Technical Report

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Interconnected Disaster Risks
2020/2021

Cyclone Amphan

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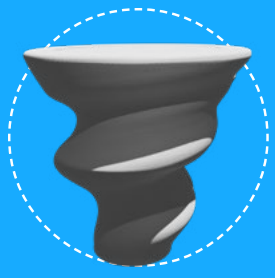

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1. Event

On May 13th, 2020, an area of low atmospheric pressure encountered exceptionally warm sea surface temperatures in the North Indian Ocean and started forming a cyclonic storm. It was classified as a tropical depression three days later, on May 16 (Kumar and others, 2021a), before undergoing rapid intensification from a cyclonic storm (Category 1) to a super cyclonic storm (Category 5) in less than 36 hours (Balasubramanian & Chalamalla, 2020). Reaching maximum wind speeds of up to 260 kmh-1 on May 18, this super cyclonic storm, given the name 'Amphan' (pronounced as Um-Pun), became the strongest cyclonic storm in the Bay of Bengal since 1999 (Khan and others, 2020). On the afternoon of May 20, Cyclone Amphan made landfall in a low-lying deltaic region straddling the border between India and Bangladesh (see Figure 1). The storm brought torrential rain and a storm surge of five metres above the average tidal height, with wind speeds reaching up to 155 kmh-1 as it hit the coast, causing devastation in the coastal regions of both countries (Basheer Ahammed & Pandey, 2021). This low-lying region has long struggled with high

Figure 1: Path of Cyclone Amphan, image Courtesy of DW

exposure to extreme weather events combined with high vulnerability driven by a number of factors, including unemployment, a high dependency ratio, unavailability of electricity, inadequate sanitation facilities, vector and waterborne diseases, and unavailability of paved roads (Sahana and others, 2019). Since Cyclone Amphan co-occurred with the COVID-19 pandemic, people were uniquely vulnerable due to the direct and indirect impacts of a novel biological hazard. As such, the response and management of the pandemic were often entirely at odds with preparing and responding to a cyclone and vice versa; the response to the cyclone was constrained by the pandemic and the respective containment measures (Pramanik and others, 2021).

Box 1 – The Bay of Bengal and the Sundarbans

The Bay of Bengal in the North Indian Ocean is the largest bay in the world. Five hundred million people live on the coastal rim that surrounds it. The Bay of Bengal has a shallow, concave topography conducive to storm surge events, and its high sea surface temperatures, which can trigger powerful cyclones, make its north coast one of the most prone areas to catastrophic surges in the world (Kumar and others, 2021b). In fact, 26 of the 35 deadliest tropical cyclones recorded have occurred here (Weather Underground, 2021). The Sundarbans are a large archipelago of islands stretched across the Ganges-Brahmaputra-Meghna (GBM) delta in the north of the Bay of Bengal. It is home to over 4.4 million people in India and Bangladesh and the largest contiguous mangrove ecosystem in the world (Ghosh and others, 2015). Around 50 per cent of people in the Sundarbans live below the poverty line, and nearly 80 per cent of households pursue small-scale rural livelihoods in agriculture, fishing and aquaculture (The World Bank, 2014). Due to the vulnerability of this low-elevation deltaic region, the local people rely on the mangrove forests and a system of artificial mud embankments for coastal protection from the frequent storm activity (Jalais & Mukhopadhyay, 2020). As climate change drives rising sea levels and sea surface temperatures that increase storm intensity and impact, the frequency of cyclonic events in the region (five to six per year on average) erodes people's ability to recover from one cyclone and be prepared for the next. This vulnerable coastal region bore the main brunt of Cyclone Amphan's impacts, and as such is the primary focus area of this report.

2. Impacts

Direct impacts

Cyclone Amphan killed 129 people and displaced 4.9 million more from their homes (WMO, 2021; IFRC, 2021). While many were able to return to their homes, thousands were left without shelter after millions of homes were destroyed (WMO, 2021). Cyclone Amphan was the most expensive cyclone of 2020 in terms of loss and damage and the fourth most costly disaster related to extreme weather, causing over US$13 billion in damages across India, Bangladesh and Sri Lanka (WMO, 2021; Kumar and others, 2021a). Critically, most of this damage is expected to have been uninsured (AON, 2020).

As coastal defences were overwhelmed with surging seawater and torrential rain, large swathes of the affected regions were flooded. In Bangladesh, an estimated 2,233 km2 of land was inundated on May 22 (Hassan and others, 2020). Agricultural and horticultural land, vital for food security and livelihoods in the region, was also heavily impacted, with up to 66 per cent of croplands on the Indian side of the border region damaged, the equivalent of 19,505 km2 (Sarkar, 2021; Basheer Ahammed & Pandey, 2021) (see section 2 – Loss of livelihoods). This inundated cropland may take years to recover and be productive. The flooding also exacerbated saltwater intrusion in the Sundarbans, where sea level rise leads to salinization and therefore degradation of soil and water quality (Dutta and others, 2021) (see section 2 – Food and water security).

This environmental degradation, combined with physical damage and erosion of the coast, also damaged the mangrove forests critical for coastal protection and livelihoods, with dense forest cover in some areas estimated to have reduced by up to 43 per cent (Mishra and others, 2021) (see section 2 – Biodiversity loss). The increased exposure and vulnerability of local communities was compounded by the extensive damage to infrastructure. Approximately 400 km of embankments and over 3,200 km of roads in India and Bangladesh were reported damaged, hindering response efforts and exposing more land to inundation (IFRC, 2021; BDRCS, 2020). In addition, Amphan damaged public health infrastructure that was already overwhelmed due to the strain of the COVID-19 pandemic, making matters worse. In West Bengal alone, 563 primary health centres, 169 sub-district primary health centres and 5,142 community-level sub-centres were damaged (IFRC, 2021). The pervasive flooding also inundated areas with debris and waste, increasing the risk of transmission of water-borne diseases.

Indirect impacts

Loss of livelihoods

In the Sundarbans, a large number of households depend on aquaculture and agriculture as primary sources of income. With fields and aquaculture ponds flooded and crops destroyed by Cyclone Amphan, these livelihoods have either already been lost or are at risk of loss in the long term, as many of the areas inundated by saltwater will remain unusable for years to come (Ober, 2020). Aquaculture and fishing provide important livelihood options for many households in the Sundarbans region, as the Sundarban area in West Bengal accounts for about 30 per cent of the total fish and aquaculture production of India (Pramanik and others, 2021). However, saltwater inundation ruined aquaculture ponds and killed 4,000 tonnes of fish and shrimp stock, causing an estimated loss to the region of over $200 million in fisheries production (Phadikar, 2021). Marine fisheries suffered damages estimated at over $5 million in damaged infrastructure and lost income in India alone (Raju and others, 2020b; Raju and others, 2020a). These agriculture and aquaculture industries also provided not only food security for the local community, but also the income to buy food, which grew increasingly more expensive as availability dwindled in the wake of the cyclone. For example, local market vendors in the Indian Sundarbans described a 20–30 per cent increase in the price of vegetables at the same time people's purchasing power was reduced (The Telegraph India, 2020) (see section 2 – Food and water security). Other important livelihoods, such as tourism and betel vine crops, were also impacted by Cyclone Amphan. The cyclone destroyed most of the betel vine leaves and disrupted the supply chain, reducing the viability of remaining crops in the future. At the same time the tourism industry, which was already shut down due to the lockdown from the COVID-19 pandemic, suffered long-lasting impacts as the cyclone damaged many boats and tourist resorts, which are a critical infrastructure for tourism in the delta (Pramanik and others, 2021).

Food and water security

Food insecurity is already a critical issue in the Sundarbans, with around 44 per cent of households living on fewer than two meals a day (Guha & Roy, 2016). The loss of livelihoods and resources as a result of Cyclone Amphan further increases the risk of food insecurity. Many households exhausted their food stores as incomes dried up and supply chains

were compromised, both in the wake of Cyclone Amphan and the COVID-19 pandemic. People were often dependent on the public food distribution system and NGOs, which provided weekly rice rations and dry-food kits (Dutta, 2020). These responses provided critical nutritional support; however, there were also allegations of inefficiency and corruption by some in the local community around how and when it was distributed by local governments (Pramanik and others, 2021). The long-term effects of saltwater intrusion on agricultural land and the resulting loss of livelihoods has direct implications for long-term food security. Around 74 per cent of people surveyed in Bangladesh reported losses due to inundation of their fields or ponds from Cyclone Amphan, and 63 per cent expect long-term food shortages (NAWG, 2020).

The damage wrought by Amphan also had cascading impacts on water security in the Sundarbans. The cyclone destroyed dozens of pipelines used to supply drinking water to the islands while brackish water breached embankments, freshwater wells and ponds, often forcing people, usually women, into long journeys on foot to the remaining functional, yet crowded, wells (Thakur, 2020). In Bangladesh alone, over 18,000 water points were reported damaged (NAWG, 2020). This damage and contamination of water infrastructure only exacerbated one of the biggest challenges currently being faced in the region: saltwater intrusion (Dasgupta and others, 2017). The low-lying deltaic landscape, rising sea level, recurring cyclones and saltwater inundation – combined with human changes to hydrology through upstream river diversion and freshwater flow reduction, the expansion of shrimp farming and agricultural irrigation – all contribute to the increasing salinization of groundwater. This is an issue of grave concern in a region where the vast majority of people depend on these underground sources of drinking water (Nahian and others, 2018). To make matters worse, recent studies concerning the Bangladesh side of the GBM delta found a link between saltwater intrusion and adverse health impacts. Incidences of high blood pressure were connected to the salinity of drinking water, indicating that the increasing threat of saltwater intrusion not only threatens water security, but may also have significant long-term health impacts (Nahian and others, 2018). Water security and human health are inexorably linked, and damage to water infrastructure and sanitation pushed people to unsafe water sources in the wake of Amphan, reduced sanitation and hygiene, and resulted in outbreaks of skin disease and diarrhoea (Rafa and others, 2021).

Loss of biodiversity

Cyclone Amphan compounded biodiversity loss experienced in previous cyclonic events, further damaging around 28 per cent of the world-renowned mangrove forests in the Indian Sundarbans, with an estimated 1,200 km2 reportedly destroyed (Sen, 2020). During cyclones, mangrove trees can suffer physical damage from wind and waves, while less-salt-tolerant species can be damaged by higher salinity (Mishra and others, 2021). Of greater concern, however, is the extent of forest being lost to coastal erosion, as once the land is lost the forest has no chance of recovery. An estimated 69 per cent of shorelines in the Sundarbans experienced landward erosion due to Cyclone Amphan (Mishra and others, 2021). In addition to the benefits local people derive from the mangroves (see section 2 – Direct impacts), the forest ecosystem supports irreplaceable biodiversity, providing habitat for iconic yet endangered species such as the Ganges river dolphin and the Royal Bengal tiger (Danda and others, 2017). As the mangrove forest continues to shrink, not only is this biodiversity threatened further, but wild animals come into increasing contact with people, often culminating in a deadly encounter. For example, as the Sundarbans mangrove forest cover gets smaller, tigers are increasingly pushed to target humans and livestock. At the same time, after losing livelihoods from events like Cyclone Amphan (see section 2 – Loss of livelihoods), people often venture deeper into the forest to forage and make a living, putting them at even greater risk of tiger attacks (Augustin, 2020). Aside from forest loss in the Sundarbans, the cyclone also caused considerable damage to nature in other areas, including the famous over-250-year-old Green Banyan Tree in the Kolkata Botanical Garden (Chowdhury & Bhattacharya, 2020).

3. Indirect Influence – Cyclone Amphan and the COVID-19 pandemic

On May 13th, 2020, an area of low atmospheric pressure encountered exceptionally warm sea surface temperatures in the North Indian Ocean and started forming a cyclonic storm. It was classified as a tropical depression three days later, on May 16 (Kumar and others, 2021a), before undergoing rapid intensification from a cyclonic storm (Category 1) to a super cyclonic storm (Category 5) in less than 36 hours (Balasubramanian & Chalamalla, 2020). Reaching maximum wind speeds of up to 260 kmh-1 on May 18, this super cyclonic storm, given the name 'Amphan' (pronounced as Um-Pun), became the strongest cyclonic storm in the Bay of Bengal since 1999 (Khan and others, 2020). On the afternoon of May 20, Cyclone Amphan made landfall in a low-lying deltaic region straddling the border between India and Bangladesh (see Figure 1). The storm brought torrential rain and a storm surge of five metres above the average tidal height, with wind speeds reaching up to 155 kmh-1 as it hit the coast, causing devastation in the coastal regions of both countries (Basheer Ahammed & Pandey, 2021). This low-lying region has long struggled with high exposure to extreme weather events combined with In May 2020, when Cyclone Amphan struck, India had been in a state of lockdown for two months in an effort to combat the COVID-19 pandemic. Compounding the health impacts and loss of life as a result of the virus, the loss of income and livelihoods due to lockdown conditions for farmers and informal workers reduced the ability of many in the Sundarbans to manage losses from a severe cyclonic event such as Amphan (Hishan and others, 2021). Some research even suggests that the reduction in air pollution as a result of the COVID-19-related lockdown, specifically of atmospheric aerosols, may have contributed to the warmer sea surface temperatures that fostered the rapid intensification of Amphan into a super cyclonic storm (Kumar and others, 2021b; Vinoj & Swain, 2020). However, the main role of COVID-19 in the Cyclone Amphan disaster was in increasing vulnerability, hindering disaster risk management and limiting adaptation options for those affected, as it did for many other of the 10 events in 2020/2021 (see main report – Chapter 3.1).

Increased financial vulnerability

Lockdowns in India implemented by the Government in response to the COVID-19 pandemic had a crippling effect on the economy and local livelihoods in the Sundarbans. With markets and shops closed, labour shortages and supply lines for essential materials restricted, incomes for local agricultural workers drastically declined in the first half of 2020 (Pramanik and others, 2021). For example, in certain sub-districts of the Sundarbans the majority of survey respondents (up to 66.6 per cent) reported no steady income under lockdown conditions. India also has one of the highest rates of informal workers, estimated to be around 90 per cent of all workers. Informal workers are those involved in small-scale, largely independent sale and production of goods and services, which are neither taxed nor monitored by governments (Chen, 2020). The lack of social protection for informal workers and their families makes them particularly vulnerable to shocks like the COVID-19 pandemic, and it is estimated that over 100 million informal workers were put at risk of job loss in India during the first lockdown in 2020 (Estupinan & Sharma, 2020). In the Sundarbans, 18 per cent of households depend on remittances from temporary migrant workers who travel to urban and peri-urban areas in other parts of the country (Arasu, 2021), up to half of whom were forced to return to their homes in the Sundarbans out of fear of infection, being stranded by lockdown or losing their jobs as lockdowns were implemented (Basu, 2020).

Reduced effectiveness of disaster response

More than one million migrant workers returned to West Bengal as the lockdowns due to the COVID-19 pandemic forced them home. Often poor and with no means of transport, some people made the journey on foot (Ober, 2020). Returning migrant workers, many coming from emerging COVID-19 hotspots such as Kerala and Maharashtra, were placed in quarantine in re-purposed cyclone shelters, reducing the number available for evacuees when Cyclone Amphan hit (Dutta and others, 2021). The cyclone shelters that were

available had to enforce social distancing rules to comply with COVID-19 restrictions. As a result, the capacity of shelters in West Bengal was reduced from 500,000 people to only 200,000 (Kumar and others, 2021b). The COVID-19 pandemic also influenced the willingness of people to evacuate to shelters, with infection risk and adequate safety facilities a major concern for many people, meaning they either decided not to evacuate to shelters or left shelters at the earliest opportunity (Ober, 2020). To better cope with the situation, schools and other institutional buildings were opened up for evacuees; however, although early warnings were given and evacuations were coordinated in preparation for Cyclone Amphan, as a direct result of the COVID-19 situation many people remained in high-risk areas.

Restricted movement

As mentioned in Box 1, the Sundarbans region is no stranger to cyclone-related disasters. However before 2020, when cyclones destroyed and inundated people's land and impacted their livelihoods, temporary migration to other parts of the country for alternative incomes was an important adaptation measure, for example in the aftermath of Cyclone Ayle in 2009 (Arasu, 2021). Due to the impact of COVID-19 restrictions on movement, travel and the informal economy, this critical adaptation measure was taken away, making people even more vulnerable to Cyclone Amphan's impacts (Basheer Ahammed & Pandey, 2021).

Feedback loops

Cyclone Amphan and the COVID-19 pandemic co-occurring at the same time and place compounded the impacts of each by reducing resilience and hindering response efforts in the affected areas. In the wake of Cyclone Amphan, health centres, particularly on the Indian side of the GBM delta, were damaged, reducing the capacity of the COVID-19 response effort (IFRC, 2020) (see section 2 – Direct impacts). In addition, cyclone relief efforts often meant people gathered to receive aid being distributed by local governments and NGOs in ways that disregarded social distancing requirements, further exacerbating the risk of infection. The increased risk was reflected in the number of COVID-19 cases in impacted areas of India and Bangladesh, with an increase in cases of approximately 70 per cent in the post-cyclonic period in some of the impacted regions (29 May 2020) compared to the pre-cyclonic period (19 May 2020) (Kumar and others, 2021b).

4. Drivers

Ocean warming and cyclones

Warmer-than-usual sea surface temperatures played a role in the cyclogenesis and rapid intensification of Super Cyclone Amphan (Kumar and others, 2021a). Warmer oceans are accelerators for tropical cyclones, with rising sea surface temperatures linked to more intense, and therefore destructive, storm formation (Sun and others, 2017; Murakami and others, 2017). Cyclones are formed as warm seawater evaporates, increasing the water content in the lower atmosphere. The warm, humid air is brought upwards by converging winds, where it begins to condense into clouds and rain. More warm air along the ocean surface rushes into this newly created vacuum and joins in the formation of this spinning mass of cloud and rain. Of particular concern, however, is the speed at which cyclones intensify in strength, as rapidly intensifying cyclones (for example Amphan, which intensified to a Category 5 cyclone in less than 24 hours) cause a disproportionate amount of human and financial losses as they are harder to predict and drastically reduce the preparation response window (Bhatia and others, 2019). In fact, ocean warming as a result of human-induced greenhouse gas emissions (GHGs) (see section 4 – Human-induced greenhouse gas emissions) is already increasing the frequency and severity of storms. There were a record-breaking 103 named storms around the globe in 2020 (see Figure 2) (NOAA, 2021).

The Accumulated Cyclone Energy (ACE) index, which integrates cyclone intensity and longevity, was above average for both the North Atlantic and North Indian Oceans (the latter being the location of the Bay of Bengal) (WMO, 2021), contributing to storms of record strength, such as Super Cyclone Amphan. A record number of named storms (12) and hurricanes (six) made landfall in the United States in 2020, seven of which caused damage costing at least $1 billion, which broke the previous record of four, ‘billion-dollar’ tropical cyclones in both 2004 and 2005 (NOAA, 2020). The increasing devastation caused by the rising intensity of these already-frequent storms will reduce the capacity of increasingly exposed populations to recover before the next catastrophe arrives.

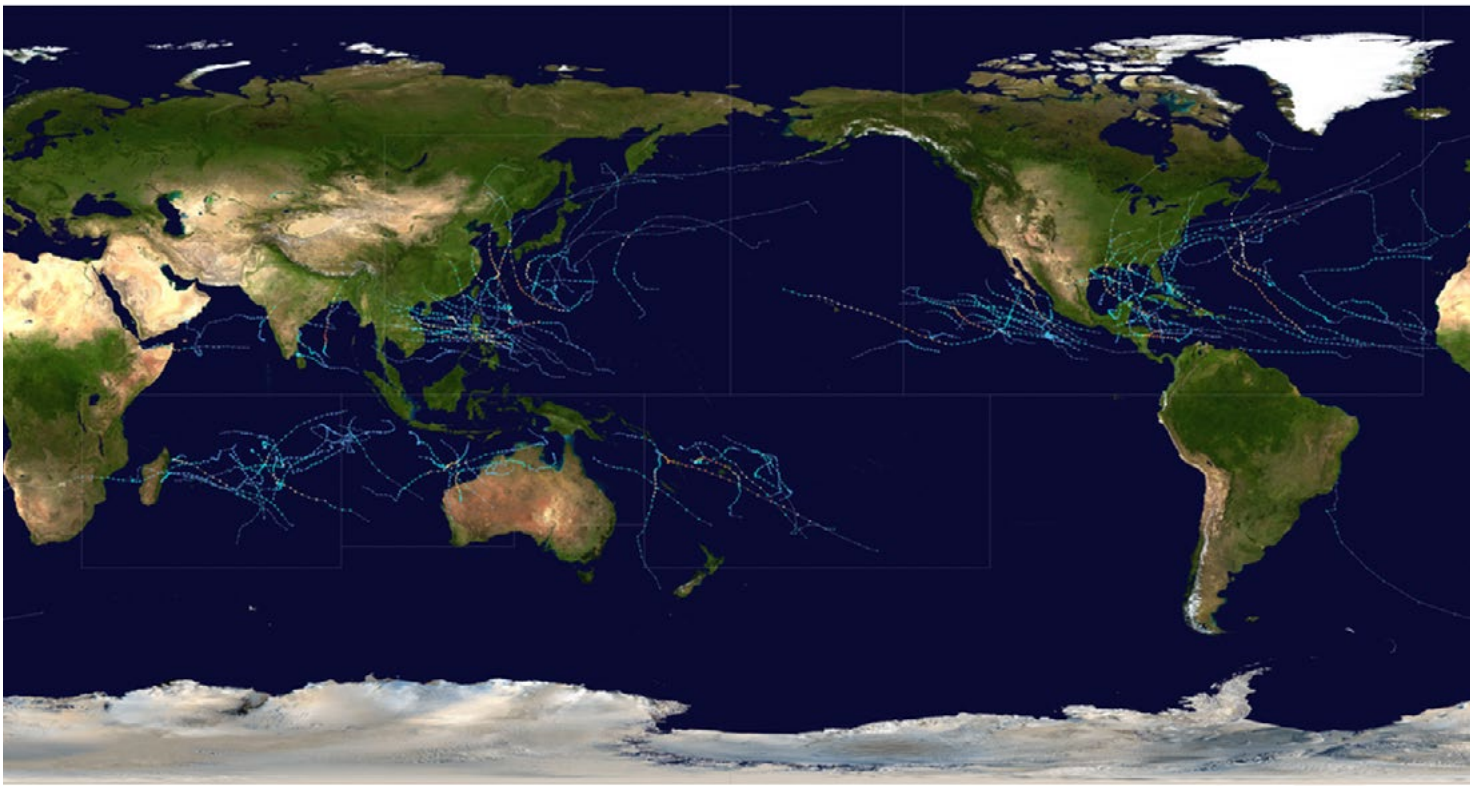


Figure 2: Tracks of tropical cyclones worldwide in 2020 (Supportstorm, 2021)

Land-use change and the loss of coastal protection

Dams – altering hydrology and the lifeline of the coast

Coastal ecosystems, and particularly mangrove forests in deltaic landscapes, rely on sediment and fresh water supply from upstream in order to avoid erosion, maintain a tolerable salinity balance and keep pace with rising sea levels. When this supply is diminished or interrupted by upstream development such as hydropower damming or other water infrastructures, the functioning of the ecosystems on the coast are impacted, and vulnerability to erosion and inundation is increased (Kondolf and others, 2018).

This has occurred in the case of the Sundarbans, where the regulation of river flows by a series of dams, barrages and embankments has affected sediment and freshwater transport, resulting in detrimental impacts on the area of mangrove forests and biodiversity on

the coast (Gopal & Chauhan, 2006). The GBM delta´s sediment load is estimated to have halved since 1960 (Rahman and others, 2018). Wave action from increased storm activity and the reduction in sediment input due to upstream dams were identified as two major drivers of a 24.55 per cent loss of coastal land in the Sundarbans (136.77 km2) in the lead up to Amphan (Bhargava and others, 2021). The cost of this loss in terms of coastal protection alone is sizable, considering the value of this ecosystem service alone is estimated at over $500 million (Sarker and others, 2020), not to mention the effects on lives and livelihoods that depend on the healthy functioning of the mangrove ecosystem.

Deforestation – what is the price of development?

The Sundarban mangrove forest, one of the largest in the world, is like many forests around the world being lost at an alarming rate, with nearly 50 per cent of the biome lost since the 1950s due to human changes to the habitat (Sarker and others, 2016). Lack of adequate protection and deforestation are, alongside erosion, major drivers for this loss of biodiversity. Mangroves in the Sundarbans are regularly felled, often illegally, to make way for aquaculture, the development of coastal communities and beaches (Rahman and others, 2010). In Bangladesh alone, approximately 50,000 hectares (~8.3 per cent) of the Sundarban mangrove forest was cut down by individuals and businesses between 2000 and 2010, mainly to accommodate shrimp farming (Didar-Ul Islam & Bhuiyan, 2016). The impact of deforestation on mangroves in the Sundarbans exacerbates coastal and riverbank erosion, further escalating the exposure and vulnerability of local people to extreme weather events like Amphan.

5. Root causes

Human-induced greenhouse gas emissions

Increased greenhouse gas emissions in the atmosphere, such as carbon dioxide, methane and nitrous oxide, absorb and trap longwave radiation from the sun, increasing temperatures on Earth's surface and lower atmosphere. Most of this excess atmospheric heat ends up being absorbed by the oceans (EPA, 2021; IUCN, 2017). Cyclones around the world are in fact becoming stronger and faster (Bhatia and others, 2019; Kossin and others, 2020), and their geographic distributions and intensity are predicted to change due to the effects of a warming ocean driven by climate change (Kossin and others, 2016; Murakami and others, 2020), increasing the likelihood of more damaging events and increasing the number of areas at risk.

Additionally, anthropogenic climate change causes sea levels to rise, leading to inundation, coastal erosion and salinization of freshwater resources on the low-lying coast (IPCC, 2019). The low-lying delta region where the Sundarbans are located faces additional threats as the land is subsiding and thus local relative sea level rise is exceeding the global mean (Brown & Nicholls, 2015). Subsidence and sea level rise drive erosion and inundation and put mangrove forests and the coastal protection that they provide at risk (Payo and others, 2016), and lead to increasing salinity levels of groundwater and soils. These factors drive the increasing exposure to hazards as warming oceans exacerbate the cyclonic hazards.

Insufficient disaster risk management

With recent advancements in both weather forecasting and disaster management the mortality rate due to tropical cyclones originating in the Bay of Bengal has been strongly reduced (Mohanty and others, 2015). Though the death toll of cyclones has been reduced, the cost of material damages has significantly increased (Khan and others, 2020). The infrastructure of the region is not prepared to withstand super cyclones and is often built in locations that are particularly susceptible to disasters. This was particularly true in the case of migrant housing communities in Odisha and West Bengal, which were completely destroyed by the cyclone (Hishan and others, 2021). While building codes for disaster-resilient structures exist in India, compliance with the codes is lacking due to cultural, economic and political barriers. Local residents of Odisha concede their ignorance on safety codes for cyclone-resilient infrastructure, as well as recognizing the economic barriers to implement any changes (Panda and others, 2020). Many of the coastal embankments that protect the coastline have not been sufficiently maintained and are overdue for replacement, especially considering the partially unsuitable materials and design used in their original construction in the 1960s. This limited their effectiveness as flood protection during the Amphan cyclone (Islam and others, 2021).

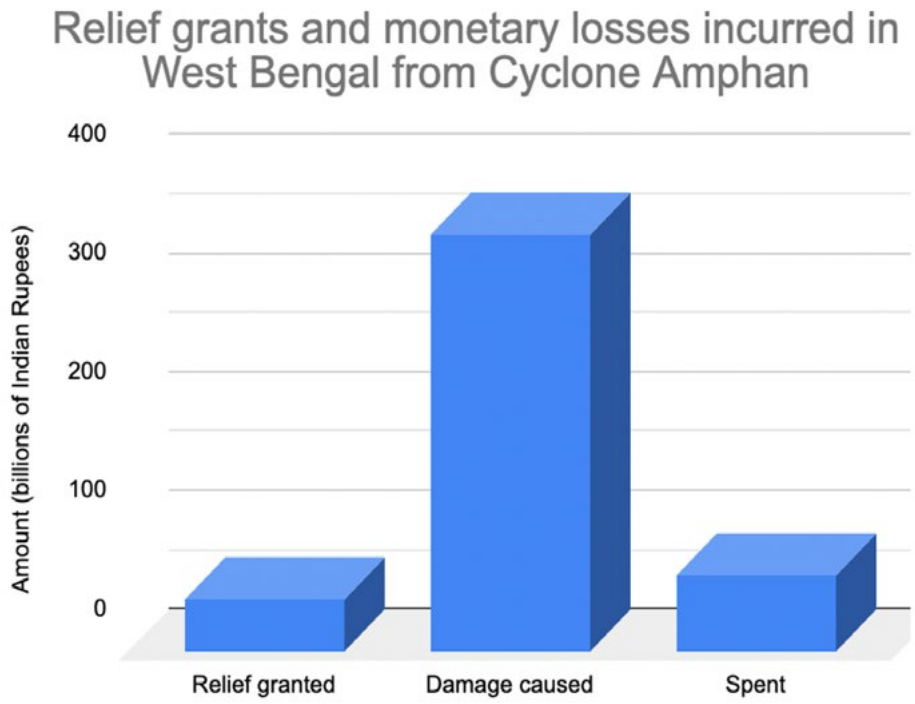
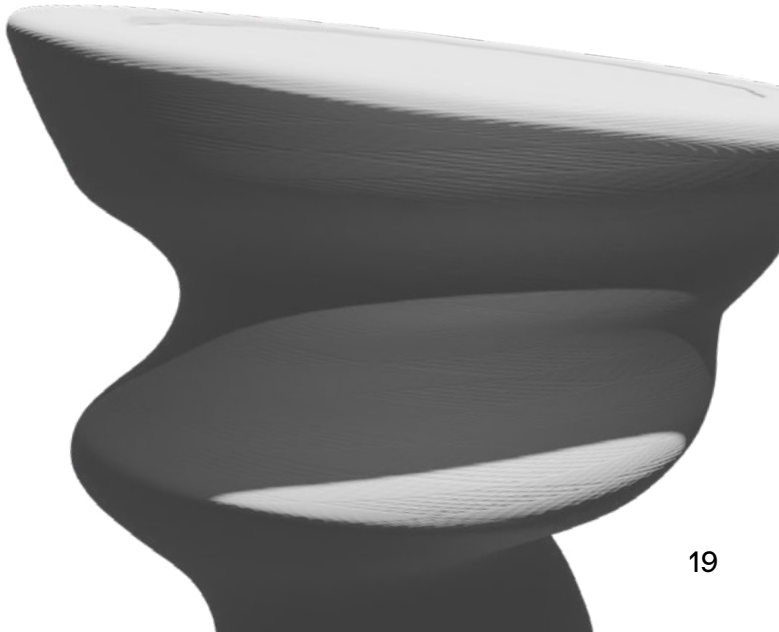


Figure 3: Relief grants and monetary losses incurred in West Bengal (Data from Konar, 2020).

The lack of funding and resources is a significant challenge in these areas, exacerbated by the economic consequences of the COVID-19 pandemic. Though the governments of Odisha and West Bengal had allocated a budget for cyclone recovery, they struggled to amass the funds necessary to meet people's humanitarian needs in the aftermath of Cyclone Amphan. The state of West Bengal was actually denied more than 500 billion rupees in dues from the central Government in 2020–2021, which was more than four times higher than the amount denied the previous year (Majumdar & DasGupta, 2020). The discrepancy in the amount of relief aid given versus the economic damage inflicted in West Bengal can be seen in Figure 3 prompting the Government of West Bengal to declare the relief insufficient to cover the initial damage, as well as the secondary impacts on GDP, budget shortfalls and social structures (Hishan and others, 2021). The COVID-19 pandemic is also credited with obstructing the political processes of disaster risk management, as the legally required meeting of the National Disaster Management Council, which coordinates disaster management and response, was not able to convene in the case of Cyclone Amphan – although the attribution of this fact to the pandemic is debated, as an online meeting would also have been theoretically possible (Islam and others, 2021). Though there was a timely evacuation of around 4.2 million people from the coastal areas in the path of Cyclone Amphan, the cyclone shelters intended to house those affected were not only lacking in space to accommodate everyone in need of shelter, but many were also insufficiently maintained. The structurally unsound nature of some of the buildings meant that the true number of safe shelters was even further reduced. In addition to these deficits in shelter capacity, social factors also impacted the willingness of those affected to seek out cyclone shelters, including fear of being exposed to COVID-19 while sheltering and the lack of facilities to safely house cattle during storm events, as some households were worried about losing the livestock that represents their main source of income (Islam and others, 2021).



Environmental costs undervalued in decision-making

The Sundarbans mangrove forest contributed significantly to coastal protection during Cyclone Amphan (Islam and others, 2021). However, environmental degradation is widespread in the Sundarbans, negatively impacting the ecosystem services it provides. Development activities are threatening mangrove coasts across the globe, as they are deforested to make way for aquaculture, growing cities, and infrastructure such as ports or hotels; they are also degraded through mismanagement and groundwater extraction (Winterwerp and others, 2020). In total, almost 10,000 km2 of mangroves were destroyed in the two decades between 1996 and 2016 – equating to an estimated seven per cent of global mangrove forests – and a further 1,389 km2 were identified as degraded in the same timeframe (Worthington & Spalding, 2018). Lack of awareness of the valuable ecosystem services that mangroves provide, and lack of consideration of these services in decision making – including their economically relevant contributions to coastal fisheries and storm protection – fostered the decisions leading to deforestation and degradation.

Upstream development along a river also strongly reduces sediment transport to downstream areas, leading to sediment starvation downstream. The most recent strong intervention was the construction of the Farakka Barrage at the apex of the GBM delta and the related channel diverting water to Hooghly district, which changes the sediment dynamics strongly (Darby and others, 2020). It has been estimated that between 1995 and 2007 the annual transport of sediment to the coast was reduced from over 356 million tonnes to only 200 million tonnes (Khan and others, 2018). As a consequence, the western part of the GBM delta is sediment starved today. As a result of sediment starvation, subsidence and sea level rise, large areas of the eastern part of the delta will fall below mean sea level, requiring either abandonment or enhanced protection (Darby and others, 2020).

6. Solutions

Ensure sediment transport in rivers and protect the shoreline from erosion, including through landscape-sensitive infrastructure development

Sediment loads for the GBM delta are predicted to further decline through the 21st century, with sediment loads decreasing substantially (Dunn and others, 2018) from the current annual value of ~500 million tonnes to just 79–92 million tonnes (Rahman and others, 2018). This decline is predicted to be driven by socio-economic changes in the catchment, such as land management practices, along with new reservoir construction (Dunn and others, 2018). The projection for the sustainability of major river deltas including the GBM delta is dire due to subsidence, submergence and a decline in ecosystem condition. Options to address this could include engineering approaches and active restoration of hydrology and sediment supply (such as in projects from the United States [Mississippi delta] and the Netherlands [Rhine River delta]), or the introduction of controlled flooding schemes such as the Tidal River Management scheme in Bangladesh (Darby and others, 2020). In the 1960s, Bangladesh constructed polders to embank waterways, which accelerated riverbed sedimentation and raised water levels, and also impeded natural floodplain deposition. In this way, infrastructure initially intended to reduce flood risk now contributes to it. Tidal river management, where polders are periodically cut away or closed in order to allow tidal flows to increase sediment deposition in low-lying surface depressions, could achieve higher land elevation and thus reduce flood risk; however, the scale of current implementation would need to be increased radically to be able to keep up with relative sea level rise (Darby and others, 2020).

Restore and protect critical ecosystems

In addition to the ongoing human-driven mangrove deforestation, Cyclone Amphan destroyed 28 per cent of the mangrove forests in the Indian Sundarbans alone. Targeted ecosystem protection and restoration is needed to achieve long-term ecosystem stability and therefore the maintenance of natural coastal protection measures. Through targeted and integrated management of mangrove forests, combined with the participation of local stakeholders, restoration efforts have better chances of success (Sen, 2021). Balancing mangrove protection and restoration with human well-being will require a reorientation of development goals. A stronger critical assessment of existing and potential maladaptation could improve development projects and help maintain the region's natural capital. One strategy would be to open development policy to participatory approaches in order to foster the creation of sustainable alternative livelihoods, while taking into account local needs and knowledge. Shrimp farming, one of Bangladesh's most important economic sectors,

has significantly contributed to the destruction of mangrove forests along the country's coastline but is simultaneously negatively affected by deforestation impacts. A potential solution to this economic and ecological dilemma could be to move shrimp agriculture to open-water shrimp farms using integrated multi-trophic aquaculture (IMTA) further from the shore, and restoring the mangrove forests in former shrimp-farming areas. However, this transformation requires strong institutional support (Ahmed and others, 2017). Raising awareness of the valuable ecosystem services that mangroves provide could foster greater support for restoration efforts.

Further strengthen disaster preparedness

Bangladesh and India are regularly hit by strong storms and cyclones and have increased preparedness levels strongly during the last decades. Bangladesh, for example, has steadily upgraded its disaster response capacity in the last 50 years. While Cyclone Bhola killed 300,000 people in 1970, the death toll of Cyclone Fani in 2019 was five. Bangladesh not only built awareness and a strong early warning system, but it also constructed cyclone shelters and strengthened buildings (Appadurai, 2020). However, the influence of the COVID-19 pandemic illustrates the need to make disaster management more adaptive to multiple kinds of hazards, including those compounding and mutually influencing each other. The space requirement in shelters during the pandemic was much higher than in single-hazard events due to social distancing needs and rules. Since some people chose not to evacuate to shelters for social reasons, consideration of these needs must also be addressed, such as preparing shelters for livestock (Islam and others, 2021). In addition to improving access to, and conditions in, cyclone shelters, early warning systems should continue to be improved. Educating the public on the levels of warning, and making sure that information is widely and equitably disseminated, is essential to protecting the population (Appadurai, 2020). Engaging local communities in this process would reduce the barriers to education strategies, which should be tailored to meet the specific needs of diverse groups of people. The same holds true for increasing participation in evacuation to cyclone shelters; fostering community involvement could begin to overcome local people's hesitation to evacuate to the shelters (Mohanty and others, 2015).

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