Evaluating the risk to Bangladeshi coastal infrastructure from tropical cyclones under climate change.

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Abstract

In many countries, infrastructure plays a crucial role reducing losses during a cyclone. Bangladesh is already extremely vulnerable to tropical cyclones, and its infrastructure is frequently damaged by such events. However, climate change is expected to make the infrastructure itself, more vulnerable to cyclonic events in the future. This paper assesses the risk to coastal infrastructure in Bangladesh under climate change, from a multi-hazard perspective. A novel risk assessment matrix is proposed, examining the likely future risk to the country's key infrastructure elements from six prioritised hazards. The hazards stem from changes to baseline climate, and from predictions of stronger cyclones as a result of climate change. We show that Bangladeshi infrastructure is extremely at risk, suggesting rapid action and mitigation measures are needed. Climate change will increase the vulnerability of infrastructure on its own, but higher storm surges related to intensified cyclones pose the greatest risk, with catastrophic impacts on all types of infrastructure. A number of recommendations to improve the infrastructure are made. Due to the severity of the risks, alternative measures to protect Bangladesh and its population should be considered. These may be natural defences, efficient evacuation procedures, integration of communities to the design and construction process, or relocation of populations. These measures may be more sustainable in the long term in a place with geophysical, geographical, social and financial contexts such as those found in Bangladesh.

1. Introduction

Climate change is a long-term evolution in the state of the Earth's climate, identifiable by changes in values of climatic properties (IPCC, 2012). Although a changing climate has always been part of Earth's evolution, there is a growing body of evidence that recent evolutions in climate are anthropogenic changes rather than natural occurrences, and that they will have unprecedented consequences on conditions of life on Earth (Berlemann and Steinhardt, 2017).

A changing climate has the potential to affect various properties of tropical cyclones, and thus intensify them (IPCC, 2012). It has even been suggested that the scale currently used to measure their intensity might require the addition of an extra category (Albert, 2018). It is therefore essential to assess how climate change will impact parameters of tropical cyclones, as such variations can have important consequences.

Along with earthquakes, tropical cyclones are the largest geophysical cause of loss of life and property (Emanuel, 1987). However, for a hazard like a cyclone to turn into a disaster, it has to take place in a location with high vulnerability, meaning it is predisposed to be negatively affected (IPCC, 2012). In addition to potentially affecting cyclones development, climate change affects the environment and society in ways that can make them more vulnerable to cyclones. It is expected that vulnerability to cyclones is going to increase because of global warming regardless of whether cyclonic intensities increase. Some studies have even argued that any evolution in cyclone behaviour as a result of a warmer climate will have an insignificant effect compared to climate-induced impacts on vulnerability (Pielke, 2005). Therefore, looking at the impacts of climate change on vulnerability is as important as looking at its impacts on the hazards. Vulnerability has different dimensions including socio-economic, environmental, and physical. It

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is the latter that will be the focus of this study, as we focus our assessment of the risks primarily on those posed to physical infrastructure along the coastlines.

Not all countries are equal when it comes to cyclone occurrence. Bangladesh, bounded on the south by the Bay of Bengal, the north-eastern part of the Indian Ocean, is exceptionally prone to cyclone formation. It is the country where the two deadliest cyclones ever made landfall (Ali, 1996; Islam and Peterson, 2009). To add to this hazardous climate, Bangladesh is also one of the countries most affected by climate change consequences worldwide (Adams *et al.*, 2011). This puts Bangladesh particularly at risk from intense cyclone activity in the future.

In May 2020, the Category 5 Cyclone Amphan formed in the Bay of Bengal and later made landfall in Bangladesh and India (Jenner, 2020). It was the strongest cyclone ever recorded in the Bay of Bengal, followed only by the 1999 Odisha cyclone, which caused 10,000 casualties (Zargar, 2020a, 2020b). The India Meteorological Department stated the cyclone wind speeds reached up to 240 km/h, with gusts as high as 265 km/h, and they predicted storm surges 3 to 5 metres high (BBC News, 2020; Nandi and Thakur, 2020).

In Bangladesh, the cyclone washed away 7.5 kms of coastal embankments and partially damaged over 32 kms of them. The embankment failures enabled surge water to flood up to 15 kms inland, rendering as much as 500,000 families homeless (Nagchoudhary and Paul, 2020; Sud and Rajaram, 2020). Kolkata, the largest city in the cyclone path, received winds unprecedented in its history (Sud and Rajaram, 2020). Additionally, 133 villages were inundated in coastal districts as a result of heavy precipitations and storm surges (Roy *et al.*, 2020). About 2 million Bangladeshi residents were evacuated to over 12,000 cyclone shelters, with the added challenge of adhering to social distancing rules, as the cyclone hit in the midst of the COVID-19 pandemic (Zargar, 2020a).

Although the number of fatalities was significantly lower than for previous cyclones that made landfall in Bangladesh – thanks to improvements in technology and governmental preparedness over the last few decades – from a meteorological perspective, this cyclone was the most extreme ever recorded in this region (Zargar, 2020a, 2020b). The Indian Institute of Tropical Meteorology stated that the Bay of Bengal recorded sea surface temperatures of 32 to 34°C continually for the first half of May 2020 – a record never seen before, and believed by scientists to have been the cause of this intense cyclone (Chaitanya, 2020).

There has been extensive research on the impact of climate change on cyclones, and on the impact of climate change and cyclones on Bangladeshi infrastructure. There seems to be little research into how climate change will make the country's coastal infrastructure more vulnerable to cyclones in the future, be it through more vulnerable infrastructure as a result of known effects of climate change, or because of potentially stronger cyclones, or both. There is strong evidence that cyclones in Bangladesh have recently achieved record intensities, as shown by cyclone Amphan in May 2020, and further research is essential to achieve resilience to future cyclonic events.

This paper reviews existing studies on the impact of climate change on tropical cyclone development. Climate hazards are identified, prioritised and integrated in a risk assessment. The paper further identifies five types of crucial physical infrastructure that are normally affected by cyclone activity in Bangladesh along the coastlines: roads, cyclone shelters, coastal embankments, houses and polders. We propose a risk framework to assess the impacts of identified climate hazards in the context of their likelihood of occurrence in the future. This framework will be used to understand the overall risks to Bangladeshi infrastructure and help prioritising specific interventions to improve resilience to tropical cyclones.

2. Cyclones and climate change

Cyclones get their energy from latent heat, a result of high Sea Surface Temperatures (SSTs) (Climate Council, 2017). Cyclone genesis benefits from a strong vertical temperature gradient which maintains convection, therefore the greater the temperature difference between SSTs and upper atmospheric levels, the higher the chances of cyclone formation. As global increases in atmospheric temperatures have been observed, the difference in temperature between levels of the atmosphere is reducing, which should lead to a decrease in the frequency of tropical cyclones (Gray, 2005). Nevertheless, the higher the temperatures, the more energy a cyclone can draw to fuel strong winds, storm surges and heavy precipitations (Emanuel, 2000; Wing *et al.*, 2007; Reed *et al.*, 2010; Hughes *et al.*, 2017). Therefore, an increase in SSTs as a result of global warming can create potential for higher cyclone intensities.

Models produced by Knutson and Tuleya (2004) and Knutson *et al.* (2015), based on a 1% yearly increase in CO_2 concentrations, all showed a CO_2-induced increase in cyclone wind intensity and precipitation rates, a conclusion also adopted by the IPCC (2013). Moreover, Knutson *et al.* (2015) also showed that, although the total number of cyclones is expected to decrease in a warmer climate, the proportion of category 4 and 5 cyclones (on the Saffir–Simpson Hurricane wind Scale, SSHS thereafter) from this number will increase. This suggests the frequency of occurrence of strong cyclones affecting Bangladesh will increase in the future. In a paper by Unnikrishnan *et al.* (2006) researchers used a climate model for the Bay of Bengal and compared results from a control run with CO_2 concentrations fixed at the 1990 levels, and from a perturbed run with increased CO_2 emissions. They found that intense cyclonic events would increase in frequency and showed that this would also result in more frequent high surges in the Bay.

When referring to a potential increase in intensity, experts are not always consistent on their definition of intensity. Some, like Anthes *et al.* (2006) only look at wind velocities, whereas others like Knutson *et al.* (2015) and Emanuel (2005a) also assess impact on precipitation rates. Webster *et al.* (2005), on the other hand, discuss the frequency of hurricanes of different categories on the SSHS, which is a function of wind speeds. However, Kantha (2013) pointed out that the SSHS can often lead to complacency, and hurricanes like Ike or Sandy have demonstrated that damage done upon landfall is not always a function of hurricane category. Other issues with the SSHS are brought up, such as the fact that it saturates at its higher end, meaning that all hurricanes in Category 5 are considered equal. This could prove especially relevant as cyclonic wind speeds are expected to increase in the future.

The influence of climate change on tropical cyclone genesis or evolution remains uncertain. The punctual nature of cyclones and the timescales of other factors associated with their genesis make it difficult to measure changes in parameters. Some climatic measurements have first been recorded less than a century ago, hence natural multi-decadal or century-wide variations cannot be differentiated from anthropogenic changes. Furthermore, when carrying out a risk assessment of the potential damage caused by a cyclone, the hydrometeorological parameters are not always those that are of direct interest to decision makers and coastal engineers in designing mitigation measures. Societal changes, including migration to coastal areas, mean damages to coastal areas have a larger economic impact, and affect a larger and denser population. However, it is undeniable that the climate is warming, and with the expectation of more frequent and more intense cyclones, it is prudent to start early preparation to reduce the risk to Bangladesh infrastructure and society.

3. Hydrometeorological Hazards in Bangladesh

Bangladesh is highly vulnerable to climate change due to its location, and some climate change impacts are already being observed. These are expected to be permanent and long-term impacts severely affecting coastal regions and infrastructure (M. A. Rahman and Rahman, 2015). Bangladesh is situated in the delta of the Ganges, Brahmaputra and Meghna rivers (GBM thereafter), meaning that variability, timing and location of flooding within the entire basin have consequences on Bangladesh (Adams *et al.*, 2011). Only 7% of precipitations in the GBM basin occur in Bangladesh, but the entire basin flow of 1,350 billion m^3 annually drains through the country, making Bangladesh prone to flooding and vulnerable to increases in rainfall (ibid). Moreover, most land is very low-lying, having elevation lower than 10 meters above mean sea level (Shamsuddin, 2008). Agrawala *et al.* (2003) highlighted that an increase in sea levels of just one meter would flood 18% of the territory.

In addition to being highly vulnerable to climate change, Bangladesh is one of the countries most affected by cyclones. Of the world’s cyclones, 7% form in the Northern Indian Ocean basin, of which 14% hit Bangladesh, which is a small country (Ali, 1996). Latitudes favourable to severe cyclones formation are within 20º - 30º, on both sides of the equator (Islam and Peterson, 2009). Bangladesh is within latitudes 20º34’ and 26º38’, making the country extremely prone to severe cyclones formation (ibid). Although the frequency of cyclonic activity in the country has never been steady, recent data shows a small increase

(Islam and Peterson, 2009). Moreover, Bangladesh has a 710 kms long coastline, and is therefore directly affected by cyclones at landfall, when they are at their highest intensity (ibid).

Cyclones affecting Bangladesh form in the Northern Indian Ocean basin, where Vose *et al.* (2012) showed that the SSTs have already increased from 1979 to 2010 by 0.1-0.2°C, which is consistent with most other basins around the world (the measured increase in SSTs in the Bay of Bengal specifically is slightly lower, at 0-0.1°C). Higher SSTs are associated with higher intensity cyclones. Before landfall, the cyclones pass through the Bay of Bengal, where shallow waters lead to the formation of particularly high storm surges, which are responsible for most cyclonic damage in Bangladesh (Ali, 1996; Agrawala *et al.*, 2003; Hossain *et al.*, 2008).

In the Bay of Bengal, cyclones are most devastating when they hit Bangladesh or western India, as these areas suffer from a flat and low terrain coupled with high population densities and weak houses (Islam *et al.*, 2011). In fact, Bangladesh is the country most affected worldwide by cyclone-related fatalities, with more than 40% of cyclones with death tolls above 5,000 occurring in Bangladesh (Ali, 1996; M. A. Rahman and Rahman, 2015). The world's two deadliest cyclones even hit the country, with 300,000 casualties in 1970 and 140,000 in 1991 (Islam and Peterson, 2009).

In addition to the shallowness of the Bay of Bengal, these high casualties result from low topography, from the triangular shape of the Bay of Bengal, and from the funnelling shape of the coastline, which helps wind push sea water towards the coast and amplifies surge (Ali, 1979, 1999). Surge heights for Bangladesh usually range between 1.5m and 9m, however, the time of landfall also plays a critical role due to tide variations (IPCC, 2007). Bangladesh currently receives two-fifths of the world's total impact from storm surges, but the World Bank estimates that the coastal area exposed to surge-induced inundation depths greater than 3 meters will rise by up to 69% by 2050 (Murty and El-Sabh, 1992; Huq *et al.*, 2010; Adams *et al.*, 2011). Moreover, a risk assessment conducted by Hoque *et al.* (2019) showed that, on the Eastern part of Bangladesh, over 60% of the 'Moderate' to 'Very High' hazard risk zones are located on the coast – which is where storm surges are at their strongest.

We identify six prioritised hazards that will be used for this risk assessment as they appear to be both most hazardous to Bangladesh and most likely to increase in frequency and/or severity.

Hoegh-Guldberg et al. (2018), Agrawala et al. (2003) and Gosling et al. (2011) estimated that climate change will have the following impacts on the baseline climate of Bangladesh:

- Higher temperatures: 3 - 3.5ºC increase over the entire country,
- Sea Level Rise (SLR thereafter) including sedimentation and subsidence effects: 0.3 - 1m increase by 2100
- Heavier precipitations: 5 to 20% increase in rainfall intensity, depending on the location.

The IPCC (2007) assesses that climate change will lead to an increase in cyclone intensities in Bangladesh. We follow this assessment, and assume the following parameters of cyclone activity in our analysis (Ali, 1999; Lavell *et al.*, 2012; Dastagir, 2015):

- Stronger winds, with peak wind velocities increasing by 10 - 22%;
- Higher storm surge (13 - 49% increase in height).
- Widespread rapid flooding (20% increase in flooded area, as a result of significantly heavier precipitations during cyclones);

The six prioritised hazards are summarised in Table 1 under two categories, baseline climate and increased cyclone activity. They will be subjected to a qualitative risk analysis to assess their impact on Bangladeshi infrastructure.

Baseline Climate-Change Hazards *Stemming from changes to the baseline climate*
Higher temperatures
Sea level rise
Heavier precipitations
Cyclone Hazards *Specifically stemming from the higher intensity cyclones predicted under climate change*
Stronger winds
Higher storm surges
Widespread rapid flooding

Table 1: The six prioritised hazards selected for this assessment.

4. Bangladeshi Infrastructure at risk

Exposure is the inventory of elements in an area where a hazard may occur (Cardona *et al.*, 2012). Not all infrastructure in Bangladesh is exposed to the impacts from cyclones, the intensity of the hazards varies across the territory. To integrate different factors of exposure to cyclones and obtain exposure maps, several studies including those of by Quader *et al.* (2017) have used combinations of various parameters such as land cover, population density, distance to sea and river and elevation to assess overall exposure. Although these factors are often poorly correlated together, and their relative importance is undefined, such assessments show that the area of Bangladesh exposed to cyclones remains largely on the coast. It is however expected this area will extend further inland as climate changes, as has already been observed with the recent event of Cyclone Amphan in May 2020, where surge water penetrated up to 15 km inland. Therefore, the quantity of infrastructure exposed to hazards from stronger cyclones is likely to increase compared to what historical studies have shown.

In the coastal areas of Bangladesh, the six prioritised hazards outlined in Table 1 will have significant effects on infrastructure. There are various types of infrastructure present in these coastal regions, and each is affected in a unique way by climate change and cyclones. To facilitate interventions and decisions aimed at improving the resilience of Bangladesh to cyclones, it is necessary to identify the types of infrastructure that receive most of the impacts from these hazards. The IPCC (2007) outlined the various impacts of 'baseline' climate change on infrastructure in the country. Their report highlighted these impacts would damage existing infrastructure through material expansion in cyclones shelters, houses and roads; softening of road surfaces; and increased embankment wear-down. The World Bank published another report highlighting that higher temperatures and heavier rainfall in Bangladesh would also increase congestion or waterlogging in polders (Adams *et al.*, 2011).

Adams *et al.*, (2011) also analysed the consequences of stronger cyclones on infrastructure and highlighted that an increase in storm surges height would result in stimulated coastal embankment erosion and also contribute to more frequent polders and embankment overtopping. Mallick *et al.* (2011) further confirmed this while also emphasising the risk of faster road inundation as a result of enhanced precipitation and the risk of cyclone shelters failure as a result of higher storm surges. They also highlighted that faster road inundation will prevent locals from finding shelter. Furthermore, the government of Bangladesh also estimated that stronger cyclonic winds could lead to partial or complete structural failure of the very infrastructure currently offering shelter during cyclones: houses and cyclone shelters (Wazed, 2012).

It appears that five types of infrastructure along the coasts are particularly vulnerable to climate change induced hazards: roads, cyclone shelters, coastal embankment, roads, and polders. Some of them – such as embankments, polders, and cyclone shelters – were designed and built specifically to offer protection from cyclones. Coastal embankments are the first barrier against storm surges as they contain water and lead to surge energy dissipation, which can significantly reduce damages and fatalities (Mallick *et al.*, 2011; Islam and Miah, 2012). The term 'embankment' also refers to rail and road embankments, but within this publication, this word will be used to refer to coastal embankments only. Current embankment capacity in Bangladesh offers protection to 35 million people (Islam and Miah, 2012) . However, most existing embankments have not been designed for appropriate surge heights and suffer from poor drainage (Agrawala *et al.*, 2003). Their important role in defence against storm surges – the main source of damage during a cyclone in Bangladesh, and the one feature of cyclones that only embankments can offer prevention against – inevitably means that embankment failure would be disastrous.

The Bangladesh coastal area consists of over 100 polders, which are man-made low-lying tracts of land surrounded by embankments, designed to limit damages related to seasonal or cyclone-induced flooding (Pukinskis, 2018). However, their protective action has already been found to be fading as a result of climatic changes that occurred since they were designed (ibid). Studies show that a large proportion of polders is vulnerable to overtopping, which is a particularly worrying issue as development around the polders has been predominant since they tend to be considered safe areas (Adams *et al.*, 2011).

Cyclone shelters are a key feature of disaster risk reduction as they are the most efficient structures capable of protecting populations from strong winds and precipitation (Dasgupta *et al.*, 2014). As they are designed specifically for strong winds and high inundation levels, their resilience is therefore normally higher than other types of infrastructure (Hossain *et al.*, 2008). However, their protective role during cyclones means that the impact of a shelter failing or becoming unfit for purpose is very high (IPCC, 2007; Mallick *et al.*, 2011). Estimates from the IPCC and World Bank state that, to ensure adequate protection for the population from 2050 climate predictions, 5,700 additional cyclone shelters will be required (IPCC, 2007; Adams *et al.*, 2011).

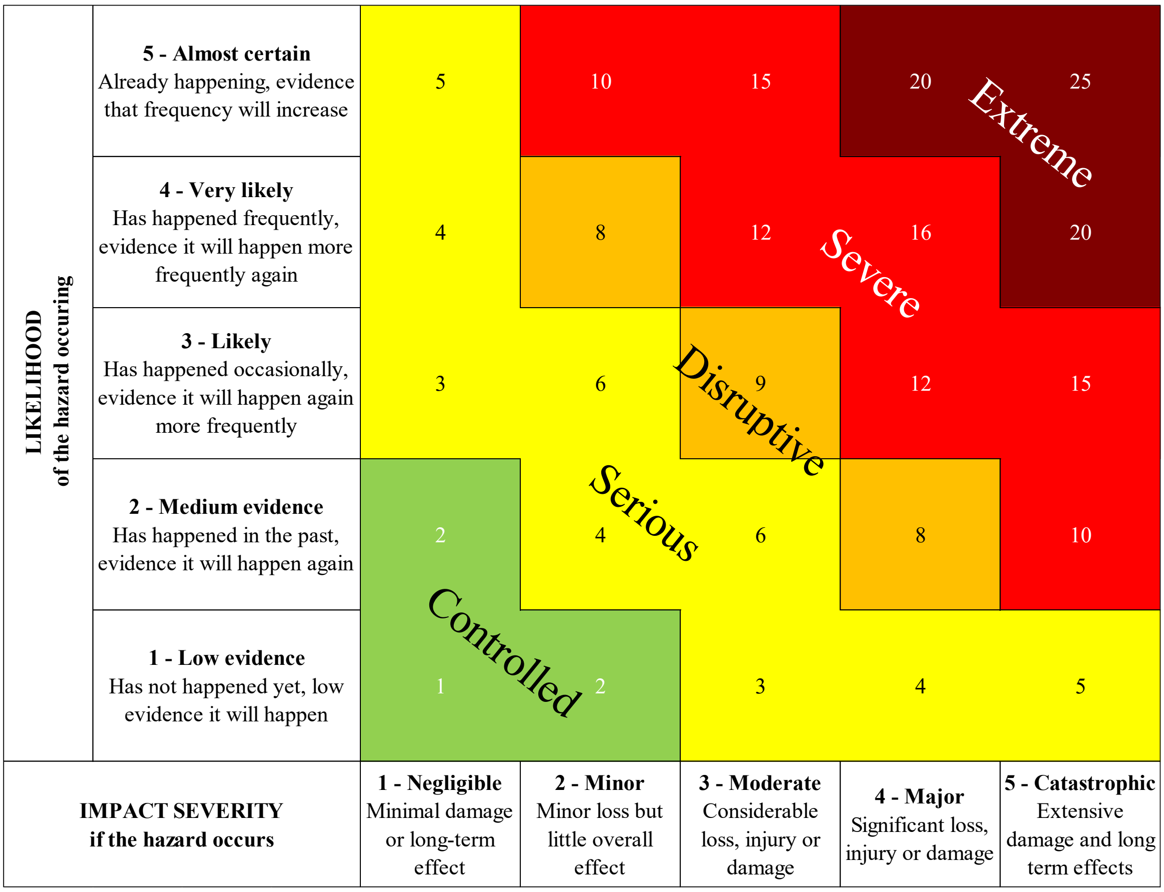
Although houses and roads are not primarily designed to offer protection during cyclones, their role in coping with hydrometeorological hazard events is key and their resilience can have an impact on damages and loss of lives during a cyclone. Houses can also provide protection for residents where access to cyclone shelters is limited. However, the lack of regulations regarding housing development in Bangladesh means construction standards are rarely sufficient to resist cyclones, even more so in the climate change scenario. Moreover, many government-built houses were constructed following disasters, which means construction was rushed and unregulated (Kabir, 2009). This means that dedicated cyclone shelters are still crucial in order to save lives during a cyclone event.

Roads are key for proper evacuation to cyclone shelters or higher elevations during a cyclone, therefore road failure would have important indirect consequences, such as preventing proper evacuation to safer areas. The coastal area of Bangladesh has a road network length of 1000km, which represents 22% of the total national and regional network (Ali *et al.*, 2002). This means that over one fifth of the country's road network is located in areas exposed to cyclones (IDC3, 1999).

Coastal areas in Bangladesh contain other types of infrastructure, including but not limited to water supply, sewage, telecommunications, railways, and others. These types of infrastructure, when located on coastal areas, where cyclones hit at their highest intensities, are also damaged. However, in order to help prioritise mitigation interventions, it is necessary to assess which types of infrastructure are most critical during cyclones. During our review of literature, it is the five types of infrastructures previously mentioned – coastal embankments, polders, cyclones shelters, houses and roads – that appeared as most crucial due to their critical defensive role during a cyclone, be it through shelter or evacuation. These will therefore be the focus of this assessment, and other types of infrastructure remain out of the scope of this research.

5. Risk framework

Risk severity matrices are frequently used to assess risk in a variety of settings. They enable stakeholders to allocate a likelihood and an impact severity to each hazard, which can be combined together to assess the level of risk. This in turn enables various qualitative risks to be compared and ranked to establish priority levels and help decision-making. Risk matrices can be adapted from standards available in the literature in order to adjust likelihood, impact and risk for each specific scenario (see eg WHO, 2012; Australian Institute for Disaster Resilience, 2020). Following from the literature, we propose, a risk severity matrix as outlined in Table 2 below. This matrix enables risk to be categorised for each type of infrastructure, for each of the six prioritised hazards, in consideration of the likelihood of these hazards occurring in the future, based on climate change predictions. The matrix is designed to go one step further than current risk maps, considering not only current risk, which is based on the current severity of the hazards, but also future risk.



LIKELIHOOD **of the hazard occuring**	**5 - Almost certain** Already happening, evidence that frequency will increase	5	10	15	20	25
	4 - Very likely Has happened frequently, evidence it will happen more frequently again	4	8	12	16	20
	3 - Likely Has happened occasionally, evidence it will happen again more frequently	3	6	9	12	15
	2 - Medium evidence Has happened in the past, evidence it will happen again	2	4	6	8	10
	1 - Low evidence Has not happened yet, low evidence it will happen	1	2	3	4	5
IMPACT SEVERITY **if the hazard occurs**		**1 - Negligible** Minimal damage or long-term effect	**2 - Minor** Minor loss but little overall effect	**3 - Moderate** Considerable loss, injury or damage	**4 - Major** Significant loss, injury or damage	**5 - Catastrophic** Extensive damage and long term effects

Table 2: Risk severity matrix.

Following the hazards in Table 1 we analyse the future likelihood of each prioritised hazard below. The IPCC (2012) stated that it is “virtually certain” that the frequency and magnitude of warm daily temperatures extremes will increase. Gosling *et al.* (2011) further quantified this increase at 3-3.5 ºC for the country of Bangladesh. The IPCC (2012) also assessed an upward trend in sea-level rise as “very likely”, and Hoegh-Guldberg *et al.* (2018) and Agrawala *et al.* (2003) estimated it would be within the range of 0.3 to 1m depending on the increase in global temperatures. Finally, the IPCC (2012) assessed the probability of an increase in heavy precipitations is “likely”, and is estimated at 5-20% increase for Bangladesh (Gosling *et al.*, 2011).

Regarding the impact of climate change on different hydrometeorological features of cyclones in Bangladesh, the IPCC (2012) stated that an increase in cyclone maximum wind speed is likely, in the range of 10 to 22% (Ali, 1999). No statements were made regarding the likelihood of an increase in storm surge height, however, research by Ali (1996, 1999) showed a correlation between stronger winds and higher storm surges, with winds assumed to contribute to around 90% of surge formation – the remaining 10% being due to cyclonic atmospheric pressure changes. Therefore, the same likelihood was assumed for higher storm surges. Ali (1999) then further quantified this increase in storm surge height from 13 to 49% depending on the extent of sea-level rise. Finally, the IPCC (2012) also mentioned “medium evidence” that flooding in some regions will increase as a result of heavier precipitations during climate extremes. With global warming, the area prone to flooding in Bangladesh is expected to increase by 20% (Dastagir, 2015).

Based on the evidence presented above from the literature, we assign a likelihood of occurrence to each of the six prioritised hazards under climate change, as shown in Table 3 below. The table shows that the likelihood of hazards stemming from the baseline climate change is higher overall, than that of hazards stemming from stronger cyclones, which is due to the extreme nature of cyclones and the difficulty associated with their prediction.

Source	Hazard	Likelihood
BASELINE CLIMATE CHANGE HAZARDS	Higher temperatures	Almost certain (5)
	Sea-level rise	Very likely (4)
	Heavier precipitations	Likely (3)
CYCLONE HAZARDS	Stronger winds	Likely (3)
	Higher storm surges	Likely (3)
	Rapid flooding	Medium evidence (2)

Table 3: Likelihood of various hazards occurring under predicted climate change.

Next, we expand on the analysis of section 4 to assess further the impact severity on each type of infrastructure, for each of the hazards. A review of the literature was carried out to qualitatively assess in detail the impact each hazard could have on each infrastructure type, and an impact severity was then attributed accordingly. The analysis can be found in Table 4 for baseline climate change hazards, and in Table 5 for hazards relating to stronger cyclones.

Hazard		Type of infrastructure affected				
		Roads	Cyclone Shelters	Embankments	Houses	Polders
BASELINE CLIMATE CHANGE	Higher temperatures	**MINOR** Increased softening as a result of material expansion (IPCC, 2007).	**MINOR** Increasing temperatures might cause material expansion and weaken concrete structures (IPCC, 2007).	**NEGLIGIBLE**	**MINOR** Material expansion might affect structural stability of houses (IPCC, 2007).	**MINOR** Increased influx of sediments from the melting Himalayans glaciers (Adams *et al.*, 2011).
	Sea-level rise	**NEGLIGIBLE**	**NEGLIGIBLE**	**MAJOR** Higher sea levels will stimulate embankment erosion (Mallick *et al.*, 2011); Embankments will be unable to protect zones due to increased sea levels (Islam *et al.*, 2011).	**NEGLIGIBLE**	**MODERATE** Polders will be more vulnerable to flooding if embankments are not high enough (Islam *et al.*, 2011).
	Heavier precipitations	**MODERATE** Brick surfaced or unsurfaced roads unable to withstand static flood conditions (Amin *et al.*, 2020); Enhanced precipitations will cause more frequent and intense damage to road surfaces (IPCC, 2007); Problem of saline intrusion will increase as a result of enhanced flooding (Mallick *et al.*, 2011); Proportion of network vulnerable to inundation from seasonal monsoon will increase (Dasgupta *et al.*, 2014); Vertical displacement of road embankments increased with higher ground-water levels (McKenna *et al.*, 2021).	**MINOR** More intense monsoon flooding will increase erosion of lower shelter levels (IPCC, 2007).	**MINOR** Wear down will be emphasised as a result of more frequent precipitation (IPCC, 2007; Mallick *et al.*, 2011)	**MINOR** Enhanced monsoon flooding will increase house wear down and stimulate saline intrusion (Mallick *et al.*, 2011).	**MINOR** Water logging in polders will become a growing issue due to heavier rainfall (Adams *et al.*, 2011).

Table 4: Impact severity for each type of infrastructure, for each hazard stemming from baseline climate change.

Hazard		Type of infrastructure affected				
		Roads	Cyclone Shelters	Embankments	Houses	Polders
STRONGER CYCLONES	Stronger winds	**NEGLIGIBLE**	**CATASTROPHIC** More flying debris and falling trees will impede access to shelters and cause secondary damage (IPCC, 2007); Stronger winds might lead to partial or complete structural failure (Wazed, 2012).	**MAJOR** Enhanced erosion due to stronger wind action; Embankment overtopping will be more frequent (IPCC, 2007).	**CATASTROPHIC** More damage inflicted to houses during cyclones and therefore higher risk of failure (Wazed, 2012).	**MODERATE** More frequent embankment overtopping as a result of stronger winds will damage polders (IPCC, 2007).
	Higher storm surges	**CATASTROPHIC** Larger proportion of network flooded; Current road surfacing unable to sustain major erosive flood impact (IPCC, 2007)	**CATASTROPHIC** Higher inundation levels might flood upper levels of the shelters and make them unfit for purpose; Faster road inundation during a cyclone will block access to shelters (Mallick *et al.*, 2011); Increase in area (and therefore population) susceptible to inundation will mean that existing shelter capacity is exceeded (Islam *et al.*, 2011).	**CATASTROPHIC** Embankments will be unable to protect some zones anymore due to increased inundation depths (Adams *et al.*, 2011); Increased pressure as a result of higher surges will increase risk of failure (Mallick *et al.*, 2011); Enhanced wave action will favour erosion (Adams *et al.*, 2011).	**CATASTROPHIC** Current house elevation might not be enough to withstand future storm surges heights (Sameen, 2018); More houses affected by saline intrusion (Mallick *et al.*, 2011)	**CATASTROPHIC** More frequent embankment overtopping as a result of higher storm surges will damage polders (Mallick *et al.*, 2011).
	Rapid flooding	**CATASTROPHIC** Faster flooding of roads essential to proper evacuation (Mallick *et al.*, 2011); Current drainage issues during cyclones will be worsened (Adams *et al.*, 2011): Roads become impassable after just 300mm of flooding (Pregnolato *et al.*, 2017).	**MODERATE** Faster road inundation during a cyclone will block access to shelters (Mallick *et al.*, 2011).	**MODERATE** Heavier precipitations will worsen existing issues with embankment drainage (Agrawala *et al.*, 2003; S. Rahman and Rahman, 2015).	**CATASTROPHIC** Houses flooded due to higher inundation levels (Sameen, 2018).	**MODERATE** Polder congestion during a cyclone will become a growing issue due to heavier rainfall (Adams *et al.*, 2011).

Table 5: Impact severity for each type of infrastructure, for each hazard stemming from stronger cyclones.

By multiplying the likelihood of each hazard occurring and the impact severity of each hazard on various types of infrastructure, as per Table 2, we obtain a value of risk which categorises each risk from controlled to extreme. Table 6 below shows the results of this analysis. The risks are assigned colours as per Table 2.

As can be seen below, all of the risks identified in this table are classified as serious, disruptive, or severe. The total risk is summarised for each hazard and for each type of infrastructure. The maximum total risk value possible for each hazard is 125, and for each type of infrastructure it is 150. The overall risk is also calculated for the main sources of hazard: namely baseline climate change hazards and cyclone hazards, to a maximum total of 375.

Source	**Hazard**	**Type of infrastructure affected**					***Total (per hazard, out of 125)***	***Total (per source, out of 375)***
		Roads	**Cyclone Shelters**	**Embankments**	**Houses**	**Polders**		
BASELINE CLIMATE CHANGE	Higher temperatures	10	10	5	10	10	45	118
	Sea-level rise	4	4	16	4	12	40	
	Heavier precipitations	9	6	6	6	6	33	
STRONGER CYCLONES	Stronger winds	3	15	12	15	9	54	167
	Higher storm surges	15	15	15	15	15	75	
	Rapid flooding	10	6	6	10	6	38	
Total (per type of infrastructure, out of 150)		51	56	60	60	58		

Table 6: Final risk value for each hazard and each type of infrastructure.

Serious risks require active monitoring under the form of regular assessments of the evolution of infrastructure functionality for relevant hazards (Achillopoulou *et al.*, 2020). Disruptive risks require an investigation, and severe risks require rapid action. Although the absence of extreme risks from this table could be seen as positive, the lack of controlled risks and the abundance of severe risks suggests rapid action is needed. The quantitative value associated with each risk helps with prioritising risks from the same risk category, and highlights which hazards have the most severe impact, and which infrastructure type is most vulnerable. Looking at cumulative risk values for each type of infrastructure, embankments and houses present the highest risks, followed by polders, cyclone shelters, and roads, respectively. However, the combined scores do not vary by much between each type, suggesting they are all at risk overall from the various changes anticipated due to climate change. Although the hazards stemming from baseline climate change were identified as more likely on Table 3, their combined risk value for all types of infrastructures is lower than that of hazards stemming from stronger cyclones. This is because although hazards from stronger cyclones are less likely to occur, their potential impacts are so severe that they present a bigger risk.

6. Discussion and recommendations

The aim of the framework presented here is to help transition from the understanding of current risks to an understanding of future risks in the climate change scenario, in order to identify which hazards will have the biggest impact, and which types of infrastructure will be most affected and should be given priority in policymaking. At the time of publication, to the best of the authors' knowledge, no study has been conducted looking specifically at the evolution of these hazards as a result of climate change and the increase in risk posed to infrastructure as a result of this.

Our assessment shows that stronger winds and higher storms surges are the two hazards presenting the highest risk, with storm surges presenting a catastrophic impact in all five categories of infrastructure. This result is in accordance with what is known of storm surge impact in Bangladesh from present day and historic cyclones, and highlights the need of improving coastal defences to fight the effects of climate change. In terms of infrastructure, embankments and houses are most at risk, and hence should be given particular attention by policymakers. However, as mentioned, all types of infrastructure are highly at risk, as even roads, which have the lowest cumulative risk, still fall within the 'severe' risk category for 3 types of hazards, meaning rapid action is needed to protect them. These results are consistent with Adams *et al.* (2011) who found that, in 2050, 44 to 59 polders will have been overtopped as a result of intensified storm surges. Our results also show that hazards from baseline climate change result in several severe risks, even in the absence of stronger cyclones. Regardless of how cyclones evolve as a result of global warming, it appears that climate change on its own will hence make Bangladeshi infrastructure more vulnerable to all cyclones.

Nevertheless, a risk framework doesn't tell the whole story. This assessment adds the individual risks per hazard to obtain a total value of risk for each infrastructure element. The cumulative effect of several hazards acting together on one type of infrastructure might however not always be represented by a simple addition, as one hazard might exacerbate the impact of another. Moreover, only the impact on infrastructure structural integrity is considered whereas, as previously discussed, vulnerability affects many dimensions. Socio-economic or eco-environmental vulnerability, for example, are outside of the scope of this analysis. The framework used here does not consider other factors affected by cyclones, such as population or the natural environment. For example, as polders have long been seen as safe areas, development around them has been predominant. Partial polder damage could therefore lead to more casualties than complete house failure, due to the number of lives affected by each. Damage to infrastructure is only one part of the narrative and, although loss of lives can be correlated with infrastructure damage, more assessments of exposure are required to be able to draft efficient policies to protect Bangladesh and its population from a warming climate.

The spatial distribution of the hazard intensity has not been considered within the scope of this analysis. The height and impact speed of storm surges, the wind velocities, and the rain intensities vary across the territory of Bangladesh during a cyclone. Analysis performed by Hoque *et al.* (2019) included the development of a risk map for the eastern coastal region of Bangladesh while considering several factors including storm surge height, precipitation intensity, and cyclone wind speed. This analysis focuses only on the current state of the hazards, without accounting for their evolution in a changing climate. Moreover, further research is needed to assess the spatial distribution of different infrastructure types in these at-risk areas. For instance, The World Bank (2015) conducted a multi-criteria analysis to prioritise polders in need of improvement. They surveyed the country's 139 polders and selected 17 to be included as part of their priority group based on their physical condition, as well as the local social, economic and environmental conditions. This is important work, which could be extended for the six types of infrastructure identified here.

One question arising from this assessment is whether or not infrastructure is the right solution to protect populations from cyclones. It appears the resilience of infrastructure will be reduced by climate change, but, in Bangladesh, resilience of infrastructure to tropical cyclones has always been poor. This is caused by various factors such as lack of governance, financial limitations, geophysical features of the country, and frequency of extreme events, and raises the questions of whether Bangladesh should turn to a different approach when it comes to tropical cyclones.

Some types of infrastructure, such as roads and houses, are not built specifically to offer protection from cyclones, but serve a different purpose. Therefore, it is essential to ensure they are resilient, as they cannot be replaced. Various engineering solutions have been researched to increase the resilience of such types of infrastructure, such as the use of stronger materials, or the increase in infrastructure elevation. Yet, achieving full structural stability in such high-risk zones is not a realistic target, especially with limited resources and in a warming climate. However, the resilience of communities to cyclones goes beyond resilience of their infrastructure; socio-economic resilience can be achieved by other means. Inclusion and empowerment of communities can be a solution in a context where full structural resilience cannot be achieved due to costs, uncertainty of climate evolution, and engineering limitations.

As far as cyclone shelters are concerned, they will always remain a key feature of disaster risk reduction as they are the most efficient type of structure to protect populations from winds and precipitation. Moreover, their role is expected to grow in the future as embankments might not be able to prevent inland penetration of surges anymore. Although the structural integrity of cyclone shelters appears at risk, it is likely that the main issues with cyclone shelters that will be faced by the people of Bangladesh concern access to shelters and shelter availability, and these should therefore become the focus of disaster mitigation policies.

When it comes to embankments and polders, their primary purpose is to offer protection from storm surges. They often are the main focus of improvement projects like those of The World Bank (2015). However, with a changing, uncertain climate bringing about higher sea levels and storm surges, the local authorities might need to rethink their main line of defence against cyclones, especially since research by Adnan *et al.* (2019) and Hui *et al.* (2012) showed that embankments and polders can exacerbate flooding during more extreme events. Hybrid solutions combining traditional engineered structures and green elements have been shown to be efficient to protect coastlines from tsunamis, and could therefore represent a viable solution for the coastline of Bangladesh. If other means of protection are developed, upgrading current polders and embankments might not be necessary.

Design and construction standards in Bangladesh could be updated to improve resilience to future effects of climate change, but full structural stability is unlikely to be achieved. Alternative solutions should be prioritised, such as the use of nature to offer protection, the implementation of better evacuation procedures, the integration of communities to the building process, and the relocation of populations to less exposed areas, as these will most likely be the most resilient, sustainable, and financially viable solutions. Finally, monitoring should be adopted as an essential tool to collect feedback on current mitigation measures and accelerate the decision-making process, as highlighted in Achillopoulou *et al.* (2020). Adopting these various measures will help local authorities estimate which disaster mitigation measures to implement in their area.

7. Conclusion

Estimating how cyclones will evolve with climate change remains an inexact science. This makes any attempt to assess future resilience of infrastructure to cyclones particularly challenging, and in turn may prevent the development of adequate climate adaptation policies. Climate change predictions come with a lot of uncertainty, but one thing that is certain is that infrastructure in Bangladesh is not resilient enough to withstand current climate and current cyclonic intensities, meaning its resilience will only worsen with global warming.

In this project, a risk framework was developed to assess the risk severity of various climate change induced hazards impacting on six types of infrastructure in Bangladesh. The outcomes show that all risks are serious, disruptive, or severe, suggesting that rapid action is needed by local authorities to improve the resilience of infrastructure. However, in addition to strengthening the resilience of some types of infrastructure that are essential and cannot be replaced, Bangladesh should consider the use of alternative solutions that might be better suited to the country’s unique geophysical, geographical, social and financial contexts. Additionally, we recommend further research and work to enable the detailed mapping of future hazard and infrastructure spatial distributions, in order to prioritise areas where rapid interventions should be initiated.

Climate change will have immeasurable costs for all countries, even in the best-case scenarios. However, it is likely that most of the infrastructure that will be in place by 2050 – when consequences from climate change are expected to be much greater than they are now – has not yet been built today. This implies that resilience of future infrastructure is still a matter of choice rather than adaptation.

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8. References

Achillopoulou, D. V. *et al.* (2020) 'Monitoring of transport infrastructure exposed to multiple hazards: a roadmap for building resilience', *Science of the Total Environment*. Elsevier B.V., 746(July), p. 141001. doi: 10.1016/j.scitotenv.2020.141001.

Adams, N., Dasgupta, S. and Sarraf, M. (2011) 'The cost of adapting to extreme weather events in a changing climate (English)', *Bangladesh Development Series*. Washington, D.C., 28. Available at: http://documents.worldbank.org/curated/en/716231468014361142/The-cost-of-adapting-to-extreme-weather-events-in-a-changing-climate.

Adnan, M. S. G., Haque, A. and Hall, J. W. (2019) 'Have coastal embankments reduced flooding in Bangladesh?', *Science of the Total Environment*. Elsevier B.V., 682, pp. 405–416. doi: 10.1016/j.scitotenv.2019.05.048.

Agrawala, S. *et al.* (2003) 'Development and Climate Change in Bangladesh: focus on coastal flooding and the Sundarbans', *Organisation for Economic Co-operation and Development-OECD*, pp. 1–70. Available at: http://www.pisa.oecd.org/dataoecd/46/55/21055658.pdf.

Albert, V. (2018) *Hurricanes Are Now So Violent That We May Need a New Category*, *Daily Beast*. Available at: https://www.thedailybeast.com/hurricanes-are-now-so-violent-that-we-need-a-new-category (Accessed: 4 July 2020).

Ali, A. (1979) *Storm surges in the Bay of Bengal and some related problems*. University of Reading, England. Available at: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.447366.

Ali, A. (1996) 'Vulnerability of Bangladesh to Climate Change and Sea Level Rise through Tropical Cyclones and Storm Surges', in Erda, L. et al. (eds) *Climate Change Vulnerability and Adaptation in Asia and the Pacific*. Dordrecht: Springer Netherlands, pp. 171–179.

Ali, A. (1999) 'Climate Change Impacts and Adaptation Assessment in Bangladesh', *Clim. Res.*, 12, pp. 109–116.

Ali, M. A., Seraj, S. M. and Ahmad, S. (2002) 'The Completeness and Vulnerability of Road Network in Bangladesh', in Ali, M. A. et al. (eds) *Engineering Concerns Of Flood, 1998 Perspective*. Dhaka: Bangladesh University Of Engineering And Technology, p. 380.

Amin, M. S. R., Tamima, U. and Amador, L. (2020) 'Towards resilient roads to storm-surge flooding: case study of Bangladesh', *International Journal of Pavement Engineering*, 21(1), pp. 63–73. doi: 10.1080/10298436.2018.1436706.

Anthes, R. A. *et al.* (2006) 'Hurricanes and Global Warming— Potential Linkages and Consequences', *Bulletin of the American Meteorological Society*, 87(May), pp. 623–628. doi: 10.1175/BAMS-87-1-XXX.

Australian Institute for Disaster Resilience (2020) 'National Emergency Risk Assessment Guidelines', *Australian Disaster Resilience Handbook Collection*. Available at: https://www.aidr.org.au/media/7600/aidr_handbookcollection_nerag_2020-02-05_v10.pdf.

BBC News (2020) *Amphan: Kolkata devastated as cyclone kills scores in India and Bangladesh*, *BBC News*. Available at: https://www.bbc.com/news/world-asia-india-52749935 (Accessed: 6 July 2020).

Berlemann, M. and Steinhardt, M. F. (2017) 'Climate change, natural disasters, and migration-a survey of the empirical evidence', *CESifo Economic Studies*, 63(4), pp. 353–385. doi: 10.1093/cesifo/ifx019.

Cardona, O. D. *et al.* (2012) 'Determinants of risk: exposure and vulnerability.', in Ield, C. B. et al. (eds) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).* Cambridge, UK, and New York, NY, USA: Cambridge University Press, pp. 65–108.

Chaitanya, K. (2020) *Chennai braces for heatwave due to super cyclone Amphan, mercury breaches 40-degree mark*, *The New Indian Express*. Available at: https://www.newindianexpress.com/cities/chennai/2020/may/19/chennai-braces-for-heatwave-due-to-super-cyclone-amphan-mercury-breaches-40-degree-mark-2145375.html (Accessed: 6 July 2020).

Climate Council (2017) *Tropical cyclones and climate change: factsheet*, *Climate Council*. Available at: https://www.climatecouncil.org.au/uploads/3cf983377b8043ff1ecf15709eebf298.pdf (Accessed: 21 January 2021).

Dasgupta, S. *et al.* (2014) 'Cyclones in a changing climate: the case of Bangladesh', *Climate and*

Development, 6(2), pp. 96–110. doi: 10.1080/17565529.2013.868335.

Dastagir, M. R. (2015) ‘Modeling recent climate change induced extreme events in Bangladesh: A review’, *Weather and Climate Extremes*. Elsevier, 7, pp. 49–60. doi: 10.1016/j.wace.2014.10.003.

Emanuel, K. A. (1987) ‘The dependence of hurricane intensity on climate’, *Nature*, 326, pp. 483–485. Available at: https://www.nature.com/articles/326483a0.pdf.

Emanuel, K. A. (2000) ‘A Statistical Analysis of Tropical Cyclone Intensity’, *Monthly Weather Review*, 128(4), pp. 1139–1152. doi: https://doi.org/10.1175/1520-0493(2000)128<1139:ASAOTC>2.0.CO;2.

Emanuel, K. A. (2005) ‘Emanuel replies’, *Nature*, 438(E13). doi: https://doi.org/10.1038/nature04427.

Gosling, S. . *et al.* (2011) *Bangladesh*, *Climate: Observations, projections and impacts*. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/climate/bangladesh.pdf.

Gray, W. M. (2005) ‘Comments on: “Increasing destructiveness of tropical cyclones over the past 30 years” by Kerry Emanuel’, *Nature*, 436(July), pp. 686–688.

Hoegh-Guldberg, O. *et al.* (2018) ‘Impacts of 1.5°C global warming on natural and human systems.’, in Masson-Delmotte, V. et al. (eds) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,* pp. 175–311. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Chapter3_Low_Res.pdf.

Hoque, M. A. A. *et al.* (2019) ‘Tropical cyclone risk assessment using geospatial techniques for the eastern coastal region of Bangladesh’, *Science of the Total Environment*. Elsevier B.V., 692, pp. 10–22. doi: 10.1016/j.scitotenv.2019.07.132.

Hossain, M. Z. *et al.* (2008) ‘Impact of Tropical Cyclones on Rural Infrastructures in Bangladesh’, *Agricultural Engineering International: the CIGR EJournal*, 2(X), p. 13.

Hughes, F., Hodkinson, J. and Montgomery, H. (2017) ‘Tropical cyclones and public health: how climate change is driving increasingly extreme weather—an essay’, *Bmj*, 359, p. j4908.

Hui, R., Jachens, E. and Lund, J. (2012) ‘Risk-based planning analysis for a single levee’, *Water Resources Research*, 52, pp. 2513–2528. doi: 10.1002/ 2014WR016478.

Huq, M. *et al.* (2010) *Vulnerability of Bangladesh to cyclones in a changing climate: Potential damages and adaptation cost.* doi: https://doi.org/10.1596/1813-9450-5280.

IDC3 (1999) *Roads in Bangladesh The Next Millennium*. Available at: http://www.rhd.gov.bd/Documents/RHDPublications/RoadsInBangladesh/Glossy_19_Revised.pdf.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by R. . Pachauri, A. Reisinger, and Core Writing Team. IPCC, Geneva, Switzerland. Available at: https://www.ipcc.ch/report/ar4/syr/.

IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Edited by C. B. Field et al. doi: 10.1017/CBO9781139177245.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by T. F. Stocker et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Islam, A. S. *et al.* (2011) ‘Performance of Coastal Structures during Cyclone Sidr’, *Natural Hazards Review*, 12(3), pp. 111–116. doi: https://doi.org/10.1061/(ASCE)NH.1527-6996.0000031.

Islam, S. and Miah, S. (eds) (2012) ‘Embankment’, in *Banglapedia: National Encyclopedia of Bangladesh*. 2nd edn. Asiatic Society of Bangladesh. Available at: http://en.banglapedia.org/index.php?title=Embankment.

Islam, T. and Peterson, R. E. (2009) ‘Climatology of landfalling tropical cyclones in Bangladesh 1877–2003’, *Natural Hazards*, 48(1), pp. 115–135. doi: 10.1007/s11069-008-9252-4.

Jenner, L. (2020) *Amphan – Northern Indian Ocean*, *NASA*. Available at: https://blogs.nasa.gov/hurricanes/2020/05/18/amphan-northern-indian-ocean-2/ (Accessed: 6 July 2020).

Kabir, R. (2009) *Post-Cyclone Sidr Family Shelter Construction in Bangladesh - Documentation of Plans and Processes*. Bangladesh: Shelter Working Group. Available at: https://designchallengebangladesh.files.wordpress.com/2014/12/post-cyclone20sidr20family20shelter20construction20in20bangladesh1.pdf (Accessed: 24 January 2021).

Kantha, L. (2013) ‘Classification of hurricanes : Lessons from Katrina, Ike, Irene, Isaac and Sandy’, *Ocean Engineering*, 70, pp. 124–128. doi: 10.1016/j.oceaneng.2013.06.007.

Knutson, T. R. *et al.* (2015) ‘Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios’, *Journal of Climate*, 28(18), pp. 7203–7224. doi: 10.1175/JCLI-D-15-0129.1.

Knutson, T. R. and Tuleya, R. E. (2004) ‘Impact of CO2 -Induced Warming on Simulated Hurricane Intensity and Precipitation : Sensitivity to the Choice of Climate Model and Convective Parameterization’, *Journal of Climate*, 17(18), pp. 3477–3495.

Lavell, A. *et al.* (2012) ‘Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience’, in Field, C. B. et al. (eds) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge, UK, and New York, NY, USA: Cambridge University Press, pp. 25–64. doi: 10.1017/CBO9781139177245.004.

Mallick, B., Rahaman, K. R. and Vogt, J. (2011) ‘Coastal livelihood and physical infrastructure in Bangladesh after cyclone Aila’, *Mitigation and Adaptation Strategies for Global Change*, 16(6), pp. 629–648. doi: 10.1007/s11027-011-9285-y.

McKenna, G. *et al.* (2021) ‘Multiple hazard fragility analysis for granular highway embankments: Moisture ingress and scour’, *Transportation Geotechnics*. Elsevier, 26(April 2020), p. 100431. doi: 10.1016/j.trgeo.2020.100431.

Murty, T. S. and El-Sabh, M. I. (1992) ‘Mitigating the Effects of Storm Surges Generated by Tropical Cyclones: A Proposal.’, *Natural Hazards*, 6(3), pp. 251–273.

Nagchoudhary, S. and Paul, R. (2020) *Cyclone kills 14 in India, Bangladesh leaving trail of destruction*, *Reuters*. Available at: https://www.reuters.com/article/us-asia-storm-india/cyclone-kills-14-in-india-bangladesh-leaving-trail-of-destruction-idUSKBN22W0MT (Accessed: 6 July 2020).

Nandi, J. and Thakur, J. (2020) *Amphan transforming into super cyclone, first after deadly 1999 super cyclone in Bay of Bengal*, *Hindustan Times*. Available at: https://www.hindustantimes.com/india-news/amphan-transforming-into-super-cyclone-first-after-deadly-1999-super-cyclone-in-bay-of-bengal/story-12vMmByNipIQwibsJwHJIO.html (Accessed: 6 July 2020).

Pielke, R. A. (2005) ‘Are there trends in hurricane destruction?’, *Nature*, 438, p. E11. doi: 10.1038/nature04426.

Pregnolato, M. *et al.* (2017) ‘The impact of flooding on road transport: A depth-disruption function’, *Transportation Research Part D: Transport and Environment*. The Authors, 55, pp. 67–81. doi: 10.1016/j.trd.2017.06.020.

Pukinskis, I. (2018) *The polder promise: Unleashing the productive potential in southern Bangladesh*, *International Water Management Institute*. Available at: https://wle.cgiar.org/sites/default/files/documents/The polder promise_WLE.pdf (Accessed: 24 January 2021).

Quader, M., Khan, A. and Kervyn, M. (2017) ‘Assessing Risks from Cyclones for Human Lives and Livelihoods in the Coastal Region of Bangladesh’, *International Journal of Environmental Research and Public Health*, 14(8), p. 831. doi: 10.3390/ijerph14080831.

Rahman, M. A. and Rahman, S. (2015) ‘Natural and traditional defense mechanisms to reduce climate risks in coastal zones of Bangladesh’, *Weather and Climate Extremes*. Elsevier, 7, pp. 84–95. doi: 10.1016/j.wace.2014.12.004.

Rahman, S. and Rahman, M. A. (2015) ‘Climate extremes and challenges to infrastructure development in coastal cities in Bangladesh’, *Weather and Climate Extremes*, 7, pp. 96–108. doi: 10.1016/j.wace.2014.07.004.

Reed, D. A. *et al.* (2010) ‘Energy Infrastructure Damage Analysis for Hurricane Rita’, *Natural Hazards Review*, 11(3), pp. 102–109. doi: 10.1061/(ASCE)NH.1527-6996.0000012.

Roy, P., Hasan, R. and Mohiuddin Alamgir (2020) *Amphan inflicts massive damage*, *The Daily Star*. Available at: https://www.thedailystar.net/frontpage/news/amphan-inflicts-massive-damage-1904977?browserpush=true (Accessed: 6 July 2020).

Sameen, S. (2018) ‘Process inclusive Infrastructure: Notions towards Cyclone Resilience in Bangladesh’, *Procedia Engineering*, 212, pp. 30–38. doi: 10.1016/j.proeng.2018.01.005.

Shamsuddin, A. (2008) *BANGLADESH: Country expands despite global warming*.

Sud, V. and Rajaram, P. (2020) *Cyclone Amphan caused an estimated $13.2 billion in damage in India’s West Bengal: government source*, *CNN*. Available at: https://www.cnn.com/2020/05/22/weather/cyclone-amphan-damage-intl-hnk/index.html (Accessed: 6 July 2020).

The World Bank (2015) *Bangladesh - First Phase of the Coastal Embankment Improvement Project : environmental and social management framework - executive summary*, *World Bank Group*. Available at: http://documents1.worldbank.org/curated/en/190421468208158055/pdf/767200BR0P1282090Box374386B00OUO090.pdf (Accessed: 25 January 2021).

Unnikrishnan, A. S. *et al.* (2006) ‘Sea level changes along the Indian coast: Observations and projections’, *Current Science India*, 90(3), pp. 362–368.

Vose, R. S. *et al.* (2012) ‘Noaa’s merged land-ocean surface temperature analysis’, *Bulletin of the American Meteorological Society*, 93(11), pp. 1677–1685. doi: 10.1175/BAMS-D-11-00241.1.

Wazed, M. A. (2012) *Cyclone Shelter Construction , Maintenance and Cyclone Shelter Construction, Maintenance and Management Policy 2011*, *Ministry of Disaster Management and Relief, Government of the People’s Republic of Bangladesh*. Dhaka. Available at:

https://modmr.portal.gov.bd/sites/default/files/files/modmr.portal.gov.bd/policies/689b5850_4308_4c11_af48_db45931a9fa0/Cyclone Shelter Construction Maintenance and Management Policy 2011.pdf (Accessed: 24 January 2021).

Webster, P. J. *et al.* (2005) ‘Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment’, *Science*, 309, pp. 1844–1846.

WHO (2012) *Rapid Risk Assessment of Acute Public Health Events*, *World Health Organization*. Available at: https://www.who.int/csr/resources/publications/HSE_GAR_ARO_2012_1/en/ (Accessed: 24 January 2021).

Wing, A. A., Sobel, A. H. and Camargo, S. J. (2007) ‘Relationship between the potential and actual intensities of tropical cyclones on interannual time scales’, *Geophysical Research Letters*, 34(February), pp. 1–5. doi: 10.1029/2006GL028581.

Zargar, A. R. (2020a) *Huge Cyclone Amphan slams into India’s coast, and it’s already a killer*, *CBS News*. Available at: https://www.msn.com/en-us/news/world/huge-cyclone-slams-into-indias-coast-and-its-already-a-killer/ar-BB14memN (Accessed: 6 July 2020).

Zargar, A. R. (2020b) *Millions flee as monster cyclone churns toward India and Bangladesh*, *CBS News*. Available at: https://www.cbsnews.com/news/super-cyclone-amphan-india-bangladesh-evacuate-millions-latest-news-2020-05-19/ (Accessed: 6 July 2020).