determined by the variations in the vulnerability and exposure conditions.

3.4 Correlation of the simulated risk with experiential impact

Eastern coast of Bangladesh was worst hit during the deadly cyclone in 1991. Cox's Bazar was one of the districts where maximum deaths were reported because of this cyclone (Hoque et al., 1993). We assume this event to be an ideal one for comparison with the cyclone risk situation of the Cox's Bazar district derived from the present analysis. We could not make a superimposed comparison of the two products because of the original impact map of 1991 cyclone being not-to-scale. In general, the effect of the 1991 cyclone has been spatially divided in to three categories i.e., worst affected, badly affected, and partly effected (Hoque et al., 1993; Ikeda, 1995). The intensity of the effects was experienced more from northwestern side of the district and diminishing towards the east. The comparison reveals a significant agreement between the observed impact of the 1991 cyclone and the simulated cyclone risk especially in the northern segment of the study area. Moheshkhali, Pekua, western parts of Chakaria and Cox's Bazar-S Upazilas of the CBD have been 'worst affected' during the cyclone (1991); all these areas fall either in very high or high risk zones projected in this study. In some parts of the CBD, the simulated scenario did not match with the observed effects, for example our analysis shows Kutubdia largely a moderate risk zone; however, it was classified as the 'worst affected' in 1991. This inconsistency is actually associated with the criterions; even if Kutubdia is a low elevation and seaward Upazila it has a least frequency of direct cyclone strikes and hosts relatively smaller size of the population with less density. Similarly, from the south of the district some parts identified as very high risk areas have been actually 'partly affected' during the 1991; this variation may be because of the zone (south) being farther from track of the 1991 cyclone.

3.5 Limitations and uncertainties

There are some inherent limitations of the data and the uncertainties involved in the pre-event risk assessment that may influence the results of this analysis and future use of the deliverables. The principal limitation of the study is that it assumes the components of the risk as static; however, in real world almost all of the selected parameters are dynamic in nature. For example, we used storm data of last hundred years as a representative of the cyclone hazard in the CBD, so few questions may be asked: (i) Is the time series data enough for deciding the hazard levels of a location (Upazila)? (ii) Is the intensity, frequency and spatial patterns of the future storms going to be same as that in the past? Given dynamic nature of the hazard, there are no certain answers to these questions. Similar concerns can be raised about the other parameters selected under exposure and vulnerability components. Such as the data used for the vulnerability assessment of the spatial scale-I is from the 2011 census and presently the figures would be different; owing to non-availability of the data from a reliable source it remains a limitation of the study. The quality of data is another important issue that influences the results; e.g., in this analysis we used ALOS DSM which is a low resolution data for developing the depth scenario of the storm surge; hence, we had to assume the depth of the storm surge as constant (10m). In reality the water depth would decrease with increasing distance towards the land area, consequently the impacts of the surge cannot be expected as constant for the whole area. Moreover, use of the administrative boundaries to represent a phenomenon is often a generalization that distorts in-situ information. Another important aspect is the use of statistical method (AHP) where the relative weightage of the chosen parameters is subjective. The relative weight assigned to each parameter selected for a particular study may differ from one researcher to another; it is therefore likely that the results of the studies even with similar objectives may be inconsistent. In spite of the various limitations and uncertainties, the deliverables of this analysis are useful from the functional and academic point of view because the multiple criteria decision making (MCDM) is logically flexible, allowing incorporation of the maximum possible conditions and factors for replicating a process; as a result, the derived scenarios often match considerably with the real world conditions.

4 Conclusions

Eastern coastal areas of Bangladesh have been repeated effected by the cyclones of different intensities. Although, past experiences have been helpful for improving the mitigation capacities of the people and the institutions in the region, the risks still keep on accumulating and disasters looming. Lack of efficient institutional mechanism, susceptible demographic structure and deprived socioeconomic conditions are the main factors effecting capacity of the community at different levels. About 3 million native people and their assets are at varying degree of cyclone risk in the Cox's Bazar district (CBD). The influx of about one million Rohingya refugees in 2017, who fled genocide, human rights violation and war crimes perpetrated by the Myanmar government has made the situation worse. The Rohingyas are not allowed to build cyclone resistant permanent structures and are therefore forced to live in densely populated temporary shelters made of plastic sheets, tarpaulins and bamboos. The humanitarian crisis has dramatically altered the cyclone risk scenario of the CBD. In view of the current situation, this study performed the cyclone risk assessment of the Cox's Bazar district and Rohingya refugee camps. The analysis was done through the combined use of the AHP and GIS within the theoretical framework of the general risk model to produce functional cyclone risk maps for the pilot sites. A wide range of criterions representing hazard, exposure, and vulnerability were selected for the risk assessment. On the whole, the approach has been valuable for understanding the spatial patterns of the cyclone risk in the CBD. It is likely that the impact of future cyclone events would be more pronouncing in the identified high risk zones than the areas that exhibited low levels of the risk. The quantification and mapping of the risk hotspots in this analysis thus offers an opportunity to develop mitigation strategies, increase the resilience of the at-risk communities and avoid the possible loss of life and properties in the CBD from the future cyclones.

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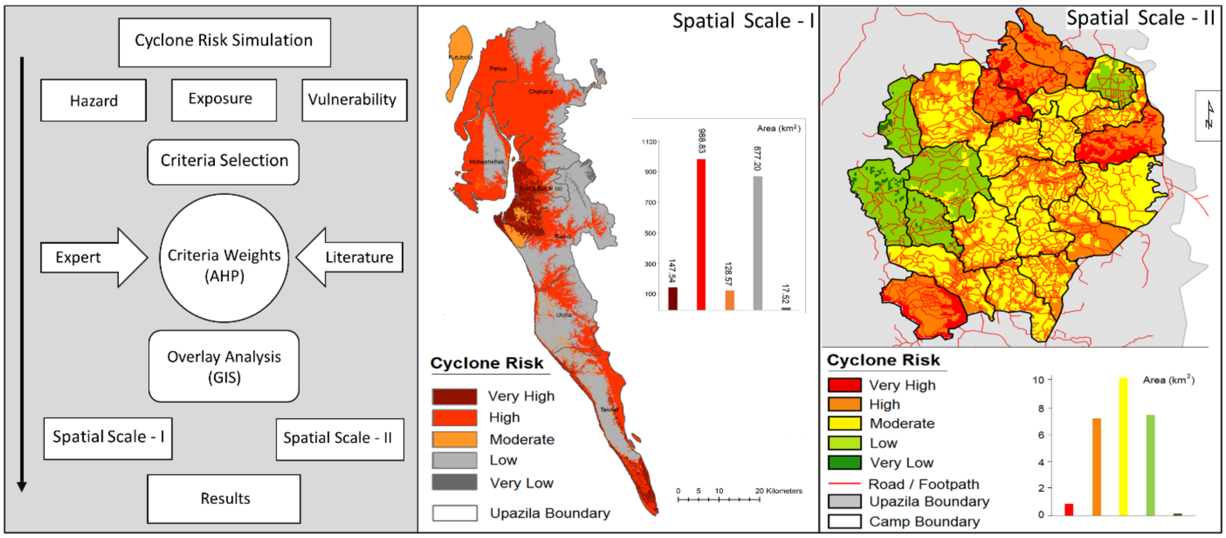
Graphical Abstract:



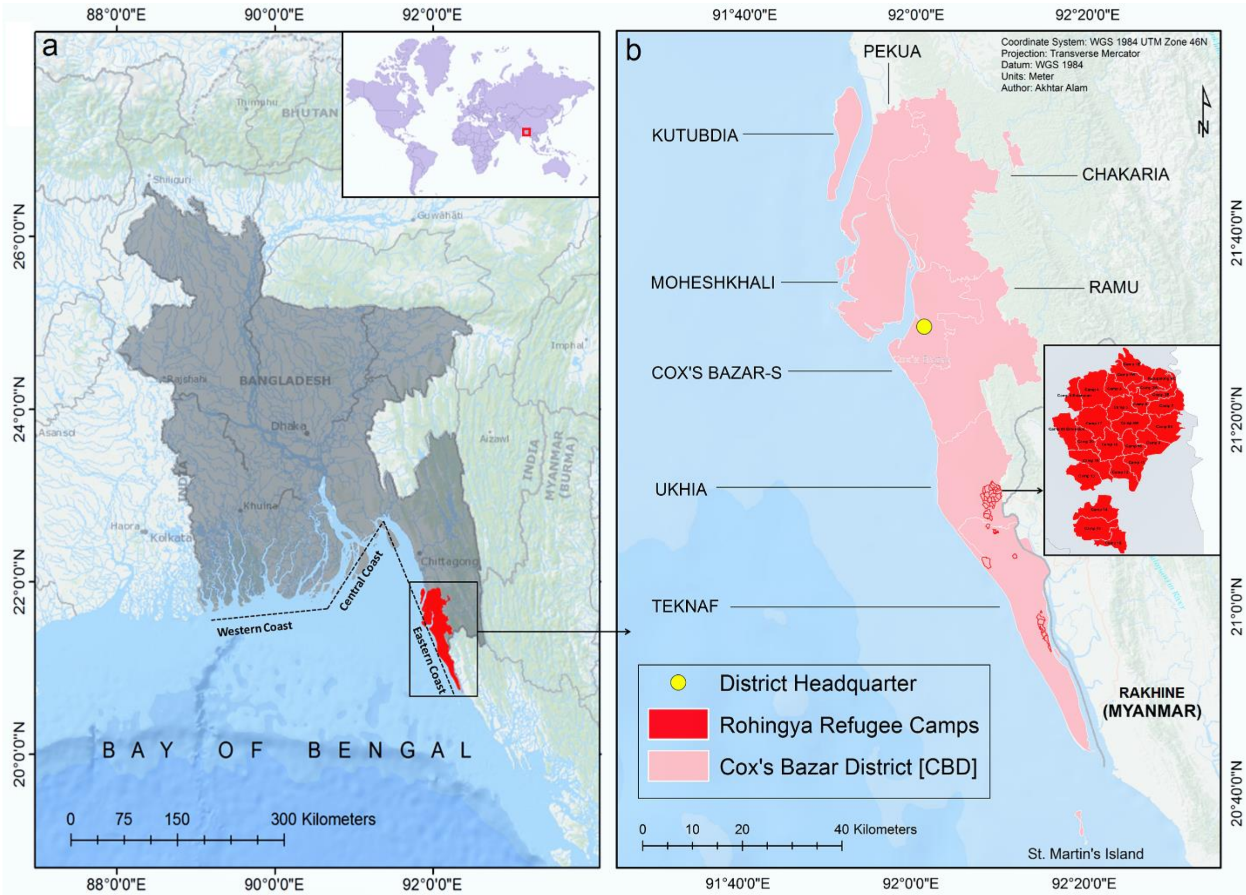


Fig 1 (a) Relief map showing the location of the Cox's Bazar district (Red) in Bangladesh; (b) different administrative units (*Upazilas*) of the district and location of the Rohingya refugee camps in the district.

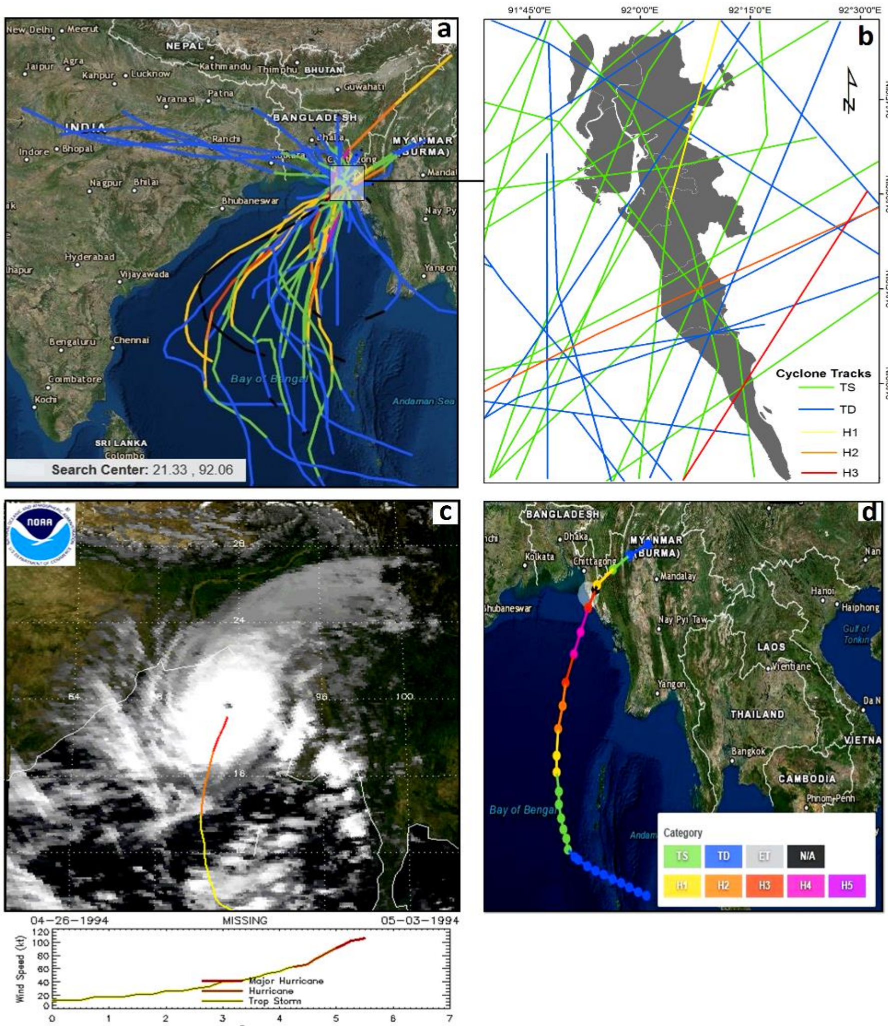


Fig 2 Cyclone storms of different intensities with track over the Cox's Bazar district from 1904-2016. (a) Tracks of the cyclones originating from the Indian Ocean, (b) closer view of the storm tracks through the Cox's Bazar district, (c) image showing the wind field, track and timing of 1994 cyclone (d) intensity of the 1994 storm (Saffir–Simpson Scale).

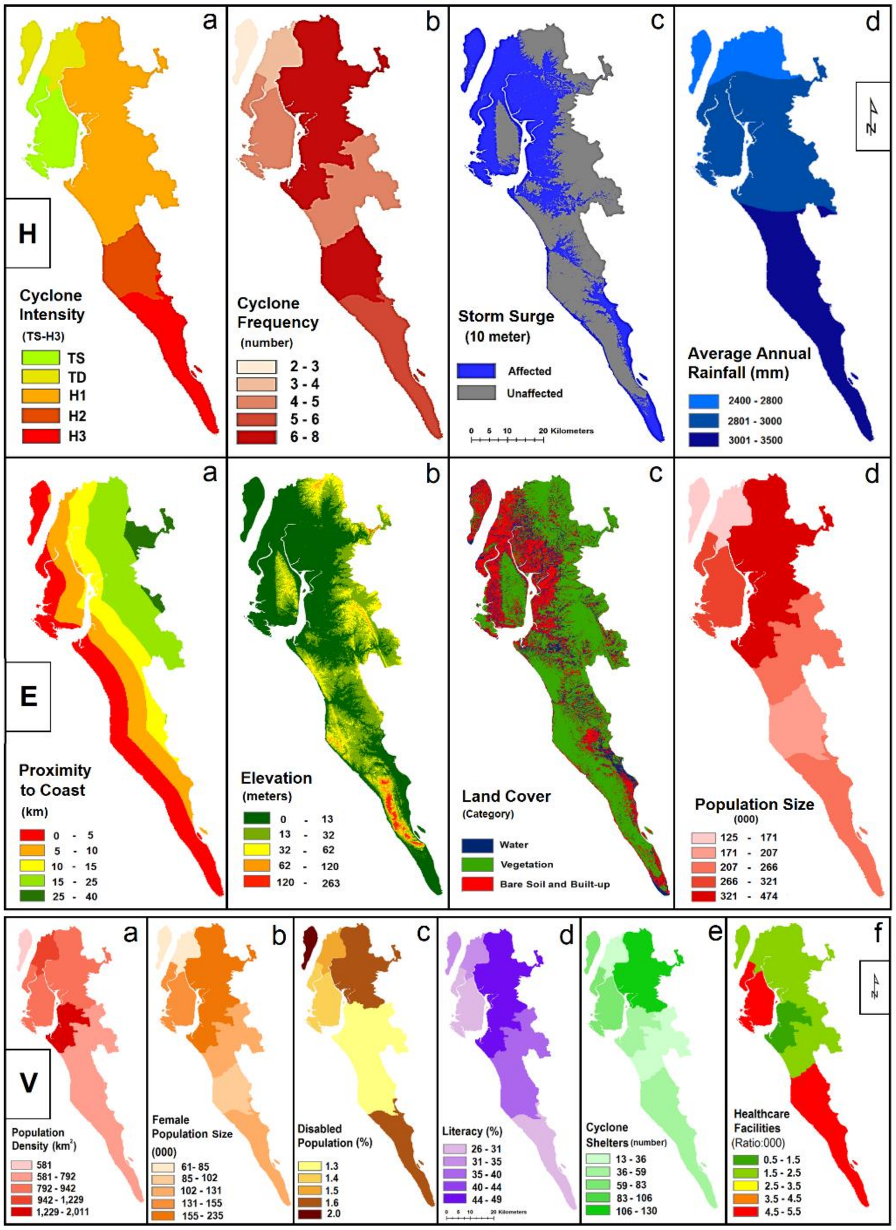


Fig 3 Parameters used for the cyclone risk assessment. [H-hazard]: (a) Intensity of the previous storms—TS-tropical storm, TD-tropical depression, H1, H2, H3 cyclone intensity on the Saffir–Simpson Scale, (b) frequency of the cyclone storms with track over the various Upazilas of the district (c) areas likely to be effected by a 10-meter-high surge (blue), and (d) pattern of the average annual rainfall (mm); [E-exposure]: (a) zoning on the basis of distance from the coast, (b) elevation ranges derived from the ALOS DSM, (c) land cover classes obtained using Landsat 8 (OLI) imagery and (d) population size; [V-vulnerability]: (a) density of the population, (b) total female population, (c) percentage of the population with disability, (d) percentage of the literate population, (e) number of cyclone shelters, and (f) availability of healthcare facilities per thousand of the population in each Upazila of the Cox's Bazar district.

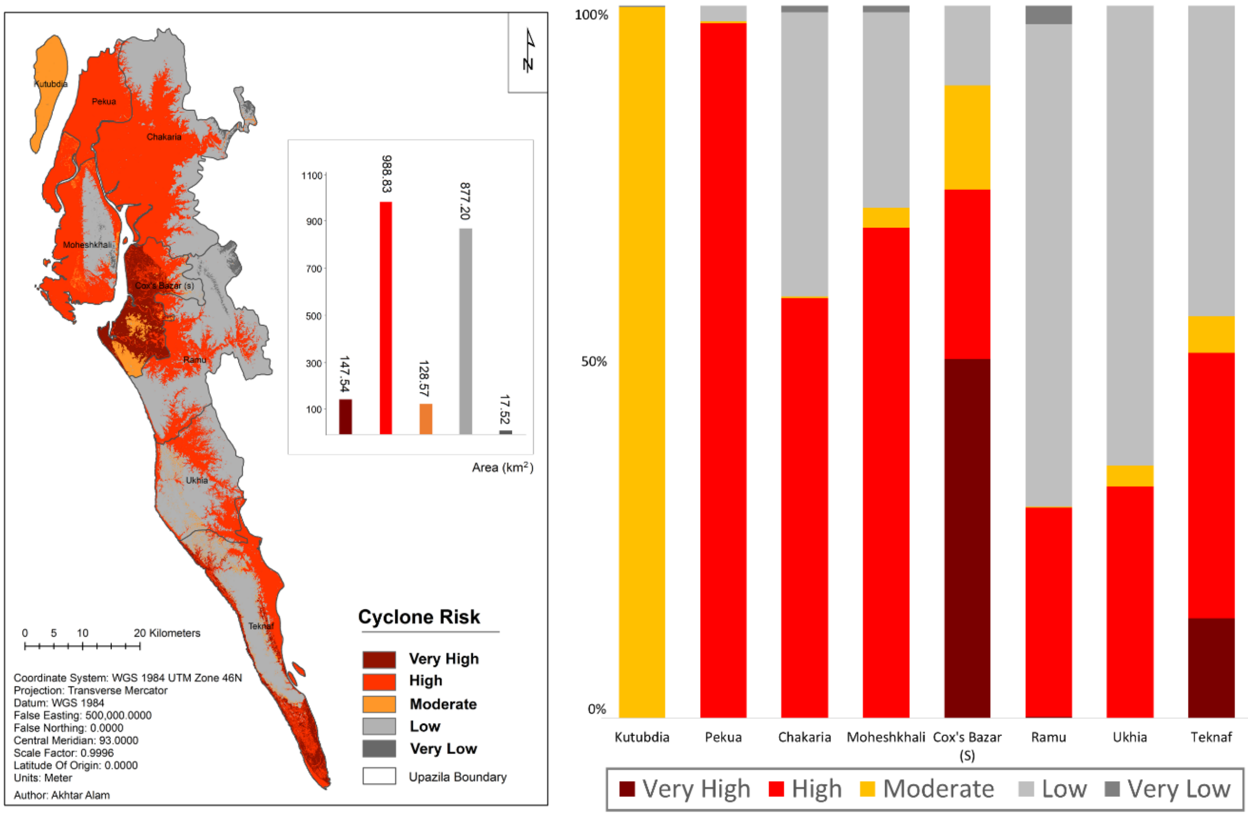


Fig 4 Simulated cyclone risk scenario of the Cox's Bazar district.

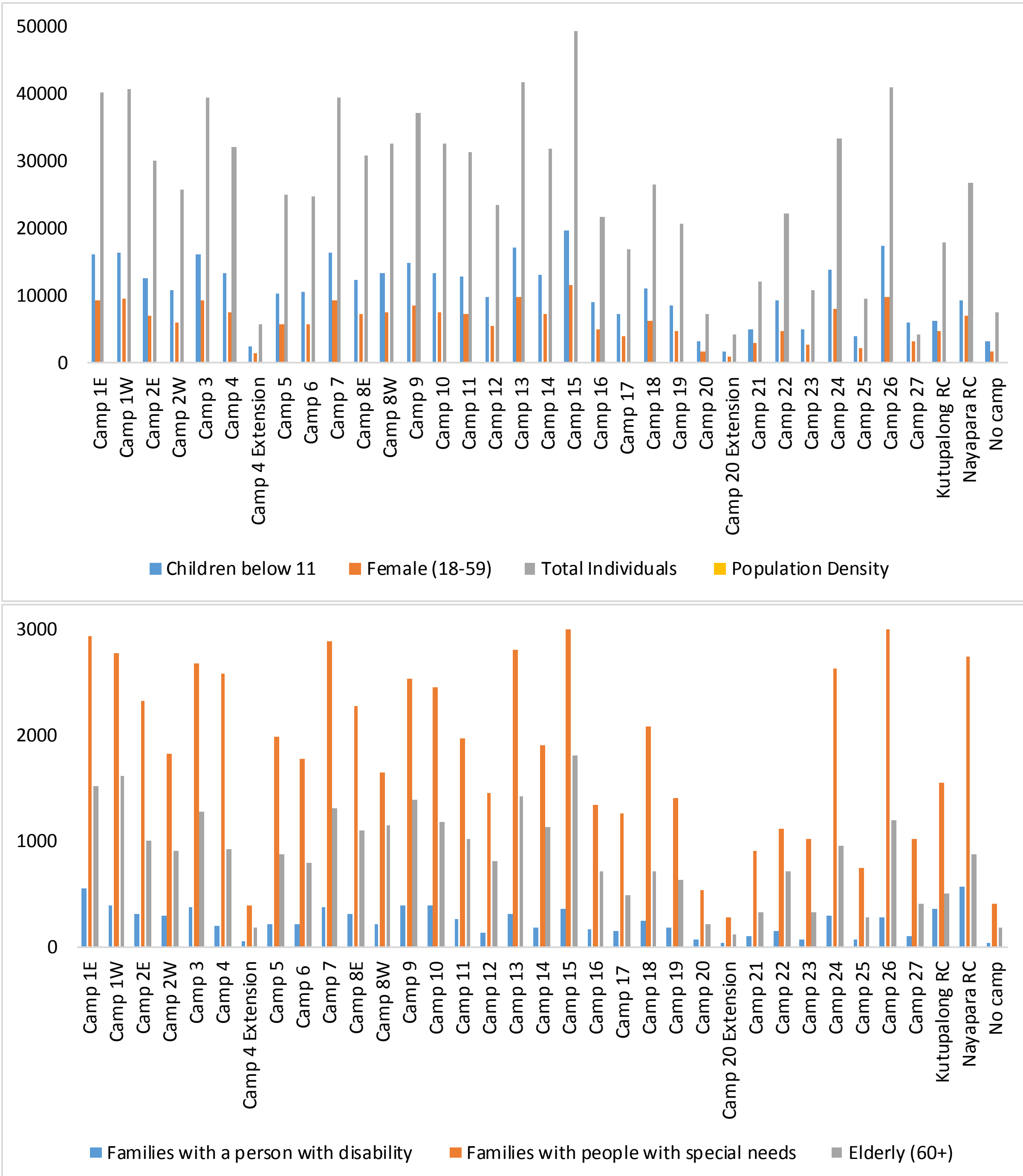


Fig 5 Demographic attributes of the Rohingya refugees that make them vulnerable.

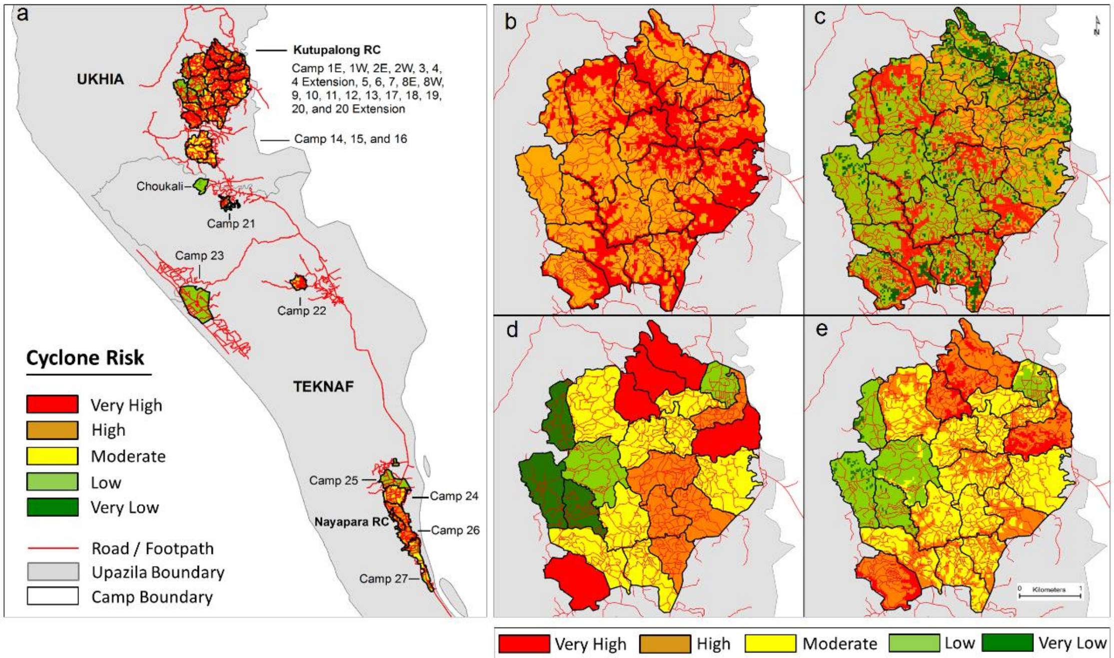


Fig 6 (a) Simulated cyclone risk scenario of the Rohingya refugee camps; (b) hazard, (c) exposure, (d) vulnerability and (e) risk — scenario of the Kutupalong-RC cluster.

Table 1 Details of the data products used in the present study.

Parameter	***Product***	***Source***
Cyclone intensity (TS-H3)	Wind speed of the storms (NOAA)	https://www.coast.noaa.gov/
Cyclone frequency (number)	Total number of the storms (NOAA)	https://www.coast.noaa.gov/
Storm Surge (m)	Projected surge height of 20 year storm and observed 1991 cyclone (~10m)	Dasgupta et al., 2010; Khalil, 1993
Proximity to coastline (km)	Distance calculated using Landsat 8 satellite image as a base in ArcGIS 10.2.	https://glovis.usgs.gov/
Elevation (m)	ALOS World 3D – 30m Version 2.1, Digital Surface Model (DSM).	http://www.eorc.jaxa.jp/
Rainfall (mm)	Mean Annual	www.bmd.gov.bd
Land Cover (category)	Satellite Image (Landsat 8 (OLI), date of acquisition 2019/02/01), UTM zone 46	https://glovis.usgs.gov/
Population size (000)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Population density (km²)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Female population size (000)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Population with disability (%)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Literacy (%)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Cyclone shelters (number)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Healthcare facilities (ratio to 000)	District Statistics (2011)	Bangladesh Bureau of Statistics (BBS), 2013
Demographic data of the Rohingya refugees	Population factsheet (15 April, 2019)	https://data2.unhcr.org/ https://data.humdata.org/

Table 2 Details of the cyclone events considered for the present analysis (1904-2016).

Year	***Month***	***Days***		***Category***
		From	*To*	***(Max. attained)***
1904	November	21	23	TS
1909	December	02	05	H1
1918	May	24	25	TS
1923	May	02	05	H1
1924	June	14	16	TS
1929	June	02	03	TD
1930	July	15	21	TD
1941	August	15	19	TD
1965	October	07	08	TD
1965	December	06	14	H1
1967	October	20	23	H1
1969	September	23	25	TD
1981	November	17	20	H1
1983	November	05	09	TD
1990	December	13	19	TD
1992	October	14	22	TD
1994	April/May	26 April	03 May	H4
1995	November	18	25	H3
1996	May	01	07	TD
2007	May	13	15	H1
2011	October	17	19	TS
2016	November	03	06	TS

Table 3 Relative importance of the selected parameters derived through AHP.

Risk Component	***Criterion***	***Priority***	***Rank***
Hazard	Cyclone intensity (TS-H3)	17.6%	1
	Cyclone frequency (number)	14.5%	3
	Storm surge (m)	16.2%	2
	Rainfall (mm)	3.0%	9
Exposure	Proximity to coastline (km)	8.6%	5
	Elevation (m)	9.9%	4
	Land cover (category)	2.5%	11
	Population Size (000)	2.5%	12
Vulnerability	Population density (km^2)	7.4%	7
	Female population size (000)	3.0%	8
	Population with disability (%)	2.2%	13
	Literacy (%)	2.1%	14
	Cyclone shelters (number)	7.9%	6
	Healthcare facilities (ratio: 000)	2.5%	10

Table S1 Scale of relative importance (adopted from Saaty, 2008)

Intensity of Importance	*Definition*	*Explanation*
1	Equal importance	Two variables contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one variable over another
5	Strong importance	Experience and judgement strongly favour one variable over another
7	Very strong or demonstrated importance	A variable is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one variable over another is of the highest possible order of affirmation
2, 4, 6,8	Intermediate Importance	When compromise is needed

Table S2 Comparison matrix of the selected criterions.

Criterion		*Hazard*					*Exposure*			*Vulnerability*					
		Cyclone intensity (TS-H3)	Cyclone frequency (number)	Storm surge (m)	Rainfall (mm)	Proximity to coastline (km)	Elevation (m)	Land cover (Category)	Population Size (000)	Population density (km²)	Female population Size (%)	Population with disability (%)	Literacy (%)	Cyclone shelters (number)	Healthcare (ratio:000) facilities (ratio)
	Cyclone intensity (TS-H3)	1	1.00	1.00	7.00	4.00	5.00	9.00	6.00	2.00	3.00	9.00	9.00	2.00	3.00
	Cyclone frequency (number)	1.00	1	1.00	4.00	5.00	2.00	5.00	6.00	2.00	7.00	7.00	5.00	1.00	3.00
Hazard	Storm surge (m)	1.00	1.00	1	9.00	2.00	1.00	9.00	7.00	3.00	8.00	6.00	9.00	2.00	7.00
	Rainfall (mm)	0.14	0.25	0.11	1	1.00	1.00	1.00	1.00	0.20	1.00	1.00	1.00	0.20	1.00
	Proximity to coastline (km)	0.25	0.20	0.50	1.00	1	1.00	5.00	6.00	2.00	5.00	6.00	6.00	1.00	3.00
	Elevation (m)	0.20	0.50	1.00	1.00	1.00	1	4.00	5.00	2.00	5.00	5.00	6.00	2.00	6.00
Exposure	Land cover (Category)	0.11	0.20	0.11	1.00	0.20	0.25	1	1.00	1.00	1.00	1.00	2.00	0.14	1.00
	Population Size (000)	0.17	0.17	0.14	1.00	0.17	0.20	1.00	1	0.33	1.00	1.00	1.00	1.00	1.00
	Population density (km²)	0.50	0.50	0.33	5.00	0.50	0.50	1.00	3.00	1	2.00	6.00	6.00	2.00	2.00
	Female population Size (000)	0.33	0.14	0.12	1.00	0.20	0.20	1.00	1.00	0.50	1	3.00	3.00	0.50	1.00
	Population with disability (%)	0.11	0.14	0.17	1.00	0.17	0.20	1.00	1.00	0.17	0.33	1	1.00	1.00	1.00
	Literacy (%)	0.11	0.20	0.11	1.00	0.17	0.17	0.50	1.00	0.17	0.33	1.00	1	1.00	1.00
Vulnerability	Cyclone shelters (number)	0.50	1.00	0.50	5.00	1.00	0.50	7.00	1.00	0.50	2.00	1.00	1.00	1	9.00
	Healthcare facilities (ratio: 000)	0.33	0.33	0.14	1.00	0.33	0.17	1.00	1.00	0.50	1.00	1.00	1.00	0.11	1

Table S3 Relative ranking within each parameter based on the potential of risk.

Component	*Criteria*	*Risk Potential*				
		Very Low	*Low*	*Moderate*	*High*	*Very High*
Hazard	Cyclone intensity (TS-H3)	TS	TD	H1	H2	H3
	Cyclone frequency (number)	2-3	3-4	4-5	5-6	6-8
	Storm surge (10m)	Unaffected	-	-	-	Affected
	Rainfall (mm)		-	2400-2800	2801-3000	3001-3500
Exposure	Proximity to coastline (km)	25-40	15-25	10-15	5-10	<5
	Elevation (m)	120-263	62-120	32-62	13-32	0-13
	Land cover (category)	-	-	Water	Vegetation	Bare soil/ Built-up
	Population size (000)	125-171	171-207	207-266	266-321	321-474
Vulnerability	Population density (Km²)	581	581-792	792-942	942-1229	1229-2011
	Female population (000)	61-85	85-102	102-131	131-155	155-235
	Population with disability (%)	1.3	1.4	1.5	1.6	2
	Literacy (%)	44-49	40-44	35-40	31-35	26-31
	Cyclone Shelters (number)	106-130	83-106	59-83	36-59	13-36
	Healthcare Felicities (ratio to 000)	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5

Table S4 Land cover classification scheme.

Land cover	*Description*
Water	Rivers, canals, ponds, swamps, and other water logged areas.
Vegetation	Forests, standing crops, mangroves, aquatic plants and other shrubbery.
Bare soil and Built-up	Agriculture land without standing crops, barren land, rocky outcrops, sandy and muddy coasts, residential areas, commercial establishments, roads and other paved surfaces.

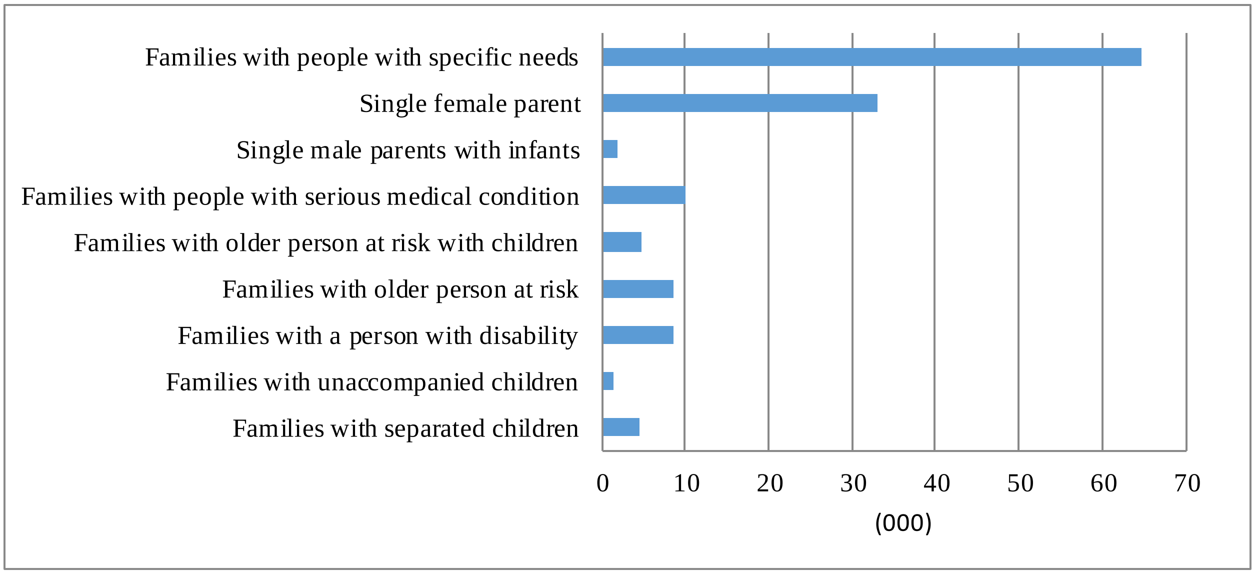


Fig S1 Specific demographic attributes of the Rohingya Refugees (Source: UNHCR, 2019).

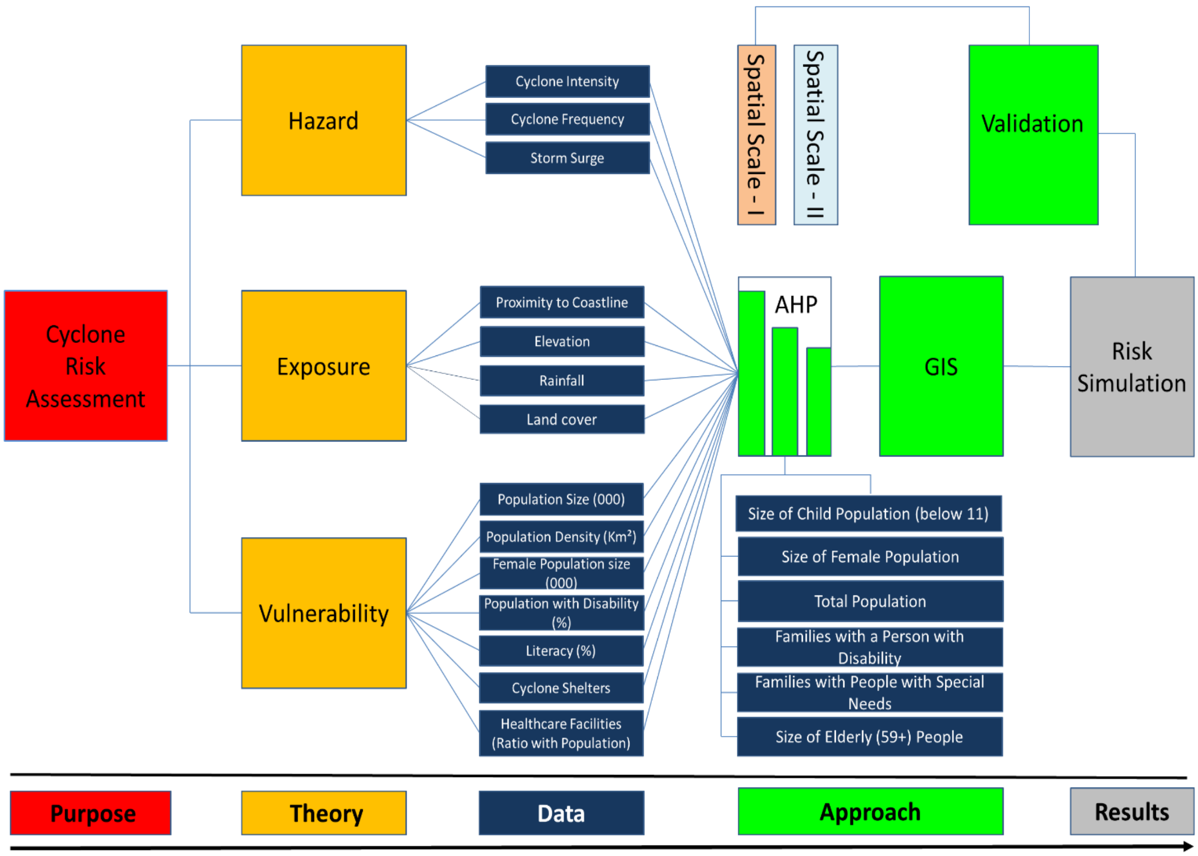


Fig S2 Structure of the methodology adopted in the present study.

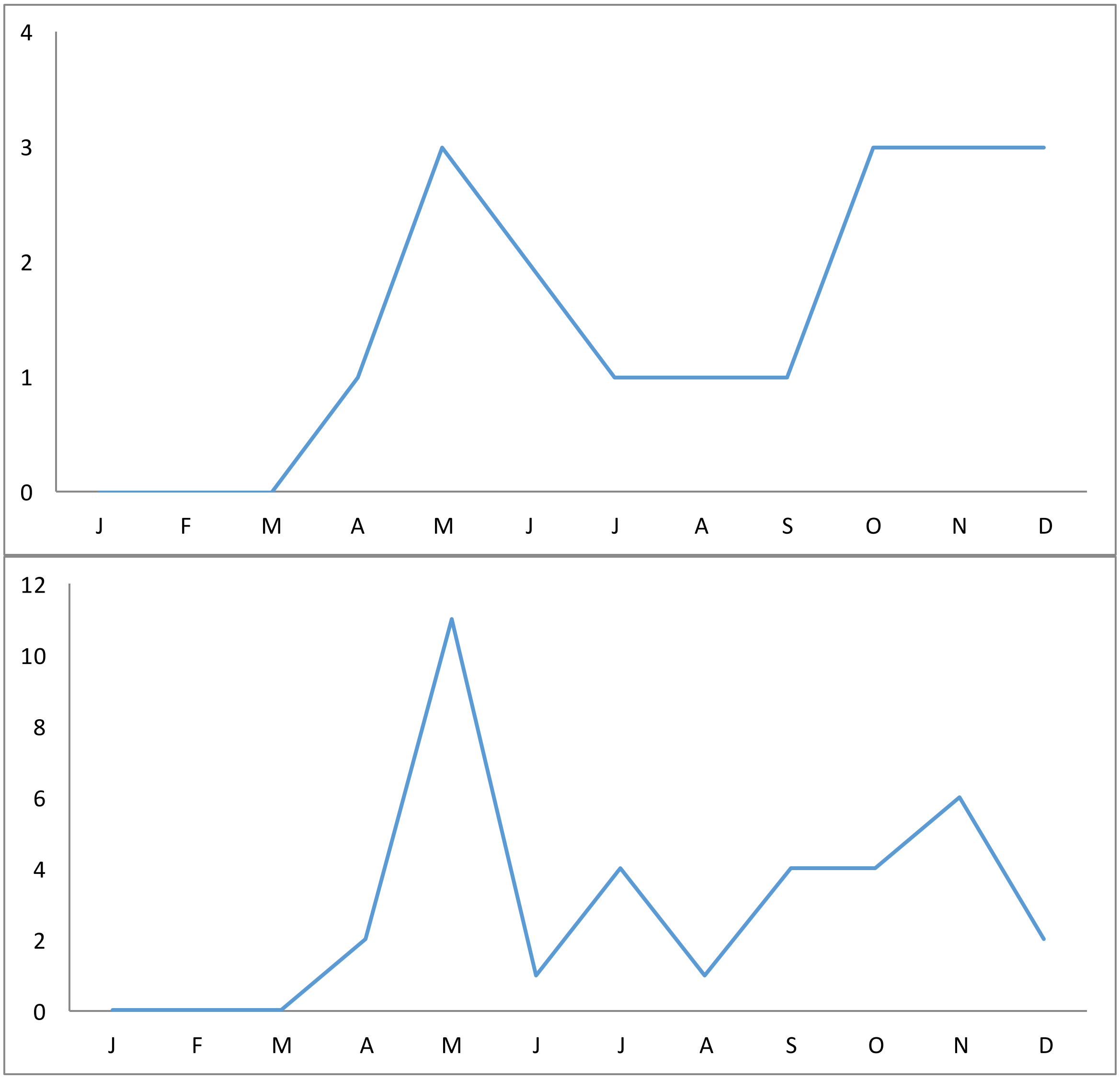


Fig S3 Temporal pattern of the cyclone occurrence. (a) All the events of the Cox's Bazar district from1904-2016 (Upper); (b) H1 to H5 category cyclones in Bangladesh from 1893-2007 (lower).

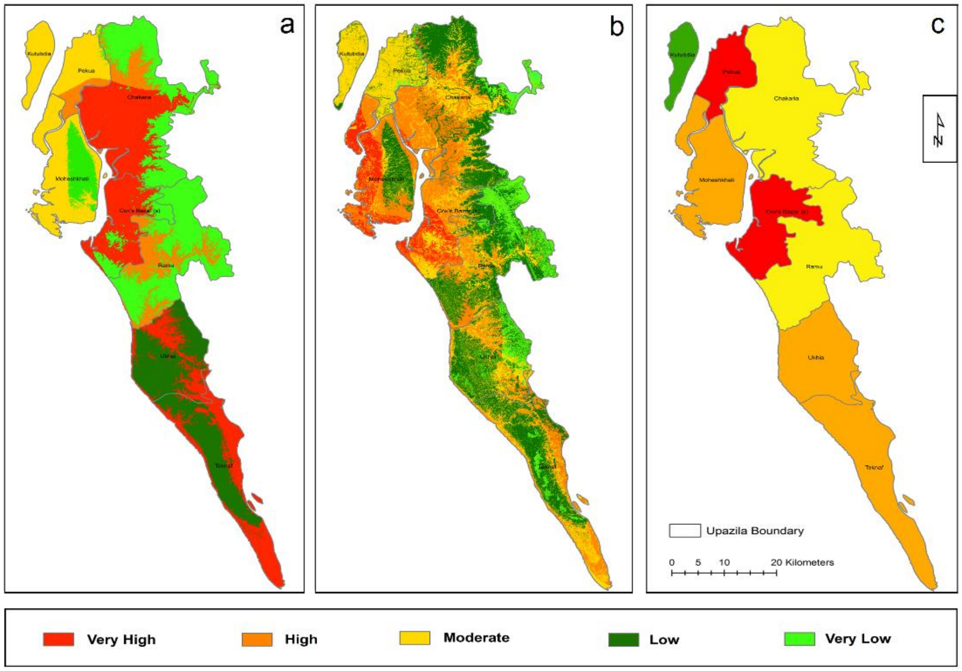


Fig S4 (a) Cyclone hazard, (b) exposure, and (c) vulnerability scenarios of the Cox's Bazar district.

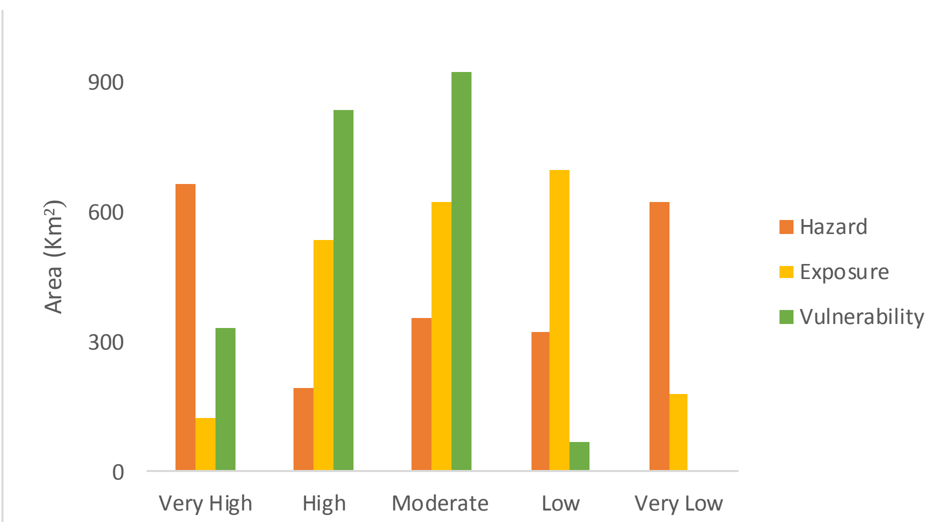
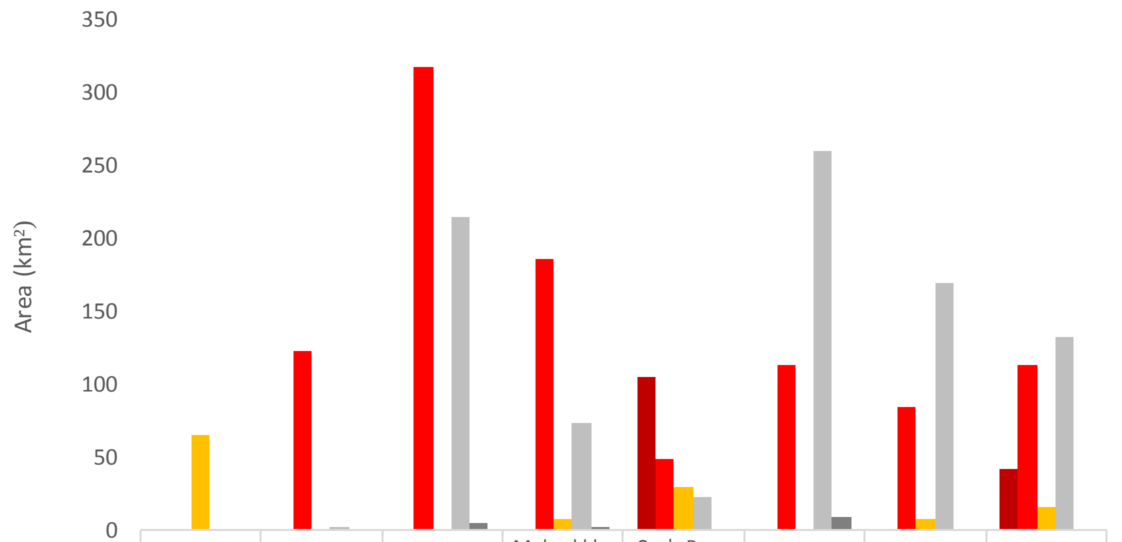


Fig S5 Area under the hazard, exposure and vulnerability classes in the Cox's Bazar district.



	Kutubdia	Pekua	Chakaria	Moheshkhali	Cox's Bazar (S)	Ramu	Ukhia	Teknaf
Very High	0	0	0.04	0	104.87	0.4	0	42.58
High	0	123.48	318.14	186.6	49.61	113.11	85.41	113.55
Moderate	66.26	0.33	0.93	7.6	30.35	0.48	7.61	15.63
Low	0	2.73	215.2	74.33	23.35	260.6	169.53	132.64
Very Low	0.11	0	5.07	2.56	0	9.77	0	0

Fig S6 Area under the different risk categories in each Upazila of the Cox's Bazar district.