Coastal hazards Fact Sheets #5: Storm Surges in Coastal Cities

What is Storm Surge?

The World Meteorological Organization (WMO) defines storm surge as a sudden and significant rise in sea level along a coastline primarily caused by the strong winds and low pressure associated with a tropical cyclone (such as a hurricane or typhoon).[i] During the past 200 years, 2.6 million people may have drowned during surge events.[ii]

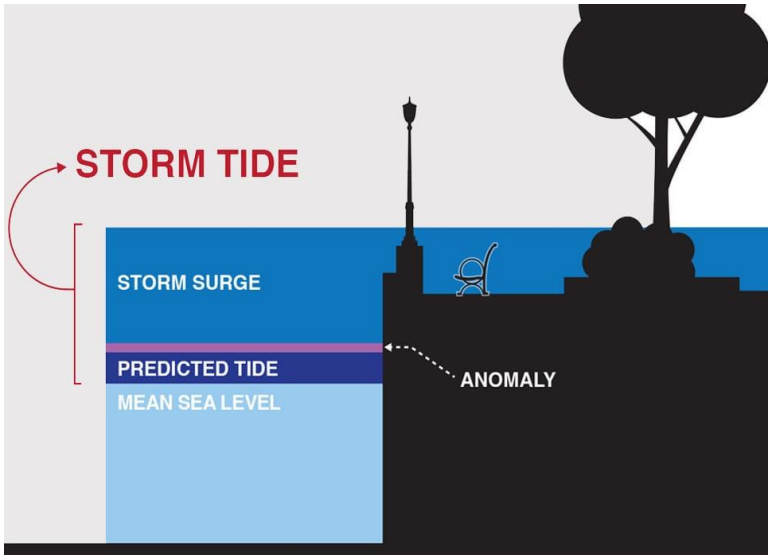

Figure 1: Figure illustrating the difference in water level during storm surge, storm tide and normal high tide as compared to sea level (Source: National Oceanic and Atmospheric Administration)

Causes of Storm Surge:

- Low Atmospheric Pressure: Storm surges typically occur during tropical storms or hurricanes. These storms are characterized by low atmospheric pressure at their centres, i.e., the eye, and are higher at the cyclone's edge. The difference in pressure between the storm system and the surrounding atmosphere can lead to a rise in sea level, hence causing storm surges.[iii]
- Strong Winds: The force of the winds swirling around tropical storms and hurricanes can push large volumes of water toward the coast. This advancing surge combines with the normal tides and can increase the water level by 30 feet or more.[iv]
- Coriolis Effect: A storm surge is caused by rising water levels where the winds are most potent. In addition, the rotation of the Earth causes winds to move towards the right in the Northern Hemisphere and towards the left in the Southern Hemisphere, which is called the Coriolis effect.[v]
- Geographic Location: Certain areas are more prone to storm surges because they are close to warm ocean waters and are influenced by weather patterns. For instance, the Gulf Coast of the United States and specific sections of the Atlantic coastline are more vulnerable to storm surges.[vi]

How does Coastal Erosion affect city systems?

City Infrastructure

- Power Grid: Strong winds and falling trees can damage power lines and substations, causing widespread power outages in the city. The storm surge during Typhoon Haiyan, Philippines (2013), knocked down power transmission lines and towers, disrupting the flow of electricity across regions.[vii]
- Transportation Networks: Storm surges can lead to the closure of roads, highways, and bridges due to flooding, debris, or structural damage. Mass transit systems, including buses and trains, can be severely affected by flooding and power outages caused by the storm. The storm surge during Hurricane Ike, which struck the Gulf Coast of the United States in September 2008, caused significant damage to transportation infrastructure, damaging at least 53 bridges. [viii]

- Water Supply and Wastewater Treatment: Flooding due to the storm can lead to water treatment plant contamination, affecting the city's groundwater supply. This can impact access to clean drinking water and create sanitation issues. It can disrupt wastewater treatment facilities, leading to sewage overflows and contamination of water bodies, causing severe health risks. [ix]
- Communication Infrastructure: Storm surges can disrupt communication networks, including cellular and landline services. This hinders emergency communication and coordination efforts during emergencies. During the storm surge in Cyclone Amphan in Bangladesh and India (2020), Winds reached 185 km/h (115 mph), and the Indian city of Kolkata, home to 15 million people, saw severe damage to buildings, power outages and destruction of communication infrastructures.[x]
- Housing and Buildings: Residential and commercial buildings can experience structural damage from high winds, flooding, and debris. This can cause high economic costs for repairment of the infrastructures and facilities. The storm surge during Hurricane Katrina (2005) in the Gulf Coast, USA, damaged more than 850,000 homes. [xi]
- Essential Facilities: Storms can damage and disrupt essential facilities such as healthcare infrastructure, including hospitals and clinics, schools and education institutes, etc.

Social Impacts

- Loss of Life and Injury: Storm surges causing floods, high winds, and debris can result in fatalities and injuries among residents, causing physical injuries and trauma. The storm surge during Typhoon Haiyan, Philippines 2013 affected more than 16 million people and left 4 million homeless. The Philippine government confirmed 6,300 dead and more than 1,000 still missing.[xii]
- Displacement and Relocation: Storm surges can force communities to relocate to safer areas, disrupting daily life and adding mental and emotional stress. The storm surge during Cyclone Idai in Mozambique in 2019 caused the displacement of 400,000 individuals, of which 160,927 were sheltering in 164 temporary accommodation centres.[xiii]

- Community Disruption and Social Inequity: The displacement can fragment communities and cause social inequity as they are forced to start their lives elsewhere.
- Health and Safety: Storm surges can cause several accounts of accidents and injuries. Access to healthcare, emergency services, and safe drinking water may also be hampered.[xiv]
- Migration and Urbanization: The displacement caused by Storm surges can also lead to migration to urban areas from rural areas, causing overcrowding, competition for resources, and social challenges.
- Increased Vulnerability: Vulnerable populations, such as the elderly, disabled, and low-income individuals and children, are often disproportionately affected by Storm surges due to limited resources and mobility challenges.

Ecosystem Disruption

- Habitat Destruction: The strong winds of storm surges can uproot trees, break branches, and damage vegetation, destroying habitats for both terrestrial and aquatic species. The storm surge during the Cyclone Nargis in Myanmar (2008) caused significant damage to ecological habitat. After the disaster, the trees and buildings were completely gone and replaced by messy rubble piles. The fields were largely submerged under brown and green floodwater.[xv]
- Landslide and Erosion: Storm surges can lead to coastal erosion and landslides, which can alter the shape of coastlines
- Water Pollution: Heavy rainfall and winds can introduce pollutants, sediments, and debris into rivers, lakes, and coastal waters, causing harm to marine species.
- Coral Reefs and Mangroves: The increased wave action associated with Storm surges can cause physical damage to coral reefs and mangrove ecosystems. The storm surge from Cyclone Nargis in Burma, Myanmar, in 2008 inundated the coastal mangroves and rice paddies in the Irrawaddy Delta.[xvi]
- Wetlands and Marshes: Storm surges and heavy rainfall can alter wetlands and marshes' water levels and salinity, affecting the flora and fauna that depend on these environments. The storm surge associated with Hurricane Sandy in the northeastern USA in 2012 led to the inundation of salt marshes, beaches, and coastal dunes.[xvii]

- Loss of Biodiversity: Alteration in the habitat of plant and animal species can result in the loss of keystone species
- Nesting Sites: Nesting sites for sea turtles and shorebirds may be impacted by Storm surges, causing nest destruction and affecting their breeding. The storm surge associated with Hurricane Sandy in the North-eastern USA in 2012 caused erosion and habitat loss, affecting shorebirds, sea turtles, and other wildlife species that rely on these habitats.[xviii]

How does Climate Change impact Storm Surge?

According to studies, the expected scenario is that storm surge heights in Europe will rise by approximately 15% on average by 2100, especially if high-emission conditions persist. This rise in sea levels is attributed to climate change because of the overall increase in sea levels and heightened storm activity.[xix]

- Increase in sea level: The most recent evidence suggests that sea-level rise could reach 1 meter or more during this century.[xx] Second, a warmer ocean will likely intensify cyclone activity and heighten storm surges.[xxi] As storm surge intensity increases, they will result in destructive flooding situations in coastal regions and adjacent low-lying areas.
- Changes in Atmospheric Circulation: According to the research conducted by the National Aeronautics and Space Administration (NASA), greenhouse gases alter the natural circulation pattern that influences ozone distribution.[xxii] Climate change can alter atmospheric circulation patterns, influencing the movement and behaviour of tropical storms and, eventually, storm surges.
- Warmer Ocean Temperatures: According to IPCC Sixth AR, By 2100, the ocean is very likely to warm by 2 to 4 times as much for low emissions (RCP2.6) and 5 to 7 times as much for the high emissions scenario (RCP8.5) compared with the observed changes since 1970.[xxiii]
  Climate change leads to higher sea surface temperatures, providing the energy needed to fuel tropical storms. Warmer oceans can increase evaporation and moisture in the atmosphere, enhancing storm development and intensification.
- Increased Water Vapor in the Atmosphere: The IPCC Sixth AR Sixth states that the total atmospheric water vapour is increasing by 1% to 2%

per decade.[xxiv] As the GHG emissions increase, temperature increases, increasing water vapour in the atmosphere. This additional moisture can fuel storm surges, leading to heavier rainfall and potentially more intense storms.

- Warming in the Upper Atmosphere: As per NASA, hurricanes are fuelled by heat in the ocean's top layers and require sea surface temperatures (SSTs) greater than 79 degrees Fahrenheit (26 degrees Celsius) to form and thrive. While the lower atmosphere warms due to climate change, the upper atmosphere cools. The temperature difference can create conditions that are more favourable for storm intensification.[xxv]

Adaptation Strategies for Storm Surge

Community Level

- Regenerating natural mangrove forests and mangrove plantations along riverbanks and around villages[xxvi]
- Consideration of health impacts of sea level rise and subsequent occurring of storm surge in community-level planning approaches[xxvii]
- Moving communities, structures and/or assets from areas that are likely to be significantly affected by storm surges.[xxviii]
- Structural modification of homes to significantly reduce risk from all but more extreme events (e.g., substitution of material and building techniques and codes so that houses are cooler and more resistant to flood and extreme weather events)[xxix]
- Households and businesses to install rainwater tanks to supplement the reticulated water supply system[xxx]
- Create irrigation systems to ensure hydration of vegetation[xxxi]
- Raise public awareness to encourage the local population to adapt and be prepared for the likely impacts of storm surges and to foster community participation in decision-making.[xxxii]
- Labour and professional skills adjustment and enhancement so that new construction codes and new farming standards can be put in place.[xxxiii]
- Support small-scale businesses and micro-enterprises that can be quickly restarted after a storm[xxxiv]
- Develop post-storm recovery plans to facilitate rapid response and aid distribution.

- Application of Nature-Based-Solutions like mangrove restoration, beach nourishment, and wetland restoration to manage tropical storms.[xxxv]
- Implement green infrastructure practices such as rain gardens, permeable pavements, and bioswales to manage stormwater in urban areas.[xxxvi]
- Educate and create awareness among local communities about tropical storm risks, their causes, and the importance of adaptation through community workshops, training, information campaigns, and programs in schools and communities.
- Establish early warning systems to monitor and create communication systems about tropical storms to alert residents to potential threats.[xxxvii]

Municipal/Government Level

- Provide financial and technical assistance to farmers to deal with weather-related changes [xxxviii]
- Better environmental management, including the creation of artificial reefs and environments[xxxix]
- Better environmental management, including the creation of artificial reefs and environments [xl]
- Installation of devices to prevent seawater from back flowing into storm drains[xli]
- Planning (1) to avoid the worst consequences of the forecasted weather events, which involves the production and frequent update of flooding and hazard maps; (2) legislation focused on (a) not permitting development on land vulnerable to hazards, or (b) establishing construction codes appropriate for the forecasted climatic conditions[xlii]
- Beach and shoreface nourishment in which the sand is spread over the beach where erosion is occurring to compensate shore erosion and restore the recreational value of the beach [xliii]
- Construction of sea walls and sea dikes, dams, channels, groynes, breakwaters, jetties, and artificial reefs, along the coastline to protect land from the impact of waves and storm surges [xliv]
- Update or develop infrastructure and building codes that require erosion-resilient designs and elevated foundations for structures in coastal zones[xlv]

- Dune construction and strengthening by planting grass, covering the face of the dune with plant debris, construction of fences along the seaward front of the dune to reduce wind speed on the surface and applying a combination of hard man-made structures topped with sand, dunes and vegetation.[xlvi]
- Adaptation of storm management plans through grey protection solutions (groynes, break walls) and promotion of green measures, including mangrove restoration and wetland management.[xlvii]
- Retreat from high-risk areas by removing infrastructures too close to the beach or rivers without proper authorization by providing compensation and demolition costs[xlviii]
- Cliff strengthening and stabilisation, changing the slope angle, and/or reducing cliff heights by removing unstable blocks, eliminating surface runoff and infiltration on the slope, securing unstable rocks to increase cohesion and stability and prevent slippage etc.
- Building storm surge gates and flood barriers to protect highly vulnerable urban areas and infrastructure where storm surges and sea flooding could have significant impacts[xlix]
- Strengthening and proper planning of road and transportation, water supply and sewage systems in case of emergencies in landslide-prone areas
- Fund research and innovation initiatives aimed at developing new tropical storm adaptation technologies, materials, and strategies[l]
- Participate in international agreements and conventions that address tropical storms, promoting cooperation and shared knowledge[li]
- Facilitate the integration between different government levels (regional, state and national) so that complex and expensive responses (e.g., rapid evacuation and/or construction of dykes) can be put in place promptly.[lii]
- Insurance to cover personal and government costs specifically associated with recovery after storm surges[liii]

Case Examples

Case Example 1

Colombo, the largest city in Sri Lanka, implemented the *Colombo Urban Regeneration Project (CURP)* to enhance resilience to storm surges and sea-level rise. The project is a combined effort between the government and local authorities in designing and implementing systems aimed at reducing flooding in the Colombo Water Basin's catchment and strengthening local authorities' capacity through large-scale investments. The project includes a flood and drainage management component by managing street and drainage infrastructure, including canals and flood gates. A concerted effort has been made to provide a higher quality of life through increased public space for the residents, such as protecting wetlands coupled with providing access and education, enhancing pedestrian walkways, and rehabilitating parks.[liv]

Case Example 2

In 2016, several cities in Vietnam initiated a project led by the Ministry of Agriculture and Rural Development, with the involvement of the Ministry of Construction and the seven provincial People's Committees, intending to improve the resilience of vulnerable communities in the provinces of Nam Dinh, Thanh Hoa, Quang Binh, Thua Thien Hue, Quang Nam, Quang Ngai, and Ca Mau. The project has added storm- and flood-resilient design features to 4,000 new houses on safe sites, benefiting 20,000 people in disaster-prone communes to date, to build 5,000 homes in total by June 2023. The project has replanted or regenerated 4,003 hectares of mangrove forest to restore Vietnam's green shield, which protects against waves and storm surges. The rejuvenated mangroves have boosted local livelihoods, with the project also supporting 4,358 people. The project has invested in improving data collection, risk mapping, and information sharing, as well as local capacity-building as well.[lv]

---

[i] https://climate-adapt.eea.europa.eu/en/metadata/publications/projections-of-extreme-storm-surge-levels-along-europe

[ii] https://www.cgdev.org/sites/default/files/1422836_file_Future_Storm_Surge_Disasters_FINAL.pdf

[iii] https://education.nationalgeographic.org/resource/storm-surge/

[iv] https://oceantoday.noaa.gov/hurricanestormsurge/#:~:text=Storm%20surge%20is%20water%20from,waves%20can%20cause%20extensive%20damage.

[v] https://education.nationalgeographic.org/resource/storm-surge/
[vi] https://www.weather.gov/media/owlie/surge_intro.pdf
[vii] https://www.climate.gov/news-features/understanding-climate/2013-state-climate-record-breaking-super-typhoon-haiyan
[viii]https://www.researchgate.net/publication/273025037_Impact_of_2008_Hurricane_Ike_on_Bridge_Infrastructure_in_the_HoustonGalveston_Region
[ix] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GL100191
[x] https://www.dw.com/en/cyclone-amphan-kills-dozens-leaves-trail-of-destruction-in-india-bangladesh/a-53521178
[xi] https://www.weather.gov/mob/katrina
[xii] https://www.climate.gov/news-features/understanding-climate/2013-state-climate-record-breaking-super-typhoon-haiyan
[xiii] https://www.undp.org/publications/mozambique-cyclone-idai-post-disaster-needs-assessment-pdnadna
[xiv] https://juniperpublishers.com/cerj/pdf/CERJ.MS.ID.555649.pdf
[xv] https://earthobservatory.nasa.gov/images/19880/cyclone-nargis-floods-burma-myanmar
[xvi]https://wedocs.unep.org/bitstream/handle/20.500.11822/14116/myanmar_cyclonenargis_case_study.pdf
[xvii] https://www.downtoearth.org.in/news/natural-disasters/wetlands-prevented-property-loss-worth-625-million-in-hurricane-sandy-says-study-58606
[xviii] https://www.downtoearth.org.in/news/natural-disasters/wetlands-prevented-property-loss-worth-625-million-in-hurricane-sandy-says-study-58606
[xix] https://climate-adapt.eea.europa.eu/en/metadata/publications/projections-of-extreme-storm-surge-levels-along-europe
[xx]https://www.cgdev.org/sites/default/files/1422836_file_Future_Storm_Surge_Disasters_FINAL.pdf)
[xxi]https://www.cgdev.org/sites/default/files/1422836_file_Future_Storm_Surge_Disasters_FINAL.pdf
[xxii] https://www.nasa.gov/topics/earth/features/ozone_recovery.html
[xxiii] https://climate.nasa.gov/explore/ask-nasa-climate/3143/steamy-relationships-how-atmospheric-water-vapor-amplifies-earths-greenhouse-effect/#:~:text=It%20works%20like%20this%3A%20As,concentration%20of%20water%20vapor%20increases.)
[xxiv] https://climate.nasa.gov/explore/ask-nasa-climate/3143/steamy-relationships-how-atmospheric-water-vapor-amplifies-earths-greenhouse-effect/#:~:text=It%20works%20like%20this%3A%20As,concentration%20of%20water%20vapor%20increases.
[xxv] https://climate.nasa.gov/explore/ask-nasa-climate/2956/how-climate-change-may-be-impacting-storms-over-earths-tropical-oceans/
[xxvi]https://wedocs.unep.org/bitstream/handle/20.500.11822/14116/myanmar_cyclonenargis_case_study.pdf
[xxvii] https://ncceh.ca/resources/evidence-reviews/community-based-adaptation-approaches-sea-level-rise-and-health
[xxviii] https://www.mdpi.com/2225-1154/8/1/7
[xxix] https://www.mdpi.com/2225-1154/8/1/7
[xxx] https://www.mdpi.com/2225-1154/8/1/7

[xxxi] https://www.mdpi.com/2225-1154/8/1/7
[xxxii] https://www.mdpi.com/2225-1154/8/1/7
[xxxiii] https://www.mdpi.com/2225-1154/8/1/7
[xxxiv]https://www.preventionweb.net/english/hyogo/gar/2013/en/bgdocs/UNDP,%202013.pdf
[xxxv] https://www.iucn.org/resources/issues-brief/nature-based-solutions-disasters#:~:text=Coastal%20vegetation%20and%20natural%20features,wave%20energy%20during%20coastal%20storms.
[xxxvi] https://www.epa.gov/eco-research/researching-green-infrastructure-tropical-climates#:~:text=Many%20communities%20are%20turning%20to,negative%20impacts%20of%20stormwater%20runoff.
[xxxvii] https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/establishment-of-early-warning-systems
[xxxviii] https://www.mdpi.com/2225-1154/8/1/7
[xxxix] https://www.mdpi.com/2225-1154/8/1/7
[xl] https://www.mdpi.com/2225-1154/8/1/7
[xli] https://www.mdpi.com/2225-1154/8/1/7
[xlii] https://www.mdpi.com/2225-1154/8/1/7
[xliii] https://climate-adapt.eea.europa.eu/en/metadata/case-studies/sand-motor-2013-building-with-nature-solution-to-improve-coastal-protection-along-delfland-coast-the-netherlands
[xliv] https://www.fao.org/3/ag127e/ag127e09.htm
[xlv] https://www.iisd.org/system/files/2021-07/climate-resilience-canadian-infrastructure-en.pdf
[xlvi] https://climate-adapt.eea.europa.eu/en/metadata/case-studies/implementation-of-the-integrated-master-plan-for-coastal-safety-in-flanders
[xlvii] https://climate-adapt.eea.europa.eu/en/metadata/case-studies/flood-protection-in-the-upper-vistula-river-basin-grey-and-green-measures-implemented-in-the-sandomierz-area
[xlviii] http://www.agglopole.fr/wp-content/uploads/2019/03/EN.pdf
[xlix] https://www.gov.uk/guidance/the-thames-barrier
[l] https://unfccc.int/resource/docs/publications/tech_for_adaptation_06.pdf
[li]https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter14.pdf)
[lii] https://www.mdpi.com/2225-1154/8/1/7
[liii] (https://www.mdpi.com/2225-1154/8/1/7)
[liv] https://www.worldbank.org/en/results/2018/09/24/metro-colombo-urban-development-project
[lv] https://undp-climate.exposure.co/taking-shelter-building-coastal-resilience-in-vit-nam