Enhancing Storm Surge Resilience for Coastal Habitat

A Framework to Support Sustainable Development

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This thesis is dedicated to my 'அம்மா' (mum) Kalyani and to my son Cavin

This research is also dedicated to all whose lives have been affected directly and indirectly by disasters

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to all whose work and efforts have contributed to the development and improvement in the field of disaster management

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DECLARATION OF ORIGINALITY

I, Anitha Devi Karthik, declare that this thesis, submitted in the fulfilment of the requirement for the award of Doctor of Philosophy, in the Edinburgh Napier University, is wholly my work that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or another institute of learning.

ABSTRACT

More than 2.4 billion people live within 100 km of the sea coastline. Between 2016-2019 there has been a rising trend in tropical cyclone's intensity and the frequency. Such cyclone events irrespective of their hurricane categorisation have persistently triggered coastal flooding such as storm surges of at least 7 ft (2 m). Over this period disaster losses from tropical cyclones have been estimated as US$ 343 billion, with over 3,333 deaths. A review of previous studies found that 47% of the Atlantic Cyclone's deaths were caused by storm surges-triggered by hurricanes and not just by hurricanes themselves. The unique characteristics of storm surge and the uncertainty coupled with the lack of hurricane intensity prediction potentially leave coastal communities and the infrastructure directly exposed to the socioeconomic risk. The aim of this research is to develop a framework which helps enhance the resilience of coastal habitat to storm surge hazard. The proposed framework considers the adaptive capacity of developing countries, and its structure is developed by reviewing the current practices and strategies of disaster management for storm surge hazard triggered by tropical cyclones identifying the gaps and challenges. A framework approach could support the future resilience, reducing the disaster losses, both in terms of lives and in terms of socioeconomic, and environmental impacts of countries. This research fits within the wider knowledge field of disaster risk management and sustainable community's enhancement adopts a qualitative exploratory research design based on case study methodology. The study focused on the implementation of four main disaster phases such as the (i) preparedness (ii) response (iii) recovery and (iv) mitigation of the disaster risk management (DRM) and disaster risk reduction (DRR) which had occurred from different events chosen for the case study and had occurred between 2000-2017. The examination of individual case studies and the cross-case syntheses of the cases resulted in identifying the commonalities and obtain insights into the DRM practices and governance in various countries. Gaps within current DRM strategies and their practices before, during and after the occurrence of the disaster were also identified which has assisted in the recommendations within this study. The findings then led to the proposal of the Disaster Adaptation to Mitigate Storm Surge (DAMSS) framework and guidelines for best practices. The findings and suggested approaches may also help governments, planners, engineers, builders, forecasters, emergency managers, relief workers, regional bodies, insurance, civil protection organisations, public and private officials of all the developing countries, to reduce future losses, where there is not the same supportive development infrastructure.

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List of Abbreviations

ABFE	Advisory Base Flood Elevation
ADCIRC	ADvanced CIRCulation
ADPC	Asian Disaster Preparedness Centre
AFP	Armed Forces of the Philippines
AEMEAD	Puerto Rico Emergency Management Administration
AMWL	Annual Maximum Water Levels
BBB	Build Back Better
BBS	Build Back Safer
BFE	Base Flood Elevation
BGS	British Geological Survey
CBBG-DR	Community Development Block Grant-Disaster Recovery
CC	Climate Change
CCC	Committee on Climatic Change
CCRA	Climatic Change Risk Assessment
CDAC	Communication with Disaster Affected Communities
CDEMA	Caribbean Disaster, Emergency Management Agency
CERC	Crisis and Emergency Communication
CAA	Clean Air Act
CIMH	Caribbean Institute for Meteorology and Hydrology
CMA	China Meteorological Administration
CMTS	Committee on the Marine Transportation System
CPD	Civil Protection Directorate (Haiti)
CRED	Centre for Research on the Epidemiology
CRRP	Comprehensive Rehabilitation and Recovery Plan
DART	Disaster Assistance Response Team
DAMSS	Disaster Adaptation to Mitigate Storm Surge (framework)
DHS	Department of Homeland Security
DLA	Defence Logistics Agency

DMC	Disaster Management Cycle
DoB	Department of Building
DoD	Department of Defence
DoE	Department of Energy
DOTD	Department of Transportation and Development
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
ECHO	European Civil Protection and Humanitarian Aid Operations
ECMRW	European Centre for Medium-Range Weather forecasting
EM-DAT	Emergency Database
EPA	Environmental Protection Agency
ETC	Extra-Tropical Cyclone
EWE	Extreme Weather Events
FAO	Food and Agriculture Organization
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Risk Map
FREDA Association	Forest Resource Environment Development and Conservation
GAO	Government Accountability Office
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Green House Gas
GIS	Geographic Information System
GIZ	German Aid Agency for International Cooperation
GOES	Geostationary Operational Environmental Satellite
GPH	Government of the Philippines
HFA	Hyogo Framework for Action

HFIP	Hurricane Forecast Improvement Project
HFS	Hurricane Forecast System
HLT	Hurricane Liaison Team
HRD	Hurricane Research Division
HSU	Hurricane Specialists Unit
HUD	The U.S. Department of Housing and Urban Development
HURDAT	Hurricane Database
HWM	High Water Marks
HWRF	Hurricane Weather Research and Forecast
IBHS	Insurance Institute for Business & Home Safety
ICT	Information and Communications Technology
IFRC	International Federation of Red Cross
ILIT	Independent Levee Investigation Team
IMD	Indian Meteorological Department
INFORM	Index of Risk Management
INGO	International Non-Government Organisation
IPCC	Intergovernmental Panel for Climatic Change
IPET	Interagency Performance Evaluation Taskforce
IRIDeS	International Research Institute of Disaster Science
IRP	International Recovery Platform
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Centre
LDC	Least Developed Countries
LDRRMC	Local Disaster Risk Reduction and Management Council
LECZ	Low Elevation Coastal Zones
LGU	Local Government Unit
LIDAR	Light distance and ranging
MAT	Mitigation Assessment Team

MDU	Multi-Dwelling Unit
MEP	Mechanical Electrical and Plumbing
MSL	Mean Sea Level
NAO	National Audit Office
NASA	National Aeronautics and Space Administration
NCEI	National Centres for Environmental Information
NDPCC	National Disaster Preparedness Central Committee
NDRRMC	National Disaster Risk Reduction and Management Council
NEDA	National Economic Development Authority
NERC	North American Electric Reliability Corporation
NFIP	National Flood Insurance Program
NGCP	National Grid Corporation of the Philippines
NGO	Non-Government Organisation
NHA	National Housing Authority
NHC	National Hurricane Centre
NIMS	National Incident Management Systems
NOAA	National Oceanic and Atmospheric Administration
NPR	National Public Radio
NRC	Nuclear Regulatory Commission
NRP	National Response Plan
NRT	National Response Team
NWS	National Weather Service
NYC	City of New York
NYCHA	New York City Housing Authority
OAA	Outreach Aid to the Americas
OCD	Office of the Civil Defence
OCHA	Office of the Coordination of Humanitarian Assistance
OECD	Organisation for Economic Co-operation and Development
OFDA	The Office of U.S. Foreign Disaster Assistance
OMB	The Office of Management and Budget
OSHA	Occupational Safety & Health Administration

PAGASA	Philippines Atmospheric, Geophysical, and Astronomical Service Administration
PAHO	Pan American Health Organization
PAR	Philippine Area of Responsibility
PARR	Presidential Assistant for Rehabilitation and Recovery
PFA	Priorities for Action
PFHA	Probabilistic Flood Hazard Assessment
PONJA	Post-Nargis Joint Assessment
PONREPP	Post-Nargis Recovery and Preparedness Plan
PRA	Probabilistic Risk Assessment
PREPA	Puerto Rico Electric Power Authority
PSWS	Public Storm Warning Signals
RAY	Recovery Assessment Yolanda
RCS	Red Cross Society
RIAT	Resilience Integrated Action Team (part of CMTS)
RMT	Response Management Team
RMW	Radius of maximum wind
SAT	Service Assessment Team
SFDRR	Sendai Framework for Disaster Risk Reduction
SHIFOR	Statistical Hurricane Intensity Forecast
SHIPS	Statistical Hurricane Intensity Prediction Scheme
SIDS	Small Island Developing States
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLR	Sea Level Rise
SST	Sea Surface Temperature
SSWHS	Saffir-Simpson Wind Hurricane Scale
TC	Tropical Cyclone
TCG	Tripartite Core Group
TSP	Transitional Sheltering Program

UNCED	United Nation Centre for Environment and Development
UNFCCC	United National Framework Convection for Climate Change
UNHABITAT	UN Human Settlements Programme
UNHCR	United Nations High Commission for Refugees
UNICEF	United Nations Children Fund
UNISDR	United Nations International Strategy for Disaster Reduction
UNITAR	United Nations Institute for Training and Research
UNDP	United Nations Development Programme
USACE	United States Army Corps of Engineer
USDOT	U.S. Department of Transportation
USGS	U.S. Geological Survey
USVI	U.S. Virgin Islands
UTC	Coordinated Universal Time
WASH	Water, Sanitation and Hygiene
WFO	Weather Forecast Office
WFP	World Food Programme
WHO	World Health Organization
WMO	World Meteorological Organization

Storm surge damage to coastal habitat

CHAPTER 1
INTRODUCTION

This chapter introduces the background to the research, detailing the motivation for this study. The chapter also discusses the aim and the objectives considered for this study and the research questions constructed to guide the process. The structure of the thesis is explained in the final section of this chapter.

1.1 Background to the research

The Intergovernmental Panel for Climate Change in their 2015 report (Intergovernmental Panel for Climate Change, 2015) stated, that they had evidenced gradual changes from extreme weather and climate-related events since 1950. One aspect of climate change is the melting ice glaciers which are predicted to cause a rise in sea levels (Henson, 2008) and other is thermal expansion factors. Therefore, sea levels are further expected to rise approximately 26-inches (65cm) by 2100 globally, with the current projection for the rate of rising of oceans (NASA, 2018; Lindsey, 2019).

Coastal areas are also exposed to extreme weather events (EWE) such as tropical cyclones, coastal floods, tsunamis, tornadoes. More than 2.4 billion people live within 100 km of the coastline (The Ocean Conference, 2017). Historically, these towns and cities grew as major trading posts. Societal change and ability to be near major transport hubs, both rail and air, has encouraged increasing populations over the last century. The more recent expansion of these coastal areas as coastal cities and mega cities may be due to many of their beneficial factors such as economies, industry sectors such as renewable energy, port facilities, shipping and logistics, seafood and marine production or oil and gas extraction.

According to the Geophysical Fluid Dynamics Laboratory (2019), intensities of the tropical cyclones are more likely to increase in the future from 1-10% for a 2 degree Celsius of global warming with the lowest emissions projections. It was also stated that the number of global events of these tropical cyclones reaching Categories 4 and 5 in the Saffir-Simpson Wind Hurricane Scale (SSWHS) is also more likely to increase. The

Atlantic hurricanes (2016-2019), involving Hurricane Matthew (2016) (NOAA: NCEI, 2017), Hurricanes Harvey-Irma-Maria (2017) (NOAA: NCEI, 2018), Hurricanes Florence- Michael (2018) (NOAA: NCEI, 2019), Hurricanes Dorian-Lorenzo (2019) (NOAA: NCEI, 2020) were all observed as major Category 4 and 5 hurricanes individually. Also, this 2019 report stated that the frequency of these tropical cyclones is also expected to increase subsequently.

Advanced computer-aided models and simulations can forecast and predict tropical cyclones and the possible path of an approaching cyclone known as the 'cone of uncertainty', five-days in advance (National Hurricane Center, 2019). However, predicting the intensity of the tropical cyclones and resultant influences on a storm surge event remains critical and complex (NPR, 2011). Storm surges which are associated with tropical cyclones and extra-tropical cyclones are predominantly becoming a major threat for lives and assets in coastal areas.

In abstract, global warming and the subsequent consequences such as sea-level rise, increase the intensity and the frequency of tropical cyclones. The limitation in hurricane intensity prediction indicates there is an increasing risk of tropical cyclone-triggered storm surges. These impending risks will place both the coastal communities, habitats and the critical infrastructures in these coastal towns, cities, and mega cities at severe risk globally of further future damage due to storm surges.

1.2 Statement of the problem

Storm surge, which is an abnormal rise in water typically produced from cyclones and hurricanes, is a complex phenomenon. This is due to their sensitivity to the slightest changes in their characteristics like storm intensity, storm speed, central pressure, continental shelf, and angle of approach towards the coast (NHC, n.d.).

Although, the occurrence of storm surge is natural, with any land falling cyclones, their severity is aggravated when taking place in highly populated coastal areas with communities, assets and infrastructures exposed, which can transform this natural event into a disastrous event.

Tropical cyclone-generated storm surges have resulted in significant fatalities and have inflicted severe economic damages in the past (Ellis & Sherman, 2015). Previous events which assert the importance of this hazard include:

- Galveston Hurricane (1900) killed more than 8,000 people in Texas
- Bhola cyclone (1970) killed more than 300,000 people in Bangladesh
- Hurricane Katrina (2005) killed more than 1,800 people
- Cyclone Nargis (2008) killed more than 140,000 people
- Typhoon Haiyan/Yolanda (2013) killed more than 6,300 people

and the more recently:

- Cyclone Idai (2019) killed more than 1,000 people.

In the last five years from (2015-2019), the USA has encountered 69 climate and weather-related events resulting in total damages estimated at US$ 531.7 billion with 3,863 deaths (NOAA, 2020). Tropical cyclone-led damage was estimated at US$ 343 billion with 3,333 deaths (NOAA, 2020), representing 65% of all estimated damage and 86% of lives lost. Part of this study investigates the proportion of storm surge damage relative to total cyclone/hurricane damage.Despite the increasing intensity of cyclones, a frequent occurrence, and the scale of these calamities, the 'space of uncertainty' around storm surge and their limitations in managing these types of hazard continues to prevail. With scientific advancements superseded by the increasing coastal extremities, the process of adaptation and mitigation measures remain critical, especially for those developing and underdeveloped countries who could not invest in storm surge barriers or engineered structures. Therefore, a potential solution through an integrated framework approach in reassessing risks, supporting preparedness, and enhancing the storm surge resilience for coastal habitat is vital for both the near term and for the future scenarios. Understanding existing disaster risk management procedures and strategies and to investigate and develop suitable approaches and strategies is, therefore, a necessity. This can not only enhance the current approach and minimise the limitations but also potentially lead to improved practices for the future.

1.3 Research aim and objectives

1.3.1 Aim

The principal aim of this research is to propose a conceptual framework for storm surge resilience and adaptation to coastal habitat. The study concentrated on the coherent and comprehensive information on the existing gaps within the disaster risk management (DRM) and disaster risk reduction (DRR) adapted in different countries to mitigate to storm surge. The framework is addressed throughout this research as Disaster Adaptation to Mitigate to Storm Surge (DAMSS) framework. The DAMSS framework is expected to enhance the preparedness for future storm surge events to support more socioeconomic resilient outcomes, for coastal habitats and communities.

1.3.2 Objectives

The research objectives serve the purpose of this study, which summarises what is to be studied. The accomplishment of each objective is to provide additional knowledge and new insight and providing a platform to convert the vision into a framework approach.

To achieve the defined aim, the following objectives were considered for investigation: -

- To analyse the current practices and strategies of disaster management for storm surge hazard triggered by tropical cyclones.
- To investigate and identify the crucial aspects, gaps, and challenges in mitigation the process and phases of disaster management and disaster risk governance followed in different regions.
- To capture the key activities and participants within the four key phases of disaster risk management providing a comparative advantage and to explore and identify the requirement for the best practices.

1.4 Research methodology

A research methodology is a fundamental prerequisite for any research. The principle step in carrying out research and obtaining the results relies on the successful choice of research methodology. This study embraces qualitative research techniques and qualitative case study methodology. With the aim of developing a framework for storm surge resilience, the research adopts a case study approach, to utilise the option of exploring various cases, their outcomes, effects, evidence, and the DRM strategies practised in the subject field. Considering the literature, the process and direction of guiding this research and in pursuance of achieving the aim and objectives, a multiple-case study method is chosen to support analysis and interpretation of data collected from the different events. Chapter 4 discusses detailed research methods, approaches and techniques.

1.5 Research design

Research designs are the plans and procedures that transform the assumptions into detailed methods of data collection and analysis (Creswell, 2009). The purpose of this research is to develop a framework reviewing the literature regarding the operational performance of disaster management strategies.

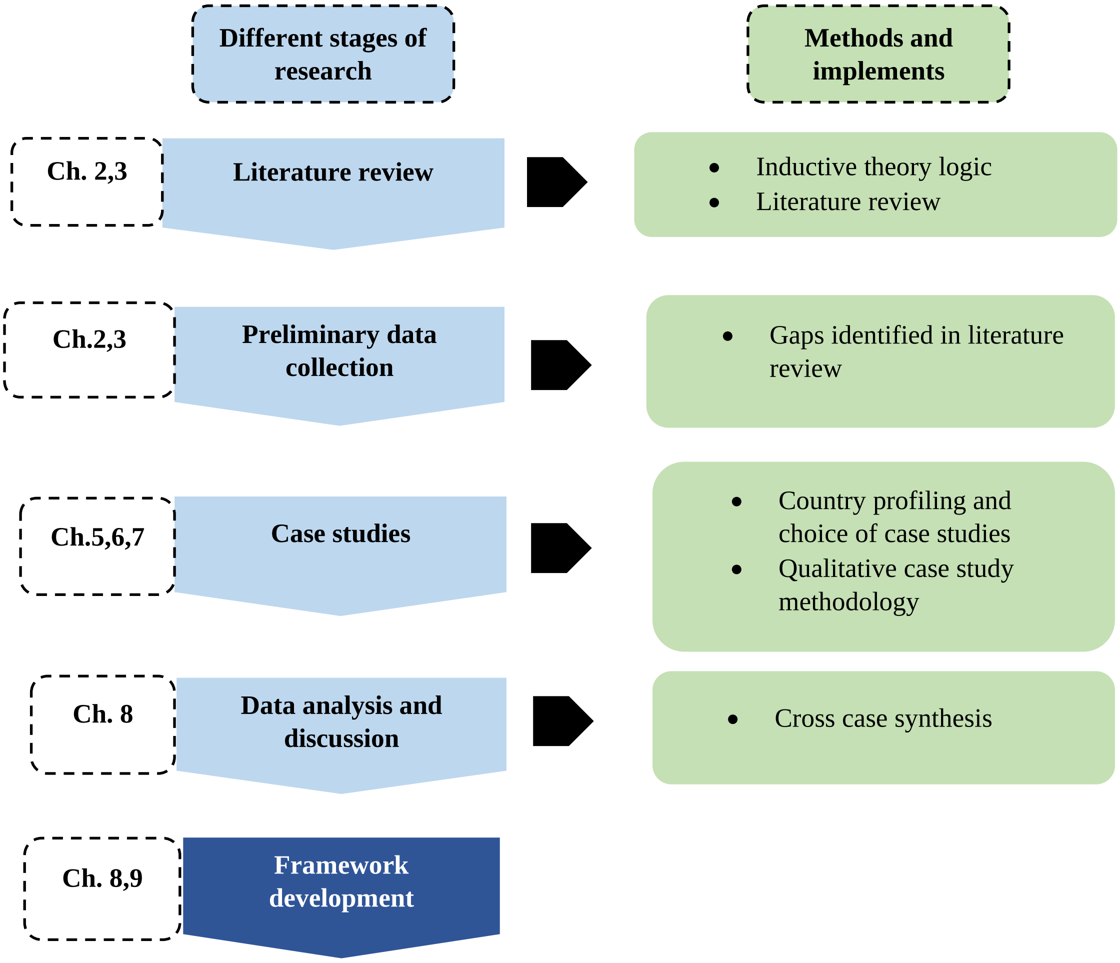


Figure 1.1 Illustration of research design

In addition, the research investigates the current limitation of the DRM and DRR strategies in developed and developing countries to storm surge. This task is integrated into the research design as illustrated in Figure 1.1.

1.6 Contribution to the knowledge

The knowledge contribution from this research focuses on proposing a framework approach for storm surge thereby contributing to enhancing the disaster risk management (DRM) and disaster risk reduction (DRR) strategies. This is achieved by understanding the intricacies of storm surge which is fundamental, in understanding the hazard, vulnerability and the underlying risks. By investigating the disaster risk governance and practices of the countries aligned to the case studies insights into key areas for lessons learnt and future approaches into a potential framework approach were drawn.

As such, much least developed countries still lack a proper disaster management framework in place and the DAMSS framework would directly enhance their strategies to enact for future preparedness and improve methods to assess and evaluate the hazard. This research will further add to the existing literature available for storm surge and contributes by highlighting the gap between current approaches and future needs. The research also adds to previous theories and will act as a base study for any following research which addresses the storm surge protection enhancing community resilience to coastal flooding.

1.7 Outline of the research

Chapter 2 describes the relationship between climate change, global warming, sea-level rise, tropical cyclones, and storm surges. By illustrating the unique characteristics of storm surge, the considerations for storm surge resilience to become a global priority is outlined. This section also discusses the storm surge measuring parameters and coastal defence mechanisms currently in practice to mitigate this hazard.

Chapter 3 investigates, reviews, and presents the historical events of storm surges. The challenges in processes of its implementation are the detailed literature review on global concerns, storm surge, policies, and laws in practice. A critical literature review on existing mitigation methods and related frameworks benchmarking the coastal protection and preparedness alongside storm surge are presented. The section further highlights the limitation of existing methods in practice elucidating the strength and weakness of any existing frameworks and provides evidence to necessitate the requirement of a future storm surge framework.

Chapter 4 outlines the research methods and design, in addition to the philosophies, appropriate approaches and strategies that were chosen to support the research. This chapter also discusses the research sampling made from the total research population, justifying the choice of case studies chosen and the reliability of the data collected.

Chapter 5 studies the disaster phases of the two major Atlantic hurricanes, which are Hurricane Katrina (2005) and Hurricane Sandy (2012). These two cases were studied from the perspective of response exhibited by the USA's as a developed country. A key element of this chapter is studying the existing planning and construction guidance for coastal locations and Base Flood Elevation (BFE) levels. BFE's are calculated elevation levels to which flood waters are anticipated to reach during a coastal flooding or storm surge event. Depending on these BFE’s the coastal new housing habitat and buildings are then designed and planned accordingly.

Chapter 6 explores the disaster phases involving two significant events which occurred in the North Indian Ocean and North West Pacific Ocean. These involve Cyclone Nargis, which occurred in 2008, and Super-typhoon Haiyan, which occurred in 2013.

Chapter 7 discusses two significant Atlantic hurricanes, as recognized from the viewpoint of Small Island Developing States (SIDS). Hurricane Matthew (2016) from Haiti’s point of view as a UN member and Hurricane Maria (2017) from Puerto Rico’s perspective as a non-UN member is investigated in Chapter 7.

Chapter 8 summaries the qualitative data analysis using cross-case syntheses. A detailed analysis of the commonalities and differences across the six cases and a gap analysis of the timeline of the key activities of DRM are analysed. The commonalities were further clustered as phase 1- preparedness, phase 2- response, phase 3- recovery and phase 4- mitigation stages integrated as the DAMSS framework. The designed framework anticipates, to define the DRM and DRR strategies while minimising the gaps in the before-impact, during-impact, and post-impact stages of disasters. A detailed discussion interpreting the key activities and their recommendations are included in this chapter.

Chapter 9 outlines the guidelines and recommendations that supplements the DAMSS framework. The purpose and benefits of the proposed framework are also discussed in addition to the discussion of the extended practical uses and the feasibility of the framework. Analysis of future retrofit safety-resilience applications to existing housing is also provided.

Chapter 10 summarises the achievements of the research aim and objectives and presents the contribution to knowledge gained from the research. The critical reflection of the limitations of the research with future recommendations was further discussed in this chapter.

CHAPTER 2

EFFECTS AND INFLUENCES OF STORM SURGES

2.1 Introduction

This chapter discusses storm surge and its characteristics which occurs predominantly from hurricanes or tropical cyclones or typhoons. The chapter also discusses the influences of storm surge and how it affects a specific region. The interconnection between climate change, global warming, sea-level rise, and storm surge is also discussed. Studying this relationship is essential to understand the storm surge characteristics, their effects, to determine future awareness and measures to be taken to mitigate these hazards. In addition to this, traditional and computational storm surge measuring methods and coastal protection mechanisms were also elaborated to identify the efficiency of current measuring systems and effectiveness towards addressing these extremities.

2.2 Storm surge: Definition

The National Hurricane Centre (NHC) defines storm surge as "a*n abnormal rise of water generated by a storm over and above the predicted astronomical tide*" (NHC, n.d.).

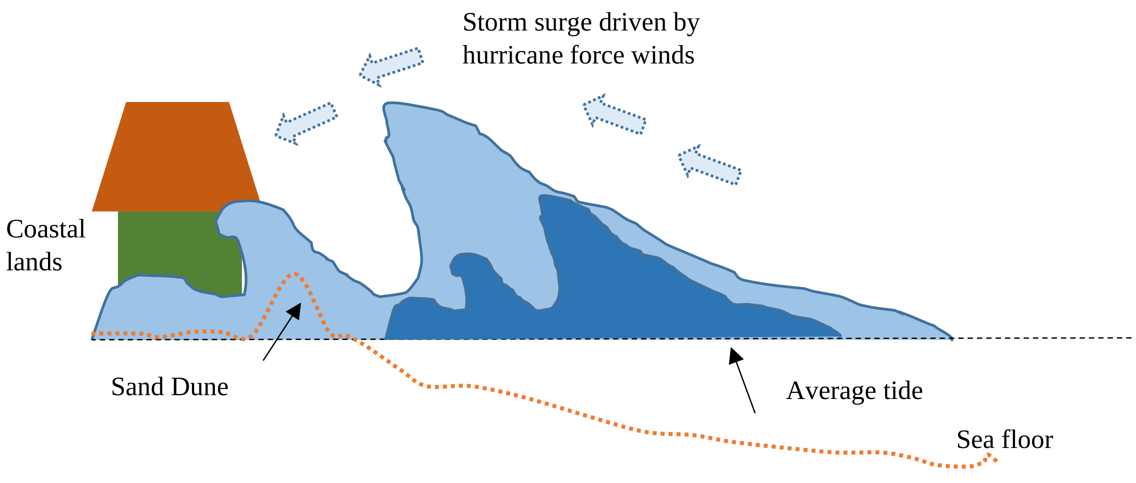


Figure 2.1 Schematic diagram of storm surge rising above mean sea level

Figure 2.1 is a basic schematic diagram of storm surge driven by the hurricane-force winds to onshore. As stated by the NHC, the abnormal rise of water is predominantly caused by tropical cyclones or hurricanes or typhoon. Although, storm surge originates from tropical cyclones, they do not entirely depend on the wind speed of the hurricane. For example, Hurricane Irma with a wind speed of 178 mph and brought a maximum of 6-8 ft storm surge (Carision et al., 2018) and Hurricane Irene with a wind speed of 70 mph brought 8-11 ft. storm surge (NHC, n.d.). From the example, the wind speed does not have a relative impact on the storm surge. To underline the complexity of this phenomenon, during a hurricane event, an emergency manager remarked that "*people worry about wind and are hit by a surge*" (Morrow et al., 2015, p. 35).

Carision et al., (2018, p. 44) defined storm surge/residual as 'the onshore rush of the sea or lake water caused by the high wind and the low-pressure centres associated with the land falling hurricanes or other intense storms. While storm tides are "the maximum water level elevations measured by a water level station during storm events" (Carision et al., 2018). Nott's (2015) simplified definition of storm tide is, they are the level of the combined inundation resulting from storm surge and astronomical tide (Nott, 2015) as shown in Figure 2.2.

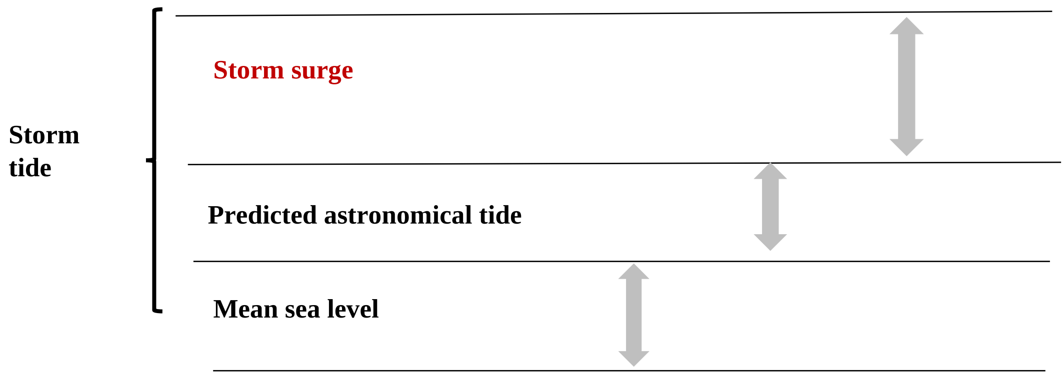


Figure 2.2 Difference between storm surge, storm tide, high tide and MSL

Figure 2.2 shows the difference between the meal sea level, predicted astronomical tide, storm surge, and storm tide. Predicted astronomical tides are "the periodic rise and fall of a body of water resulting from gravitational interactions between sun, moon, and earth" (Carision et al., 2018).

Furthermore, storm surge also bears a huge similarity and difference with tsunamis (Nirupama & Murty, 2016). This misconception of the similarities between tsunamis and storm surge can be observed especially in developing and least-developed countries. Typhoon Haiyan is a perfect example where the storm surge was misunderstood as a tsunami by the coastal communities (Morgerman, 2014). Both the phenomena share the similarity of being classified as long gravity waves and both can produce in coastal floods inundating from the near-shore to the far shore in-land eventually resulting in substantial loss of lives and economic damage. The major difference is tsunamis' can be seismic or non-seismic and are mostly associated with earthquakes and sometimes with meteorites and landslides. But storm surges are associated only with tropical or extra-tropical cyclones (Nirupama & Murty, 2016).

Table 2.1 Similarities and differences between tsunami and storm surge

	Tsunami	***Storm surge***
Similarities	- long gravity waves - Results in coastal flooding	- long gravity waves - Results in coastal flooding.
Differences	- Hydrological (Seismic/non-seismic) - associated mostly with underwater earthquakes	- meteorological - associated only with tropical and extra-tropical cyclones

Though tsunamis and storm surges share some similarities they significantly vary in characteristics remarking two different phenomena as shown in Table 2.1. Tsunamis are classified as 'hydrological hazards' and often are propagated from deep oceans caused by a marine earthquake (EM-DAT, n.d.), but storm surges are 'meteorological hazards' typically caused by water being pushed from cyclonic winds. Storm surge is not generated from deep oceans rather they occur on the surface of the ocean. Due to the seismic force exerted from the earthquakes, tsunamis are generally capable of producing harbour waves which can inundate the coasts further inland than storm surges. However, storm surges were also capable of inundating further inland like a tsunami particularly those coasts with estuaries, bays and creeks connected to the ocean. Coastal topography, the bathymetry of shallow coastal water, the slope of the continental shelf were other storm parameters capable of influencing the storm surge inundation further inland (Nirupama & Murty, 2016). According to EM-DAT classification, tsunamis are geophysical and storm surges are meteorological (EM-DAT, n.d.).

Storm surge is also mixed up with other factors such as seiches and storm tides. Seiches are nothing but the oscillation of standing wave in the opposite direction back and forth like a seesaw motion. In 2008, a 12-16 feet (3.7-5.5m) seiches were created in Lake Erie further leading to flooding. These are usually formed in water bodies such as bays, lakes, and ocean shelves and harbours during severe storms. The extended period between the high and low oscillation was often mistaken for astronomical tide (NOAA, 2018).

2.3 Climate change, consequences, and storm surge

2.3.1 Climate change and storm surge

Before the 20th century, the direct linkage between climate change and the increase in the hurricane intensity lacked evidence (Emanuel, 1991). However, the IPCC fifth assessment report (IPCC, 2015) observed that since 1950, there is evidence of gradual changes in extreme weathers and climate-related events. According to IPCC (2015), even though the global change in cyclone intensity cannot be related to any specific cause, it is undeniable that since 1970, the intensity of tropical cyclones has increased globally. The recent global tropical cyclone events from the years 2015 – 2019 as shown in Figure 2.3 should be considered as a substantial indication of a change in climate patterns specifically in tropical cyclones and storm surge history, which is also one of the motivations for this research.

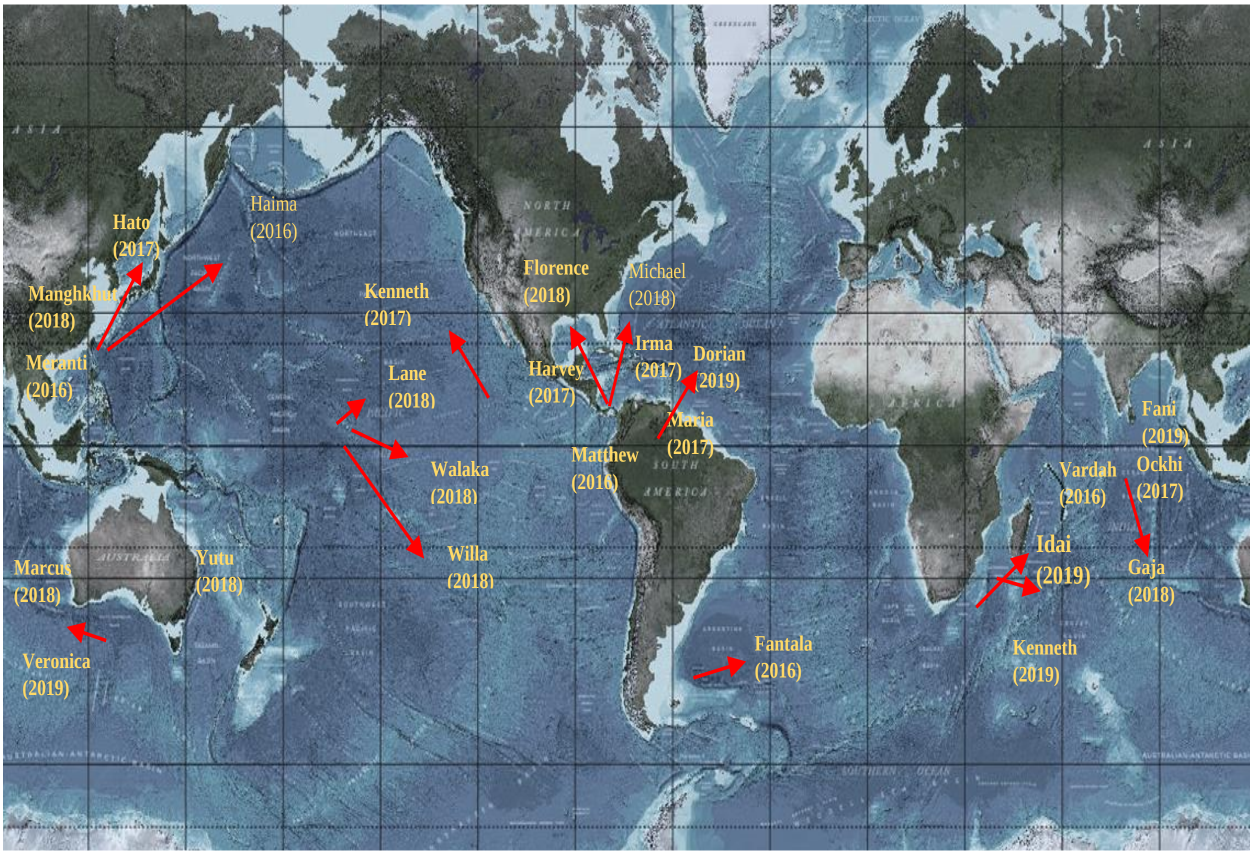


Figure 2.3 Overview of major tropical cyclone events which occurred globally in tropical water from 2016-2019 (Base map image: GEBCO)

Figure 2.3 shows the recent events as major Category 3 and above cyclones, triggering at least 7ft (2m) storm surge shows the new evidence indicating the increase in cyclone intensities throughout the tropical and extra-tropical regions. Although, the current data range is small, this could provide useful evidence in future when aggregated with past and present events. It may also possibly alter previous assumptions and conclusions regarding climate change and its consequences such as tropical cyclones and storm surges.

According to the National Hurricane Centre (NHC), the mid or pre-seasonal outlook estimated that the 2017 Atlantic Hurricane Season would have at least 11-17 named storms out, of which, 5-9 will develop as hurricanes and 2-4 major hurricanes. The pre-seasonal predictions advised the hurricane season would be an above-normal year with 45% of likelihood of occurrence (NOAA, 2017). However, the actual Atlantic hurricane season (2017) was observed with seventeen named storms out of which ten tropical depressions developed as hurricanes from which six hurricanes were major above Category 3 hurricanes. The variation in the prediction was later claimed as an extremely active hurricane season due to the weak or non-existence El Nino factor (NOAA, 2017; NOAA, 2017). Although, various external factors were interfering with the seasonal predictions, the underlying factor of the increasing number of hurricanes and their increased intensity and possibility of becoming major hurricanes is inevitable.

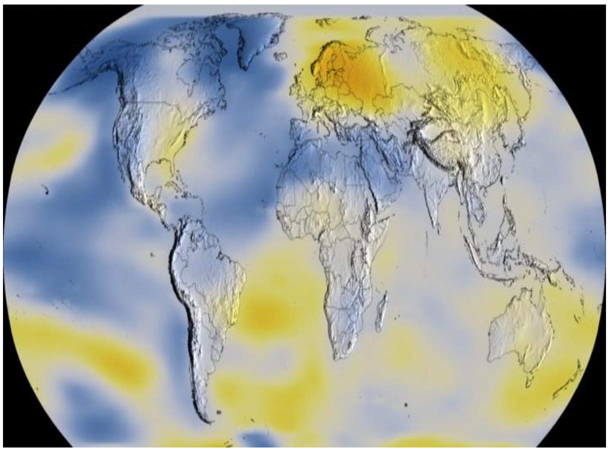
The increase in the number of hurricanes means that these hurricanes could potentially trigger a greater number of storm surges. They further underline that, if these indications were to be ignored, and should the current opportunities be overlooked, may result in lack of action towards adaptation or mitigation for future coastal extremities.

2.3.2 Global warming and storm surge

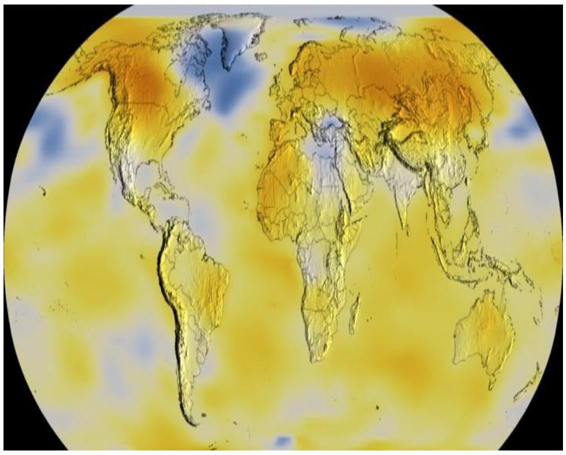
Like climate change, the attribution of global warming with cyclone activity not directly linked until the 1990's. Soon after, some significant events which occurred globally were identified to have a link with the changing precipitation and the hydrological cycle of these tropical cyclones particularly the extreme weather events (EWE) (Trenberth, 2008). This relationship was further defined as the influence of the surface temperature from global warming which affects the temperature of the sea (Rahmstorf, 2017).

Global warming influences coastal flood risk in two ways mainly (*i*) the melting ice glaciers which directly contributes to the rise in sea levels, (*ii*) influencing the ocean temperature resulting in hurricanes which bring coastal flooding through storm surge (Henson, 2008). The theory of the formation of hurricanes requires warm ocean at a certain temperature.

The increase in the global temperature in 1975 and 1991 is shown in Figure 2.4(a) and (b).



2.4 (a)



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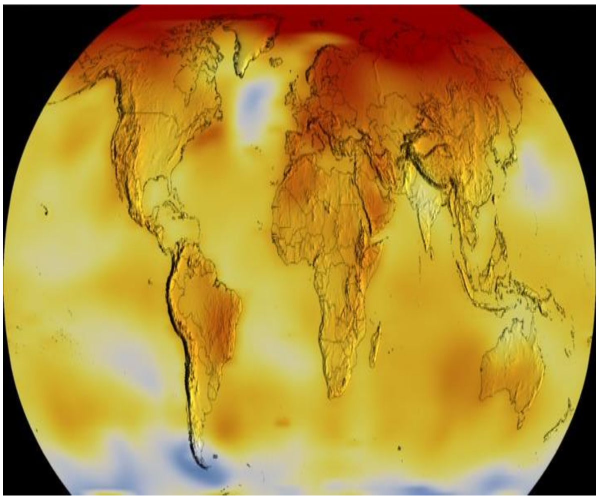
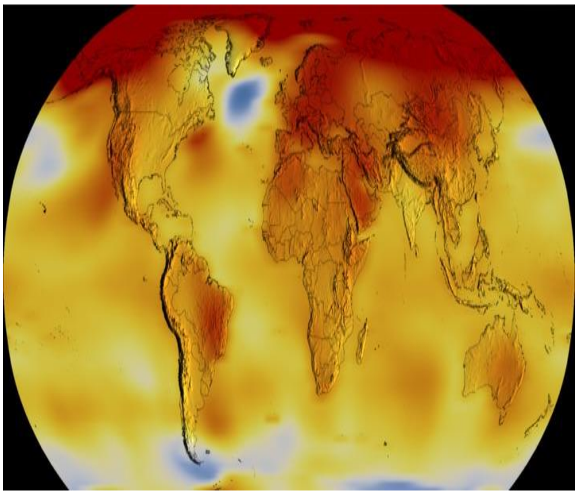


2.4 (c)



2.4 (d)

Figure 2.4 Global temperature recorded in (a) 1975, (b) 1991, (c) 2015 (d) 2018 AA in May 2016 [source: NASA (2020)]

To potentially intensify and develop further, the cyclone still needs convention between the warm ocean and low barometric pressure on the sea surface. A minor change in the sea surface temperature (SST) to 1℃ can majorly impact the cyclone’s intensity (Miles et al., 2017) followed by rapid changes in the storm activity thereby changing the surge statistics (Rahmstorf, 2017). Furthermore, the NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) model projections suggests that the intensities of tropical cyclones are likely to increase by an average of 1-10% for a 2℃ global warming (NOAA, 2019). In line with Miles (2017), Rahmstorf (2017) and NOAA (2019) findings, Figure 2.4(c) and (d) the increase in the global temperature. The visualization of global temperatures for the year 2015 and 2018 visually highlights how the increase in the temperature can result in the formation of an increased number of tropical cyclones eventually bringing storm surge to their potential coast. Furthermore, the recording of OSPO-NOAA (2013), also outlines that the NOAA’s satellite observation of the global sea surface temperature (SST) contour charts has identified the increase in the sea temperature along the tropical waters. According to Emanuel (1991), water temperature above 27℃ is typical for a tropical depression to be formed and further develop into a matured hurricane.

Joined efforts to mitigate global warming, such as the Kyoto Protocol aimed to minimize the emission rate globally were initiated in 1992 (UNFCCC, n.d.). However, countries like China and the USA delayed their ratification and withdrew their participation regardless of their high- greenhouse gas (GHG) emission index which did not significantly contribute to the mitigation efforts. Achieving the target of global warming prevention require strong commitment from all the high-GHG emission countries and non-participatory motives, shall merely remain as a limitation of such initiatives (Henson, 2008; Hare, 2013). Continuing to work towards reducing global warming, is a long-term adaptation however, these are essential to reduce the impacts of coastal extremities which could occur anytime in the given year.

2.3.3 Sea- level rise and storm surge

Rising sea levels are indirect impacts of climate change consequences. Their effects are not immediate however, rising sea levels amplifies the risk to existing coastal extremities. Sea level rise (SLR) varies from region to region and factors such as land subsidence, regions with high tide range and wave height influences the change in sea-levels (Wahl, 2017). Due to the change in these influential factors, countries which are currently not vulnerable to SLR’s may become vulnerable in the future. Rising sea-levels tends to shift the tidal behaviour thereby changing the storm surge behaviour (Henson, 2008). This implies that SLR may set a new base for potential storm surge and countries which are currently not vulnerable to storm surges may become vulnerable in the future from elevated storm surge baselines.

According to Muis et al., (2016), socioeconomic development has been observed to be the prime driver of increasing coastal risk in many countries, and he claims that this may be changed in the future as sea-level rise to be the prime driver for increasing risks. Sea level rise along the coast varies vastly due to the factors such as (i) shape of the coastline (ii) coastal bathymetry. To understand the extremity of rising sea levels and calculate their future impacts, a time-series based recording of sea levels which measures the changes in storm regimes is required (Muis et al., 2016). Although, this is easily adapted from the tide gauge observations, many regions have a limited number of tide gauges. This limits the measurement of extreme sea-level rise and their estimation (Wahl, 2017; Muis et al., 2016) leaving the uncertainty around these hazards to persist for the future.

2.3.4 Tropical Cyclones and Storm surge

According to Emanuel (1991, p. 179), "*a mature hurricane is idealized as a natural Carnot engine, where the hurricane converts the heat energy extracted from the sea to mechanical energy*". He further claims that the tropical cyclones comprise a wide range of fluid-dynamical process which includes rotation, convection, and interaction between air and sea. The intensity of the storm results from the low central pressure. A typical cyclone event can produce various associated perils such as strong winds, storm surge, tornadoes, coastal flooding, inland flooding from rainfall, rip currents and large rogue waves (Emanuel, 1991). Tropical cyclone or hurricanes or typhoons are the same phenomena, addressed by different names in different regions and they typically occur in the tropical zone close to the equator line. Figure 2.5 illustrates how the same phenomenon is identified by different names depending upon the region of occurrence.

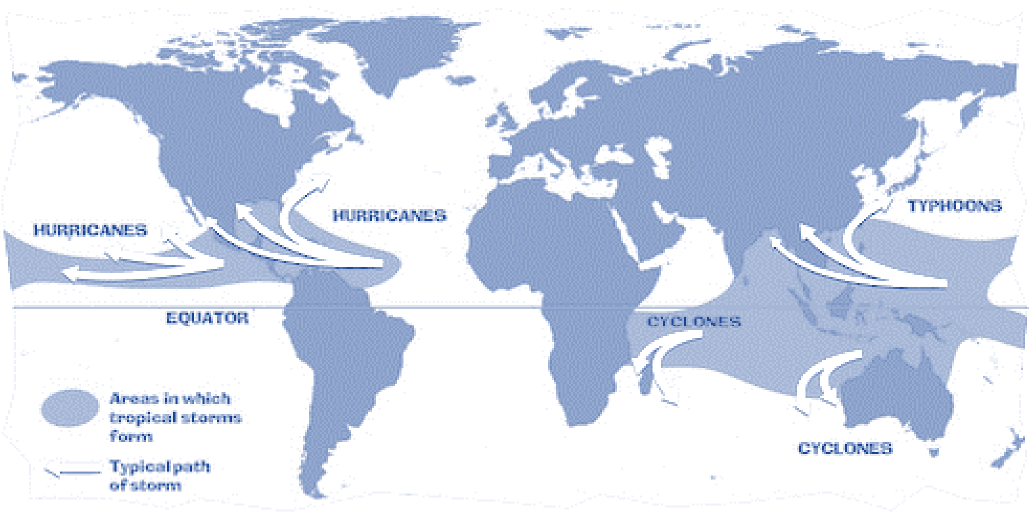


Figure 2.5 Illustration of occurrence of tropical cyclone, hurricane, typhoon by region [source: NASA (2018)]

From all the associated perils of a tropical cyclone, storm surges predominantly occur from tropical cyclones and extra-tropical cyclones when combined with high tides. Tropical cyclones-related surge observations or database on a global scale is not available (Needham et al., 2015). Figure 2.6(a) shows the hurricane trio of Katia-Irma -Jose in 2017 Atlantic hurricane Season and Figure 2.6(b) show the clustering of storms Florence-Isaac-Helene from the 2018 Atlantic hurricane season.

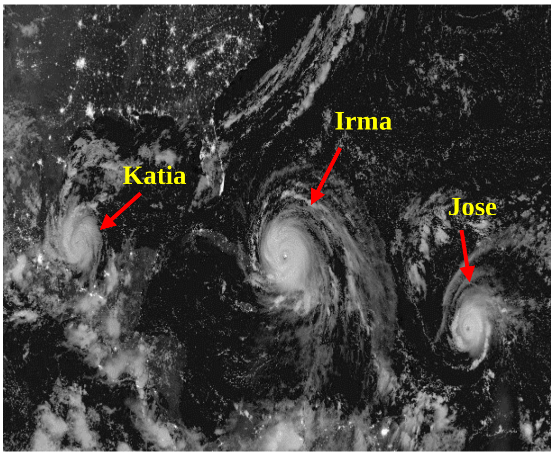


Figure 2.6(a) NOAA-GOES 16 captured the 2017 Atlantic hurricane season [source: NASA (2017)]

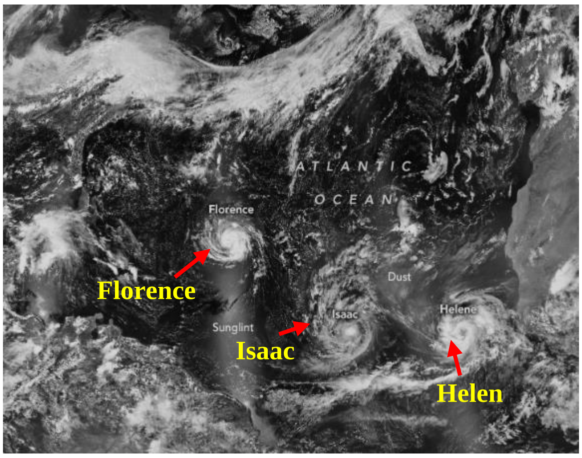


Figure 2.6(b) NASA-VIRUS on Suomi NPP Satellite captured the 2018 Atlantic hurricane season [source: (NASA, 2018)]

The clustering of the storms observed for two consecutive years in the Atlantic Oceans shows the increase in the frequency of tropical cyclones. The clustering may also lead to another impact. As the frequency decreases between two cyclones, particularly when the distance between the two cyclones is within 900 miles (1448-km), may

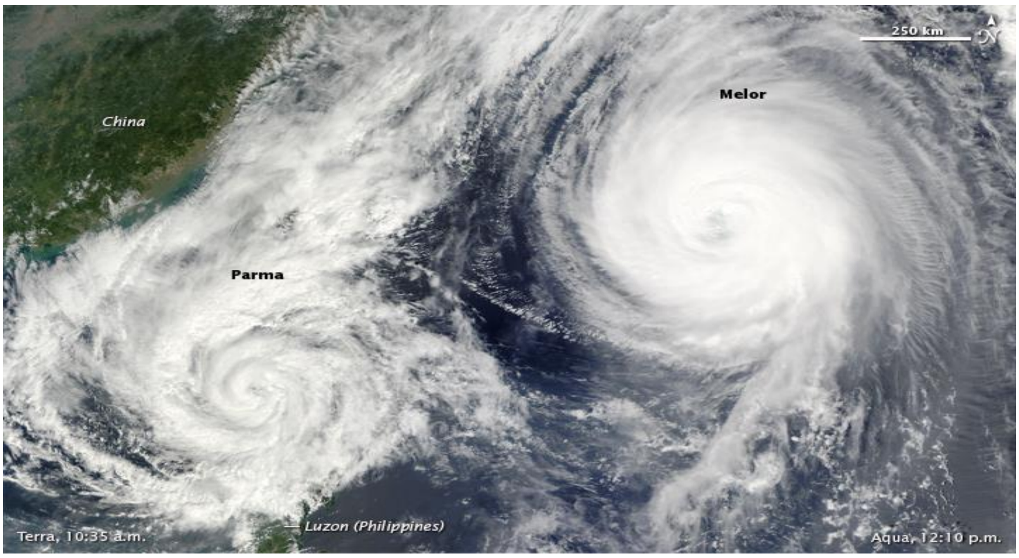


Figure 2.7 Fujiwhara effect displayed by Super Typhoon Melor and Typhoon Parma (7 October 2009) captured by MODIS NASA's Aqua satellite [source:(NASA, 2009)]

effectively lead in creating an interaction between the two cyclones resulting in a '*Fujiwhara effect*'. Figure 2.7 shows the Fujiwhara effect highlighting the interaction between two or more cyclones. During the 2005 Atlantic hurricane season, Hurricane Wilma, interacted with Tropical Storm Alpha, and their interaction resulted in Hurricane Wilma developing into a Category 5 storm as per the Saffir- Simpson Wind Hurricane Scale (SSWHS) causing potential economic damage and loss of lives (Morsink, 2018). Similarly, Typhoon Bopha (2000) also known as Typhoon Pablo, a Category 5 typhoon interacted with Super-typhoon Saomai (2000). Their movement was masked by each other causing fatalities of more than 1,000 lives from Typhoon Bopha. The Super-Typhoon Saomai was also a Category 5 typhoon but resulted in 28 deaths (Wu et al., 2003).

The interaction between a weakening previous cyclone followed by a strengthening succeeding cyclone or vice versa may result in producing a major hurricane which may further amplify the underlying risk of storm surges (National Weather Service, n.d.). In some rare situations, both the cyclone can maintain the same strength and both the cyclone may result in significant damage from both hurricanes and storm surges.

2.3.5 Wind damage vs Water damage

Land falling tropical cyclones not only produce strong winds that can damage the coasts but, also result in extreme coastal flooding such as coastal surges. Storm surges are abnormal rise in sea levels, which occurs from low barometric pressure and the cyclone's sustained strong winds which pushes the water towards the coast. According to Muis et al., (2016), storm surges triggered by tropical cyclones (TC) can produce larger waves than extra-tropical cyclones (ETC) or any other low-pressure weather system. Nevertheless, extra-tropical cyclones were also capable of producing high surge levels like TC's when combined with high astronomical tides.

A cyclone does not always result in bringing a storm surge to the coast. Precise conditions are required to produce the surges (NHC, n.d.). To study the precise conditions and to identify the blind spot understanding the link between the tropical cyclone and storm surges and the factors influencing the storm surge characteristics needs to be studied. Evolution of innovative technologies has minimized this uncertainty to a degree, but not to the entirety.

Also, understanding the hurricane's potential and their intricacies such as the intensity prediction remain critical within hurricane monitoring and forecast (Horn, 2015).

According to Hansom et al., (2015), the limitations in prediction is not only due to the uncertainty in hurricane intensities but also due to the interference of various external factors and the dynamics around the tropical cyclones which are largely impacted by the storm surge (Hansom et al., 2015).

2.4 Storm surge characteristics

Of all the geophysical risks, storm surges are unique, due to their characteristics of being highly sensitive to any minor change in the storm parameters. Figure 2.8 shows the cyclone parameters which influences the storm surge.

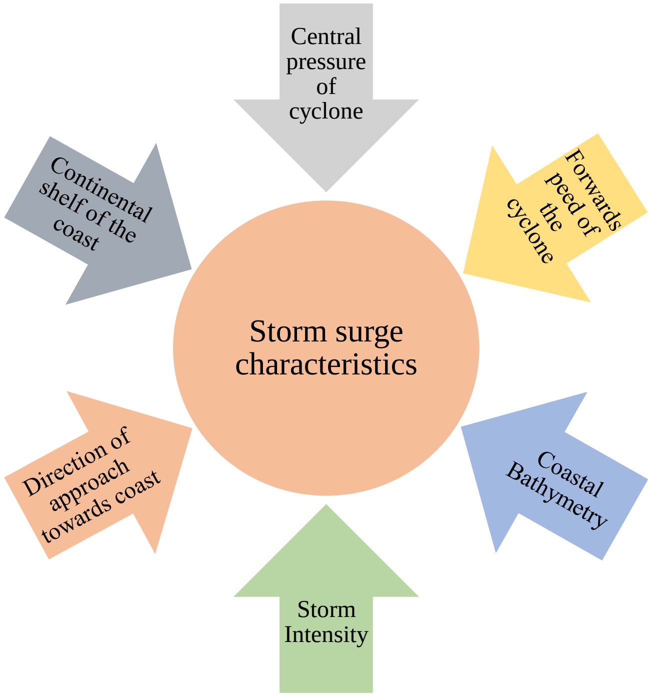


Figure 2.8 Storm surge characteristics influenced by the storm parameters

Decoding the dynamics between storm surge and storm parameters continue to have potential gaps which is also why it is challenging to minimise the substantial loss of lives and property damage (Ellis & Sherman, 2015). Therefore, understanding the storm surge characteristics is the key to enhance the awareness. This is one of the important factors that led to the thinking if a framework would possibly create this awareness in understanding storm surge.

2.4.1 Cyclone forwarding speed

The forwarding speed of a cyclone is observed as one of the vital parameters that impacts the storm surge inundation levels. When severe storm winds act over wide-ranging shallow waters, they tend to create significant storm surge levels. Long surface waves are examined often, but short surface waves, which move faster enhancing the surge levels, were often overlooked. These overlooked short surface waves when matching with the local bathymetry ends in bring large surge waves to the coast (Rego & Li, 2009). The critical forwarding speed of the hurricanes is observed to have the highest possible surge levels. As cyclone speed plays a key role, stalled or slow-moving storms were observed to prolong the storm surge inundations or inland flooding from continuous heavy rainfall. Hurricane Isaac (2012) and Harvey (2017) are perfect examples of fast and slow-moving hurricanes which resulted in significant surge inundations with former, and 60-inch record rainfall for the later (Dolce, 2018; Emanuel, 2017).

2.4.2 Angle of approach

The cyclone's angle towards the coast determines the storm surge inundation location (Drews & Galarneau Jr, 2015). It becomes essential to observe the hurricane mechanism to further understand the storm surge characteristics and predict storm surge location. Various observation of part cyclone events and their movement mechanisms has led to a conclusion that the wind-driven surges are high on the right side of the hurricane (Drews & Galarneau Jr, 2015).

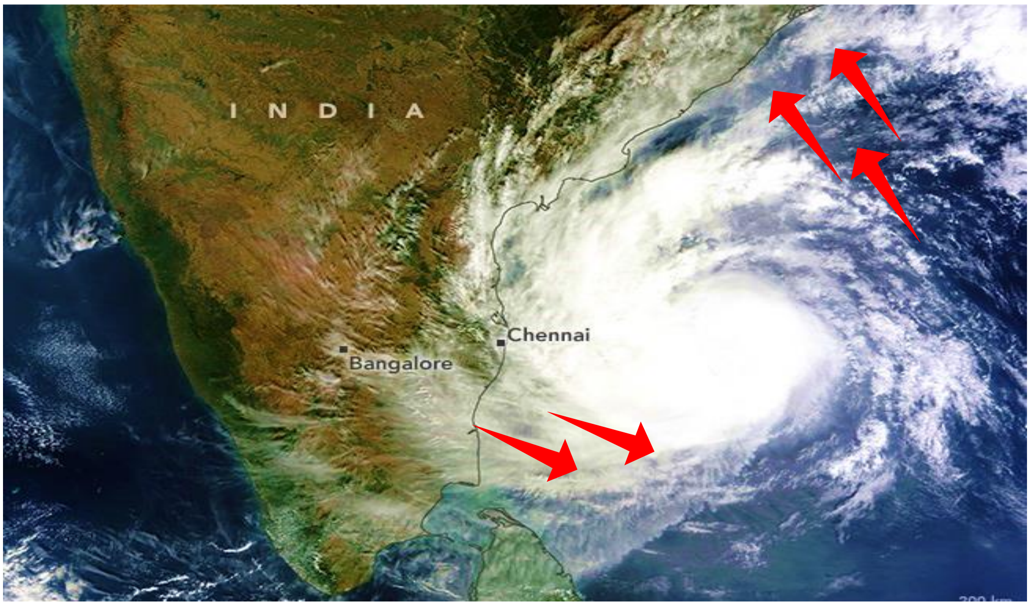


Figure 2.9 Cyclone Vardah during landfall at Chennai, India on 11 December 2016 captured by NASA Suomi NPP- VIRUS) [source:(NASA, 2016)]

Figure 2.9 shows the movement of Cyclone Vardah towards the south-eastern coast of India showing the inward wind on to cyclones left-hand side and outwards winds on to their right-hand side where wind-driven surges were produced. This is due to the counterclockwise rotary motion of the hurricanes. The hurricanes engulf the winds towards their left-hand side pulling the winds inward and pushing the wind outwards on their right-hand side as it was moving forward (Emanuel, 1991).

During the landfall of Hurricane Katrina (2005) at the Louisiana/Mississippi border, it was concluded from the observations that storm surge would come from the southern direction of Louisiana coast as the hurricane's eye was moving southwards.

Figure 2.10 Image showing the breached levees in New Orleans during Hurricane Katrina [source:(Google Earth)]

However, the adjacent flood walls were breached from the north, impacting the southern parts of Lake Pontchartrain as shown in Figure 2.10 leaving 80% of the city of New Orleans to be flooded by storm surge (Drews & Galarneau Jr, 2015). A similar scenario also occurred in Tacloban during Typhoon Haiyan (2013). Higher storm surge levels of 22.9 ft (7m) measured at Tacloban, some 23 km north of Typhoon Haiyan's track (Soria & Switzer, 2016). Though the theoretical angle of approach and the general hurricane direction mechanisms suggest the approximate location, the practical estimation of storm surge continues to be critical.

2.4.3 Continental shelf

Enhanced propagation or counterbalanced action to the dynamics of the storm surge depends on the interaction of surges with the slope of the continental shelf, and width of the shelf. Surges tend to propagate on gentle and shallow slopes and the effect is lowered on steep and narrow slopes (NHC, n.d.). For example, the Floridan Peninsula has a steeper shelf as illustrated in Figure 2.11(b). Therefore, the typical surge would find it hard to propagate unless the maximum levels are exceeded. However, the Gulf Coast of Louisiana or Mississippi is shallow as illustrated in Figure 2.11(a) and can easily be inundated with higher surges.

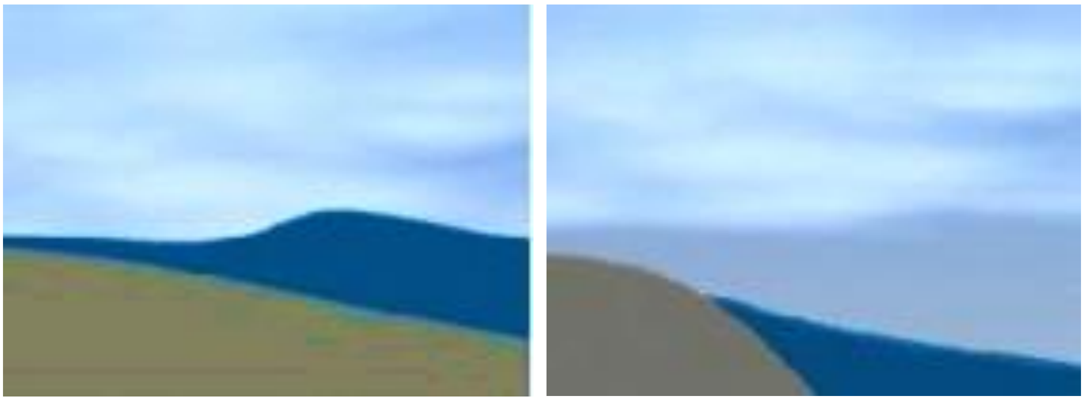


Figure 2.11(a) Storm surge in a gentle slope(left) (b) Storm surge in a steep slope (right) [source: (NHC)]

2.4.4 Influence of coastal bathymetry

Shallow water and coastal bathymetry can influence the storm surge. Exceptionally steep waves may form at shallow waters near the coast (Hansom et al., 2015). Along the east Asian coastline, typhoons have caused significant waves that are above the observed storm surge levels. This is observed as the influence of the bathymetry near the coastline which accelerates the wave energy as it approaches the coast. The developing tropical surges resulting from the typhoons increases the surging water levels to a higher magnitude. The wave energy which is maintained throughout the approach is doubled just before the landfall (Needham et al., 2015).

2.4.5 The complexity of storm surge and inundation levels

The variation in storm surge heights and inundation levels depends on various factors. The low atmospheric pressure, the forward speed, the radius of maximum winds, angle of approach of the storm towards the coast, onshore and offshore coastal bathymetry, continental shelf, and the shape of the coastline are the factors. Under optimal conditions, a typical storm surge can exceed 22 ft (7m) in height (Nott, 2015). Estuaries and bays tend to funnell the effect of storm surges by pushing the water further inland. Typhoon Haiyan (2013) is such an example of a typical typhoon which flooded the city of Tacloban with a 20 ft (6.096 m) storm surge under optimal condition (Hernandez et al., 2015). The 1997 Typhoon Linda which occurred in Mekong Delta triggered a storm surge inundating

80 km inland from the river mouth up to the region's capital city Can Tho (Takagi, 2017) as shown in Figure 2.12. These were the examples of an amplified destruction resulted from the funnelled effect of storm surges.

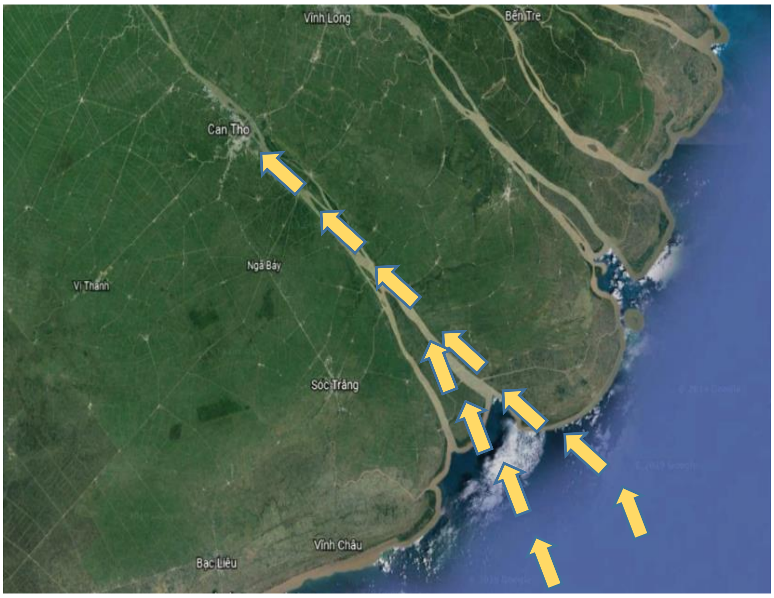


Figure 2.12 Funnell effect of storm surge in the Mekong River Delta [source: (Google Earth)]

2.4.6 Land subsidence, soil and draining water on storm surge

Land subsidence and loss of wetlands increases the vulnerability of existing coastal lands (Henson, 2008). Land subsidence can further build up the risk of coastal flooding and storm surge by weakening the flood control structures. Continuous subsidence leads to altered floodplains and submerged wetlands (Miller & Shirzaei, 2019).

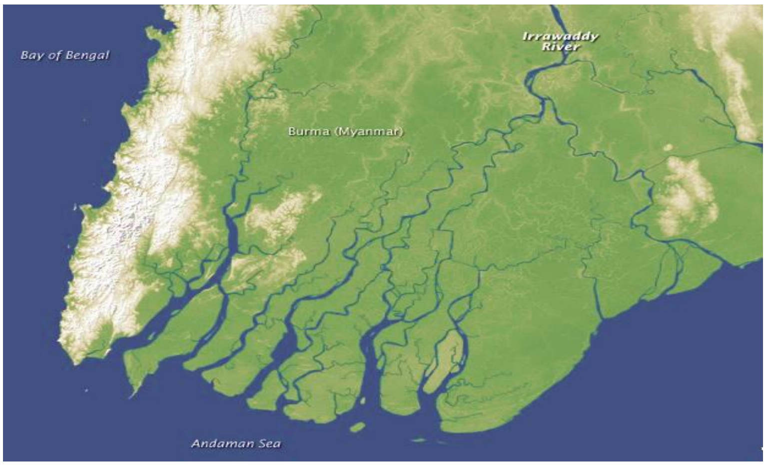


Figure 2.13 Sinking river deltas, Irrawaddy River, NASA satellite image [source: (space shuttle - SRTM)]

In other words, lands subsidence and submerged wetland can determine the level of inundations and impending effect to occur from storm surges. Figure 2.13 is an elevation map, made by Shuttle Radar Topography Mission with high-elevations in white and low-elevation is in green of the Irrawaddy River delta region in Burma (Myanmar). It is clear much of the delta region is below the elevation level (Simmon & Allen, 2009). The combined effect of sinking coastal lands or deltas, together with the rising sea -levels become the perfect base for future storm surges to propagate inland farther from estimated ranges (Syvitski et al., 2009).

2.5 Reverse or Negative storm surge

Hurricane Irma (2017) exhibited a negative storm surge effect. In Florida, a rare reverse surge or negative surge was witnessed in the dry land and receded high water levels were observed far behind as shown in Figure 2.14(a) whilst, passing through Tampa, (Borenstein & Galofaro, 2017). This phenomenon of seawater covering the low coastal zones receding inwards (an effect like the foreword occurrence of the tsunami) and away from the shore uncovering or leaving the land below normal level or in a dry state is known as reverse storm surge. Preliminary estimations suggested that Tampa Bay, Florida would be inundated with at least 10ft of water.

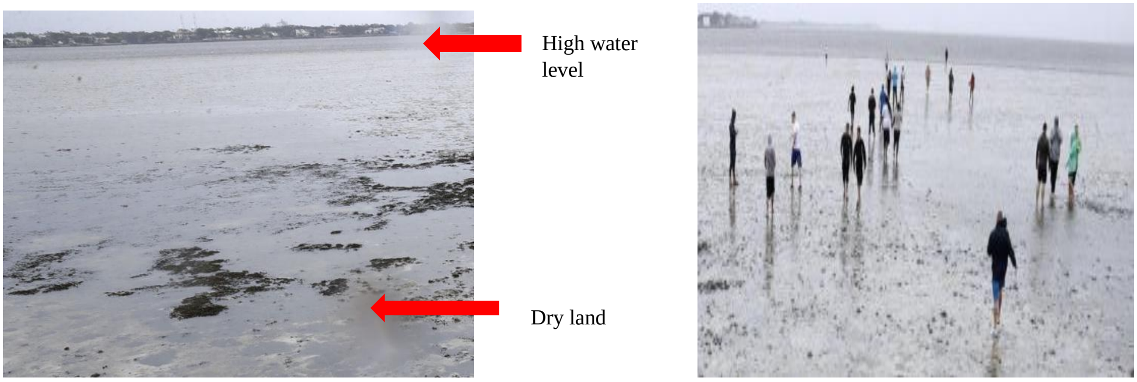


Figure 2.14 (a) Old Tampa Bay, in Tampa Florida during Hurricane Irma (2017) on 10 Sept. 2017 (b) People observed to be walking on Old Tampa Bay, Florida during a reverse storm surge [source: Borenstein et al., (2017)]

However, the highest water level was experienced in areas which are miles away from Florida whilst near coasts were observed dry (Borenstein & Galofaro, 2017). Coastal residents of Tampa Bay, Florida were observed walking on the bay as shown in Figure 2.14(b) to witness this rare effect, highlighting lack of hazard awareness. The absence of the receding water or ‘negative storm surge’ effect is addressed as Positive storm surge.

2.6 Storm Surge measurement methods

2.6.1 Tidal stations

As tidal cycles are predictable, all the water level above the predicted astronomical tide is calculated as storm surges (NHC, n.d.). Tide gauges can record accurate data of tides and increased water levels (NHC, n.d.). NOAA has deployed around 300 tidal stations along the US coastlines and can provide real-time information on water levels every 6 minutes (NOAA, 2018). But in most developing and underdeveloped countries, these tide gauge stations are scarce and are usually distributed far and wide-ranging intervals to capture the accurate peak level (Needham et al., 2015; NHC, n.d.). Furthermore, storm surges with higher magnitude often destroy or damage the gauges resulting in system malfunctioning thereby causing data loss (NHC, n.d.). A complete tropical surge database has not been developed yet to aggregate the global surge database. As surge characteristics are very regional and are influenced mostly by local parameters, global storm surge measurements are limited.

2.6.2 High Water Marks

The identification and recovery of marks showing the highest elevation of floodwaters post-hurricane or flood events are termed as high-water marks (HWM) (Koenig et al., 2016). Some common HWM's are as follows:

- Mud lines (as shown in figure 2.15 (a))
- Rafted debris lines
- Scars on trees (as shown in figure 2.15 (b))
- Wash lines
- Eroded banks (The Associate of State Floodplain Managers, 2014)

These HWM's were perceived as valuable data to understand recent and past flood events (The Associate of State Floodplain Managers, 2014). The observed HWM's at a particular location is useful to determine flood's return frequency, wave propagation and in basic comparison analysis (The Associate of State Floodplain Managers, 2014).

It is the second most-accurate method for storm surges measurement after tide gauges. HWM's are useful alternatives where the real-time monitoring equipment does not exist or in case of malfunction or before being damaged by coastal surge.

The only limitation of HWM's is the flood data can only be collected where available and possible chances are more to be mixed up with wave run-up or set-up (NHC, n.d.). For example, Post-typhoon Haiyan, eyewitnesses were used to gain insight where HWM's could not be concluded from a storm surge or wave run-ups. The U.S. Geological Survey (USGS) maintains a database which includes the HWM's for storm surge and other flood events (Koenig et al., 2016). Figure 2.15(a) shows the USGS surveyor measuring the HWM post a hurricane.

Figure2.15(a) USGS Surveyor measuring a high-water mark (HWM) [source: USGS]

Figure 2.15(b) HWM of saturated water from trees [source: The Associate of State Floodplain Managers(2014)]

Figure 2.15(c) HWM project initiative post-hurricane Sandy [source: FEMA(2018)]

Post-Hurricane Sandy (2012), FEMA and NFIP initiated an HWM initiative project as shown in Figure 2.15(c) to create awareness of flood risk as an action of mitigation (FEMA, 2018). Although, in developing and underdeveloped countries storm surge measurement is carried out from HWM’s, they are measured only for official purposes. Lack of funded community initiatives which creates public awareness was not observed. The limitation of HWM’s in storm surge measurement is the confidence in differentiating between a surge water elevation and a possible wave run-up.

2.6.3 Pressure sensors

The pressure sensors measure the barometric pressure to calculate the storm surge duration, estimated time of arrival at a point, retrieval time and their depths. These are temporary solutions and are usually installed around the structures before the arrival of the hurricanes (NHC, n.d.). However, these systems record the data at a point of a given time and are not real-time (NHC, n.d.).

2.6.4 Saffir Simpson Wind Hurricane Scale (SSWHS) and storm surge

Tropical cyclones are categorized on a scale of 1 to 5 based on their sustained wind speed. This scale is known as the Saffir-Simpson Wind Hurricane Scale (SSWHS). This scale gives an estimated relative wind speed and their potential property damage (Schott et al., 2019) as shown in Table 2.2.

Table 2.2 Hurricane categorisation according to Saffir-Simpson Wind Hurricane Scale with their corresponding wind speed and potential property damage [source: (NHC, n.d.)]

Category	***Sustained wind speed mph***	***Sustained wind speed km/hr.***	***Surge Ft (m)***	***Potential damage***
Category 1	74-95	119-153	3.9- 4.9 (1.2-1.5)	Very dangerous winds will produce some damage
Category 2	96-110	154-177	5.9-7.9 (1.8-2.4)	Extremely dangerous winds will cause extensive damage
Category 3	111-129	178-208	8.9- 11.8 (2.7-3.6)	Devastating damage will occur
Category 4	130-156	248	12.8- 17.7 (3.9-5.4)	Catastrophic damage will occur
Category 5	>157	>252	>17.7 (5.4)	Catastrophic damage will occur

The scale was originally developed in the year 1969 by wind engineer Herbert Saffir and meteorologist Robert Simpson, who was the then director of National Hurricane Centre and was named the Saffir-Simpson Hurricane Scale (Schott et al., 2019). The original scale developed in 1969, included details of storm surge, rainfall reading which was later removed by NHC in the year 2009. The scale was then tailored to reveal hurricane intensity estimate and called as SSWHS.

Significant events such as the Hurricane Charley (2004), Hurricane Katrina (2005), Hurricane Ike (2008) had various contradictions concerning the SSWHS. Hurricane Katrina (2005) made landfall in Louisiana as a Category 3 hurricane. According to the older version of SSWHS, the corresponding storm surge that was related with Category 3 hurricane should have likely produced a maximum of 11.8 ft (3.6 m). However, Hurricane Katrina triggered a 27.8 ft (8.47 m) storm surge (NHC, n.d.). Similarly, Hurricane Charley (2004) which was a Category 4 produced a 6-8ft (1.8-2.4 m) and Hurricane Ike (2008) which was a Category 2 produced a 20 ft (6.1 m) storm surge. Summarising from these understandings that hurricane wind intensity does not have any impact on the storm surges and the level of storm surges have various exemptions included within the scale. Therefore, in 2009, the NHC decided to tailor the SSWHS by removing the storm surge scale (NHC, n.d.; NHC, n.d.).

The NHC had concluded on various exemptions, that the storm surge levels were not affected by the hurricane's intensity and their categories. The primary focus of this research is not to recommend the addition of storm surge levels with the current SSWHS scale. However, the researcher considers that including the storm surge readings could be provisional (not accurate) to create a basic awareness. Figure 2.16 shows the pictorial view of the estimated property damage which corresponds with the hurricane category and their respective sustained wind speed. This version is adapted to visually show the impact from the hurricane's heavy winds. The visual representation, however, does not seem to represent the underlying storm surge which can potentially inundate the properties. But certainly, this reveals how the hurricane's heavy winds alone can produce significant damage.

Figure 2.16 Visualisation of hurricane categories and their intensities [Image Source: The Comet program/MetEd]

A typical Category 2 hurricane which can blow off roofs, exposing the property for further coastal flooding. Flying debris could result in causing moderate to serious damages to people, pets, and livestock and in worst-case resulting in deaths.

The following were observed as the limitation of the SSWHS.

- The scale relates only to the maximum sustained surface wind speed. The observations of significant events using this scale only communicates the maximum sustained winds experienced at a particular location and do not communicate the peak intensity reached by the tropical cyclone in its lifetime (Schott et al., 2019). This leaves the underestimation of the real potential of the tropical cyclone.

- The scale does not reveal on the associated impacts such as storm surge, rainfall, or tornado data (Schott et al., 2019). This is key to the early warning system. Having the storm surge reading within the hurricane category scale (though it is not related to the wind speed) immediately identifies that storm surges are associated perils of hurricanes and could be predictable during the dissemination of storm surge warning. The SSWHS scale without the storm surge readings may now project storm surge and hurricanes as two different phenomena and not related to each other. This is another motivation for the framework to create prerequisite awareness in addition to the current existing hurricanes scale.
- Although, this scale defines the estimated property damage from their corresponding hurricane category, the scale does not define the other factors such as change of wind direction, age of the structure and high winds (Schott et al., 2019).

2.7 Existing coastal protection methods

2.7.1 Engineered coastal defence

Storm surge barriers, sea walls and flood walls are the best examples of engineered coastal defence. Storm surge barriers were considered as the most successful mitigation technique with the Netherlands (Deltawerken Online, 2004). A significant part of the Netherlands was below sea level and continuous exposure to storm surge flooding due to their intricate water channels and estuaries connecting to the North Sea. The Netherlands suffers from various hazards such as rising sea levels, storm surges, storms and is also below the sea level with high subsidence rates as a continuous threat for the country (Rijkswaterstaat: Ministry of Infrastructure and Water Management, n.d.).

The North Sea Flood of 1953 impacted the delta region of the Netherlands killing more than 2,000 and flooding 150,000 hectares of farmlands (Deltawerken Online, 2004). To mitigate against these flooding events and the prolonged exposure of vulnerable communities and infrastructure resulted in the investment of storm surge barrier called ‘D*elta works’* (Rijkswaterstaat: Ministry of Infrastructure and Water Management, n.d.). Although, plans were made to construct the delta work post-1953 storm surge event, the actual works began in 1959 following the implementation of the ‘*delta law’* which was passed in 1959 after which the organisation of the construction of the dams were determined (Deltawerken Online, 2004). The country has deployed flood defences for more than 3,700 km as shown in Figure 2.17.

Figure 2.17. The Delta region of the Netherlands protected by various coastal barriers (storm surge barriers, sluices, dams) [source: Deltawerken Online (2004)]

The delta works consists of dams, sluices, dykes, levees and storm surge barriers to enhance the flood protection along the coasts of Netherlands and Zeeland. The delta works project which includes three locks, six dams and five storm surge barriers was completed in 1997 (Rijkswaterstaat: Ministry of Infrastructure and Water Management, n.d.). Figure 2.17 shows the cluster of flood barriers that has remarkably proven to be successful in mitigating storm surge and coastal flooding in the Netherlands (Rijkswaterstaat: Ministry of Infrastructure and Water Management, n.d.). Due to the innovation in flood mitigation, the delta works is considered as one of the most innovative and sustainable solutions was also included in the wonders of the world (Deltawerken Online, 2004; Rijkswaterstaat: Ministry of Infrastructure and Water Management, n.d.).

Figure 2.18 shows different flood barriers of the '*Delta work'* project. The Maeslantkering or Maeslant barrier is a movable flood barrier for storm surge mitigation. Developed countries do not face economic difficulties. Countries with enhanced adaptive capacity not only encourages such coastal investment for long term solution but also capable of responding and deploying resources during emergencies as short-term solutions. The high investment cost, maintenance cost and the topographical implications of constructing a storm surge barrier, may also restrict developing and under-developed countries from practically implementing such measures. Furthermore, the substantial time taken for the delta works cannot be engaged by least developed or even developing countries in a practical set-up.

(a) Hartelkering dam

(b) Maeslantkering or Maeslant barrier

(c)The Oyster dam

(d) Holland Ijssel storm surge barrier

(e) The Easter Scheldt storm surge barrier

(f) Osterschelde barrier

Figure 2.18 The delta works project of the Netherlands [source: (Holland Tourism) & Deltawerken Online (2004)]

Figure 2.19 exhibits the cost of storm surge barrier built across different countries globally. Storm surge barriers could be a direct and immediate solution to mitigate these hazards. But it incurs huge construction and maintenance cost which is beyond the adaptive capacity of developing or underdeveloped countries. In addition to the cost, factors such as time, environmental impact, topography, feasible foundation conditions, makes the storm surge barrier as an impractical solution for many vulnerable zones. It also depends on the durability and sustainability of a flood barrier that could serve as a permanent solution for the long term.

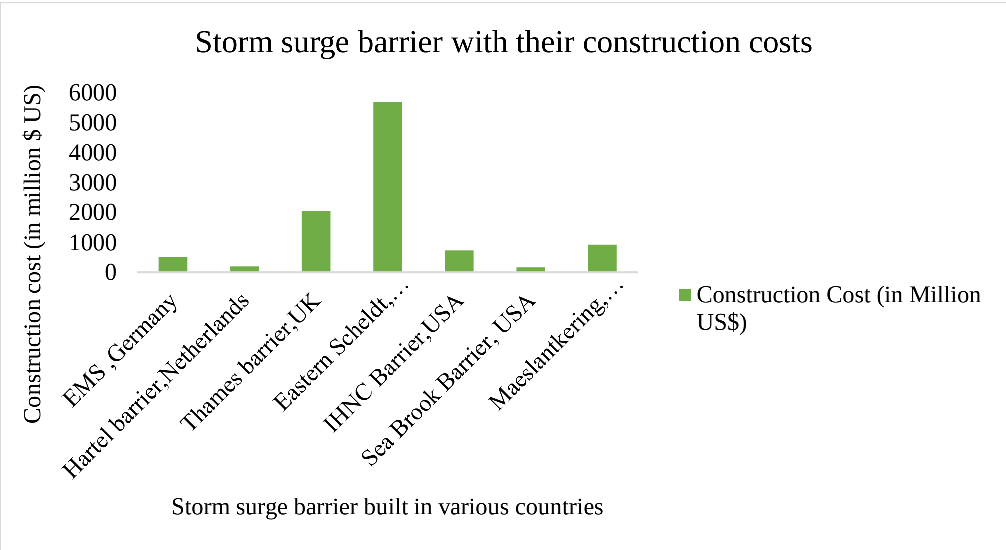


Figure 2.19 Global storm surge barriers and their corresponding construction costs [source: Linham & Nicholls (2010)]

Even developed countries cannot opt for storm surge barriers as a solution all the times. The extended construction period and costs is also another factor that is challenging even for a developed country such as New York. The Request for Proposal (RFP) for the New York-New Jersey's storm surge barrier was proposed soon after hurricane Ike in 2008. However, the proposal is still in the early phase of being considered for execution due to its high investment and its environmental impact on the Hudson River and the neighbourhoods (Hill et al., 2009).

During Hurricane Katrina (2005), the losses were extensive not only because of the magnitude of the storm, but also due to the failure of levees of New Orleans which also aggravated the loss (Muis et al., 2016; Knabb et al., 2005). The rising surge waters engulfed the Lake Ponchartrain thereby flooding all the nearby canals and communities by overtopping and subsiding all flood walls as much as depths up to about 20 feet and breached the flood defences at various times and locations. 80% of the city of New

Orleans were inundated by the severely strained levee system and flood defences which further resulted in 1,500 deaths in Louisiana (Knabb et al., 2005).

Many coastal cities and mega cities have already implemented flood and coastal defence systems as a precaution measure to reduce these risks (Horn, 2015). However, the upgraded flood protection measures are constantly under the risk (Tobin, 2018). This is due to various factors such as the changing coasts from newly built coastal developments, attractive coastal economy, which leads to coastal sprawl with both people and assets exposed. Under such circumstances, implementing a flood defence system remains obsolete and these coastal cities and their surrounding areas continue to be exposed to extreme weather events. As the safety standards of these coastal protection systems are expressed as the allowed probability of exceeding a certain water level as required protection level (Ke et al., 2018). The low safety standards of these coastal protection systems also increase the coastal vulnerability. Besides, the future predicted risks of rising sea levels, land subsidence, increasing trends of economic and population growth could further reduce the level of protection. Although, the level of protection could be evaluated by comparing the crest height of the defence system to the return period of water levels using the flood frequency analysis (Ke et al., 2018). This raises a question on the durability of existing engineered coastal protections and their safety standards in case of return frequency of any such event if it is short. This also questions their sustained level of protection in the verge of current and increase in sea level extremities.

2.7.2 Non-engineered coastal defence

As outlined earlier, it is also not practically possible to build a storm surge barrier at every vulnerable coast. Non-engineered coastal defences are a natural way of protecting the coasts avoiding the construction of structures or engineering coastal defences (Blankespoor et al., 2017). These are preferable for hard flood defence areas as they allow zones near-shore to naturally adapt to the changing conditions. Such non-engineered natural coastal defences are beach replenishment, natural dunes, mangrove vegetation, and salt marshes which could act as a natural buffer in storm surge attenuation (Blankespoor et al., 2017). Breaches in hard engineered coastal protection such as sea wall or flood wall may occur during extreme surge events and in worst-case scenarios. For example, during Hurricane Katrina (2005), levees and flood defences along the coastal New Orleans communities were breached (Knabb et al., 2005). This remains as a classic example where an engineered coastal defence could not serve as a reliable permanent and long- term solution for storm surge hazard. Whilst a country's capability may not often support a quick recovery their economic damage caused by these disasters, it is hardly practical for such countries to invest in building storm surge barriers and fund for further maintenance. Therefore, a feasible and realistic option such as non-engineered coastal defences should be considered as an alternative way in addition to the engineered structure for future storm surge and extreme scenarios.Wetland mitigation can be an economic option to mitigate storm surges. Bangladesh is a disaster-prone country to cyclones, storm surges, coastal erosion, floods, and droughts and hold a multi-hazard profile (Ali, 1999). The south-western part of Bangladesh is surrounded by the world's largest mangrove forest popularly known as 'Sundarbans'. Mathematical models and studies have shown mangrove forests have significant attenuation rate to storm surges (Blankespoor et al., 2017). Although, these mangrove forests cannot completely dissipate the energy created by storm dynamics they can certainly act as a deterrent to storm surges. These natural buffers when planted in the large region can diffuse the storm surge inundations reducing damage rate (Blankespoor et al., 2017). Despite the densely populated mangroves, other factors may also have an impact. Shallow, uneven topographical shelf, deltas with intricate creeks and channels, complex estuaries and river system simply multiply the exposure and vulnerability to storm surges (Ali, 1999).

2.8 Summary

This chapter discussed how and why storm surge is a complex phenomenon and the intricacies in storm parameters. A new set of data observed from 2015-2018 showed how the increase in the intensity and the frequency of the hurricanes could become a potential threat to the coastal communities. The vulnerability and exposure to storm surge is only expected to be amplified, with increase in ocean warming, rising sea levels and increased intensity and frequency of tropical cyclones. Literature in the subject field also highlighted the ambiguity around storm surge and how this misunderstood hazard remains unexplored. The incapability of the hurricane scale to associate with the storm surge further increase the complexity around storm surge hazard and underlines areas of incompetent existing measures. Furthermore, failure to address storm surges with an appropriate solution would result in complications in the process of mitigation even with a hard-engineered solution in the future. These limitations became the primary driving factor for innovation of the framework approach to mitigate this hazard. Especially when such hazards exist in the developing and the least-developed countries, where a framework to mitigate storm surge could be an economically efficient alternative to the hard-engineered structures.

CHAPTER 3
LITERATURE REVIEW

3.1 Introduction

This chapter focuses on the literature by discussing and reviewing the context around storm surge, related challenges in adaptation and mitigation, performance of existing measurement and monitoring systems, and risk approaches. The review provides an opportunity to identify the potential gaps in cyclone-triggered storm surge adaptation and mitigation. The identified gaps will be investigated further through individual case study analysis in later chapters assisting further in the development of the framework. An overall view of the understanding and awareness of coastal communities and residents regarding storm surge during emergencies is discussed in this chapter. The review of previous tools, techniques, and frameworks used in storm surge measurement and their limitations discussed within this chapter became fundamental for the development of the Disaster Adaptation to Mitigate Storm Surge (DAMSS) framework.

3.2 Storm Surge: a global priority

Tropical cyclone triggered storm surges can produce catastrophic coastal flooding. Observational evidence of significant events highlight that storm surge is the primary factor which had caused significant economic damage and loss of life relatively to tropical cyclones (Seo & Bakkensen, 2017). It is difficult to predict the likeliness of the substantial losses that will occur in terms of number of people being killed or affected, or the economic and infrastructure damage of any region from storm surge. This is perhaps because of the uncertainty of storm surge and their sensitivity of reaction to a minor change in any of the storm parameters. Parameters such as central pressure, storm intensity, and storm forward speed, angle of approach to the coast, shallow continental shelves and local coastal bathymetry influence the storm surge characteristics (NHC, 2008). The funnelled effects of storm surges discussed in Chapter 2 further emphasise the seriousness of these hazards and their capability of inundating the cities inland by inducing river overtopping.

According to SURGEDAT (2015) there were more than 700 identified storm surge events globally since 1880 (Needham & Keim, 2012).

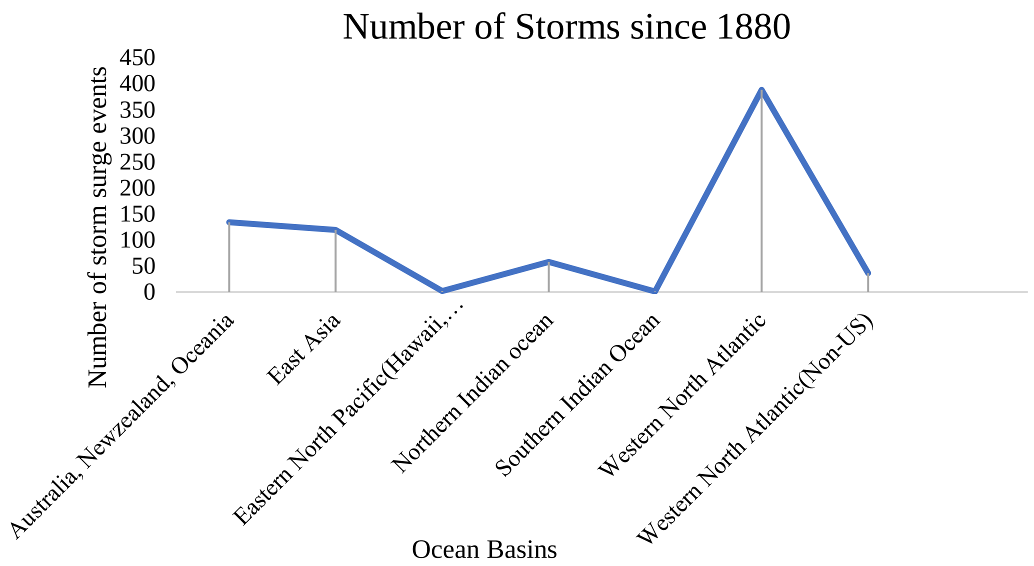


Figure 3.1 Overview of storm surge events in various ocean basins [source: SURGEDAT]

Figure 3.1 shows the vulnerability of all the ocean basins and the prospective damage to their adjacent coastal communities and infrastructures. The database further provides a probability of risk from storm surge events highlighting the vulnerability of the tropical region for various inundation heights. Based on the data set the following global peak surge map shown in Figure 3.2 the global vulnerability from storm surges.

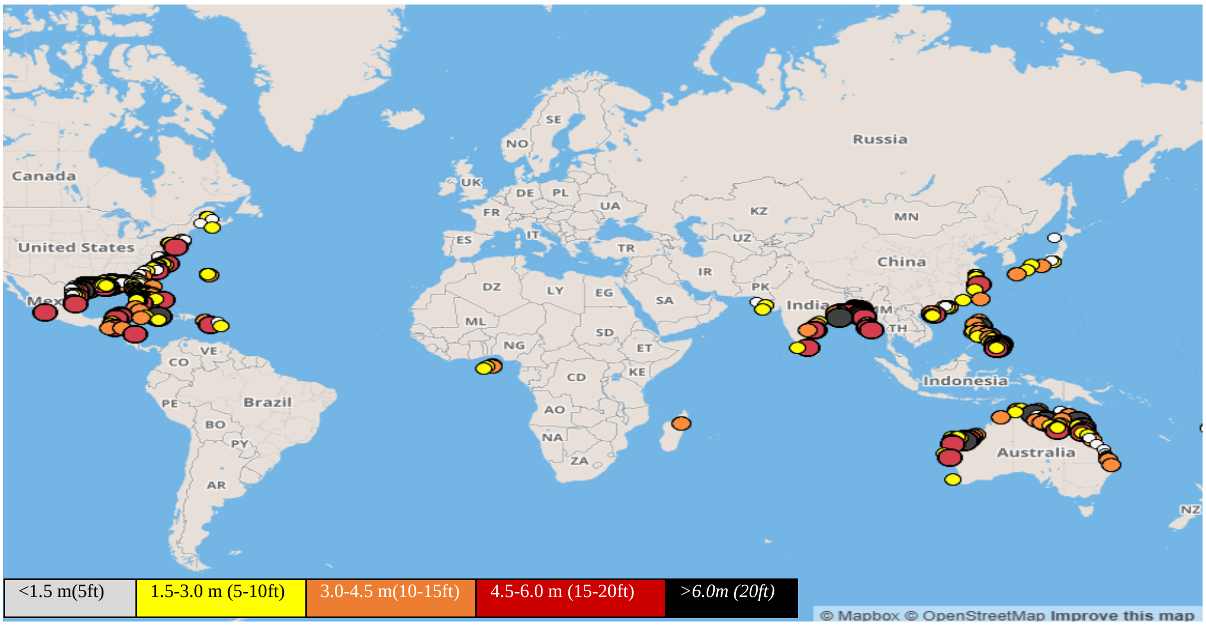


Figure 3.2 Global peak surge map [source: SURGEDAT]

But Jakobsen et al., (2006) stated that the North Indian Ocean especially the Bay of Bengal has experienced the most severe storm surge events with maximum observed surge levels as 39.4- 46 ft (12-14 m). The Bay of Bengal is observed to have a 'deep layer of warm water', which fuels the energy of the tropical system to quickly organise and develop further strengthening within a shorter period. A similar strengthening from the deep warm waters also occurs in the Gulf of Mexico and is reflected during the rapid strengthening of Hurricane Katrina (Hurricane Science, 2008). Nargis underwent rapid intensification from a weak Category 1 to a strong Category 4 cyclone due to the warm water of Bay of Bengal within a period of 24 hours (Fritz et al., 2009).

While the Atlantic Basin and the Gulf of Mexico ranks second to experience a maximum surge level of 27.8 ft (8 m), during Hurricane Katrina (Knabb et al., 2005). The East Asian typhoons have encountered a maximum surge level were around 9.8-19.7 ft (3-6 m) (Li et al., 2004). The surge levels in Australia and Oceania were observed to be the same as the levels in the East Asia. Oceania experiences long-term impacts which include freshwater contamination and loss of food supply but, their maximum surge levels are comparatively lower than the level observed in other regions (Needham et al., 2015). Summarising the facts regardless of the different surge levels occurred in different ocean basins, it can be implied that storm surges are a global phenomenon and can be destructive resulting in significant damage.

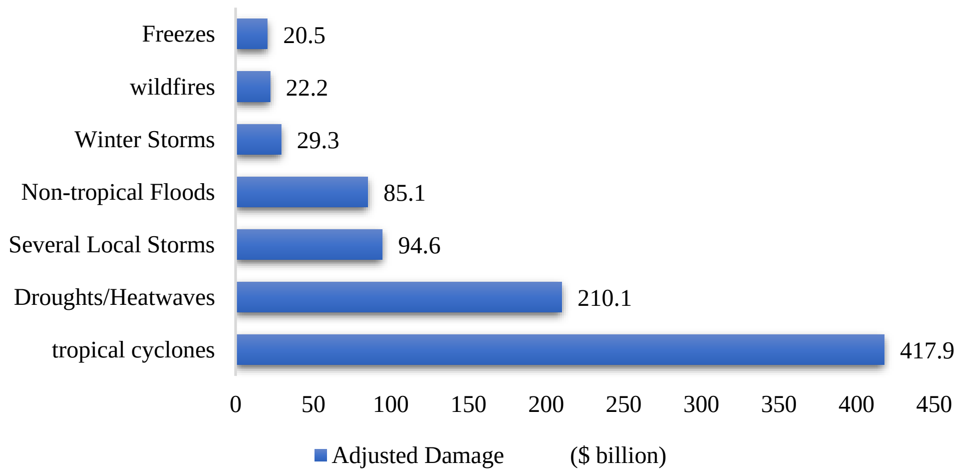


Figure 3.3 Billion-dollar events and their cost of damage by disaster type from 1980-2011 (inflation-adjusted to 2011 currency) [source: Smith & Katz (2013)]

Another study by Smith & Katz (2013), claims that tropical cyclones were responsible for the 47% cost of damage in the United States. The estimated cost of damages by disaster types from 1980-2011 is US $417.9 billion as shown in Figure 3.3. This cost could further be raised to US $753.9 billion if merged with the damage cost from the recent storms notably, the cost of the damages from Hurricane Sandy (2012) and Harvey-Irma-Maria (2017).

Hurricane-force winds are hazardous to coastal communities and infrastructures; however devastating impacts have often resulted from cyclones only when associated with storm surges (Seo & Bakkensen, 2017). In line with Smith's (2013) study, Edward N. Rappaport, the then acting director of the US National Hurricane Centre (2017-2018), carried out another analysis on 'direct deaths from Atlantic tropical cyclones' for a given period of 1970-1999. His study initially recorded that most of the cyclone-related fatalities were associated with rainfall and were not attributed to storm surges. His results further claimed that, only six deaths were directly attributed to storm surges for a period of 30 years from 1979-1999. However, before summarizing the results, the 2005 Atlantic hurricane season proved Rappaport's claims to be incorrect. The loss of 1,833 lives from Hurricane Katrina (2005) challenged his claims. This demanded reassessment of the study period from 30 years to 50 years from 1963-2012, instead of 1970-1999 (Rappaport, 2014).

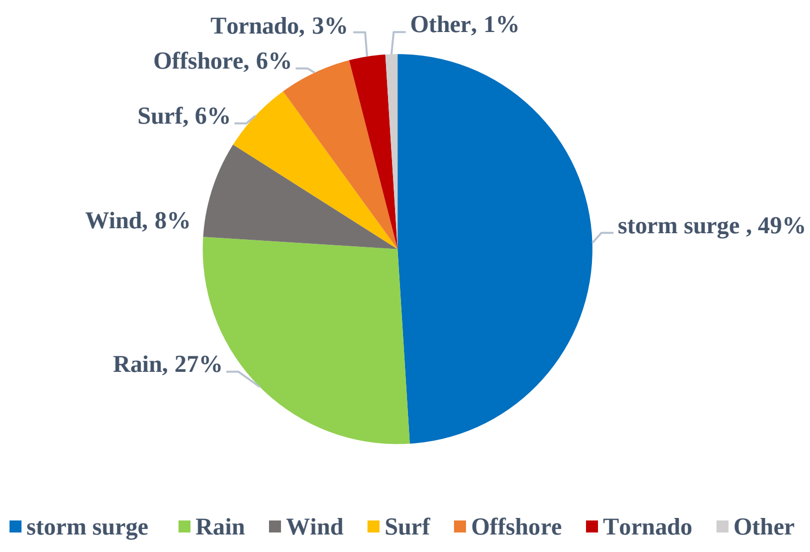


Figure 3.4 Percentage of fatalities caused by Atlantic Ocean hurricanes and their associated hazards [source: Rappaport (2014)]

According to the Rappaport (2014), the accumulation of new data contradicted the previous results. New results stated that 49% of deaths from Atlantic hurricanes are directly associated with storm surge as indicated in Figure 3.4. During these 50 years, 650-700 Atlantic tropical cyclones were recorded. The extension of the study period emphasised the key fact that most catastrophic storms were not necessarily the strongest or 'major hurricanes' according to the SSHWS (Rappaport, 2014). The revised study and the findings agreed that about half of the death were caused by storm surges. Rappaport's study has its exclusions such as global cyclone deaths associated with storm surges were not included and only certain 'period' was considered to conclude the results.

The addition of the recent significant storms in the US cyclone history, which occurred from the year 2015-2018 would further influence this 49% percentage deaths statistic caused by storm surges. A fact to be underlined is that any period 'without a storm surge event' need not necessarily remark or conclude that the effect of storm surges was decreased. Rappaport, further suggests that "*A call to action for the nation's hurricane research and operations program to develop and implement new storm surge mitigation strategies*" (p. 344).

A recent study by Bouwer & Jonkman (2018) claims that, the global mortality rate from the storm surges is decreasing. According to the measured statistics, the mortality rate of the global coastal storm surge events from the compiled and recorded data on loss of lives since 1900, has seen a consistent decrease, with an exemption of South East Asia (Bouwer & Jonkman, 2018). The study also states that the mortality from flash floods and river floods were higher than the mortality caused by storm surges. The dataset utilised by Bouwer & Jonkman (2018) was imported from the EM-DAT, an international database for global disasters.

Bouwer & Jonkman (2018) further claims that continuous innovations in risk projections and forecasts have decreased the mortality rate from storm surge compared to previous decades, such as the 1900 Galveston storm which resulted in 8,000 deaths (Knabb et al., 2005). As claimed by the study, it is true that the 1900 Galveston hurricane's death rate has not been surpassed for many years until Cyclone Nargis (2008) which resulted in 140,000 deaths (Fritz et al., 2009). The 6,300 deaths from Super-typhoon Haiyan (2013) underlines the fact, that technical advancement alone is not sufficient to mitigate the effects of storm surges (National Disaster Risk Reduction and Management Council, 2015).

While agreeing on the fact that efficient early warning systems, advanced technologies and effective risk communication could reduce the higher risks imposed from these hazards, a previous study of Jonkman & Vrijling (2008) states that the fatality from storm surges was not recorded consistently in national and global level.

The official death toll from Hurricane Maria (2017) is 65 (at the time of research) whilst a specific study conducted by Milken Institute School of Public Health (2018) has identified that the loss of 2,975 lives were associated with the event (Milken Institute School of Public Health, 2018). After Hurricane Katrina (2005), the major loss of lives in the Caribbean and US territories was caused by Hurricane Maria (DHS & FCC, 2018). The death toll from Maria concurs with Jonkman & Vrijling (2008) statement but highlights the fact that there is lack of consistency in disaster fatality record management.

The study of Bouwer & Jonkman (2018), also exempted the South East Asian cyclones, an ocean basin which is highly prone to typhoons, super-typhoons and storm surges and focuses more on the USA. This exemption, if included would largely alter the previously observed results and would certainly diverge from the primary claim of mortality trend being decreased from storm surges. Nevertheless, Bouwer & Jonkman (2018), themselves have stated that the mortality rate from storm surges has not declined for southeast Asia and the rest of the Asian countries which majorly comprises developing and under-developed countries.

To answer the question that if the mortality rate of developing countries has also decreased, the decrease in the mortality rate from storm surges could also be ‘momentary’ over the observed period. Therefore, the risk imposed on the coastal communities and infrastructure from this hazard cannot be concluded with the observation. Also, decreasing death rate is also subject to change with future changes. Moreover, this study emphasises how these hazards should not be deviated from being considered perilous irrespective of the advanced monitoring systems in place.

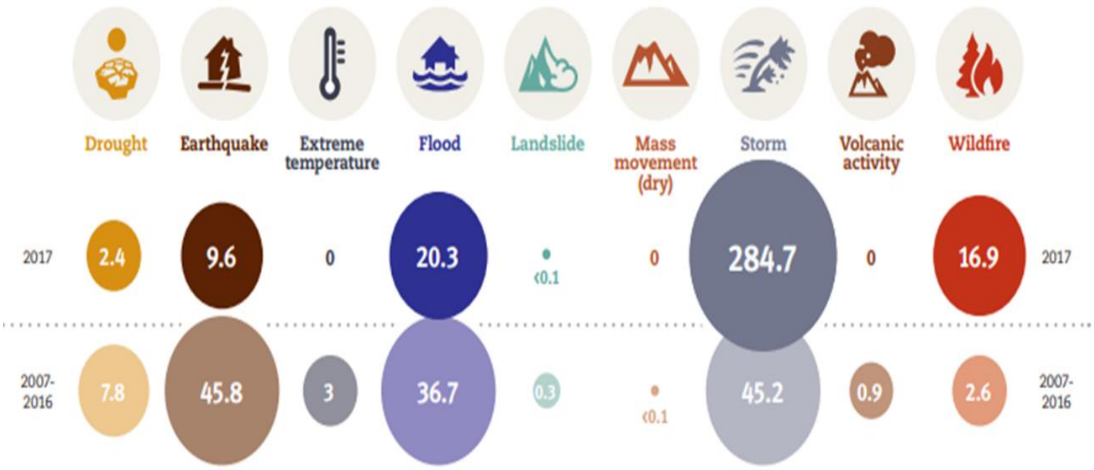


Figure 3.5. Economic losses (billion US$) by disaster type: the year 2017 compared to 2007-2016 [source: CRED (2018)]

Figure 3.5 shows the economic losses by disaster type (in billion US$) of 2017 in comparison with the 2007-2016 losses. The 2017 Atlantic hurricane Season is claimed to have been one of the significant years in the US hurricane history in term of tropical cyclones and storm surges (Smith et al., 2018). The observation by CRED (2018) highlights the significant socioeconomic damage of US$ 284.7 billion for the year 2017 from the tropical cyclone and storm surges. It is during this year, the death toll recorded from a single event during Hurricane Maria (2017) was observed with 2,975 deaths (Milken Institute School of Public Health, 2018) in Puerto Rico. These observations clearly remark the changing risk and an obvious disparity to previous observations and claims on storm surge being as less hazardous with decreasing death rate.

The addition of new data from 2016-2018 if integrated with existing findings, certainly alters the previous observations considerably. Estimated versus the actual losses from storm surge hazard shows that the understanding of storm surge characteristics may not necessarily be comprehensive. This could further result in an improper future risk assessment with an already miscalculated base data. This supplements the recommendation of review of existing approaches or a possible reassessment as they could result in the inappropriate analysis of storm surge characteristics and may mislead future risk assessment and approaches.

3.3 Lack of data and ambiguity in storm surge classification

As mentioned earlier in Section 3.2, despite the occurrence of more than 700 events over a century, storm surge seems to remain unrecognized widely. This may be possible because it was considered as an associated threat from tropical cyclones. In Figure 3.6 the data reported to EM-DAT displays the maximum number of disasters per type has occurred of which, most number of disasters occurred were related to flooding with 3,148 events followed by storm with 2,049 events (Wallemacq & Below, 2017).

The Emergency Management Database (EM-DAT) is an international database for reported disasters. As per EM-DAT storm surge which typically takes place with the occurrence of the tropical cyclone was classified under 'convective storm' category (EM-DAT, n.d.). This is a sub-sub-disaster type of storm. Despite the effort of the database to record the events does not differentiate the number of storm surge events associated with tropical cyclones.

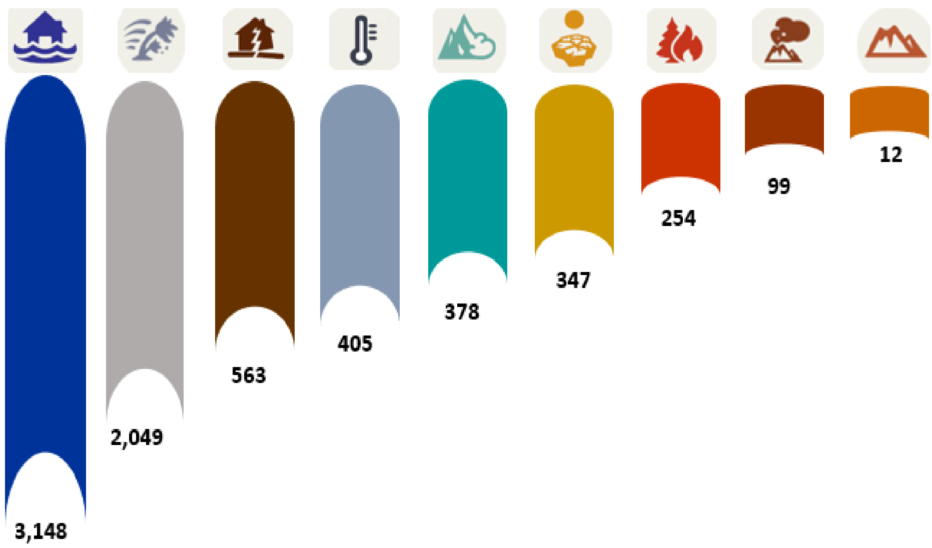


Figure 3.6 Number of disasters per type (1998-2017) [source: Wallemacq & Below (2017)]

The word 'convection' from the term convective storms denotes that any property that is being transported through fluid movement most often associated with heat transfer. Severe convective storms often refer to hail, lightning, tornadoes, and straight-line winds (Doswell, 2001).

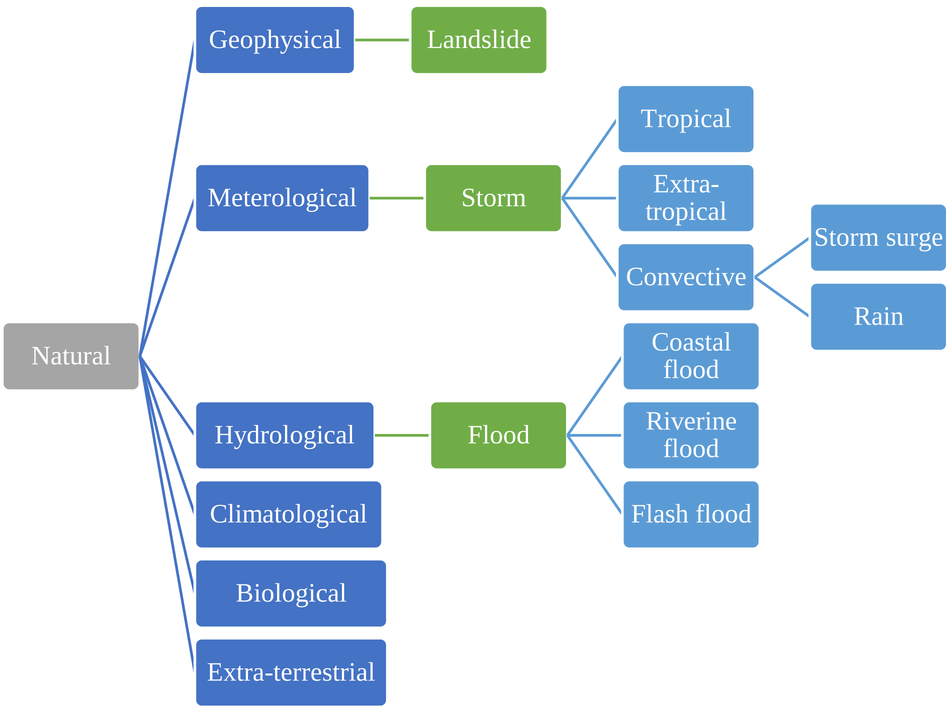


Figure 3.7. A general classification of natural disasters [source: (EM-DAT, n.d.)]

Figure 3.7 shows the classification of a natural disaster, disaster sub-type and disaster sub-sub type labelled by EM-DAT. By categorising storm surge under ‘convective storm’ or grouping many disasters TC-triggered storm surge as TC’s may continue to leave this hazard as less estimated or known hazard. Also, storm surge is a type of coastal flooding it is further conjectured that storm surge may also be classified and reported in various situations as coastal flooding. This classification is observed to show that there is no direct association of storm surge with a tropical or extra-tropical storm from which predominantly storm surge occurs. Further, storm surges which can induce river overtopping in the lands in estuaries and the classification does not show any connection with storm surge. Coastal flooding, which usually occurs from high tide or storm surge is also recorded individually remarking that this to be a separate event from storm surges.

Lack of data continues to prevail especially for this hazard. This may further mean as incorrect hazard classification obscuring the underlying actual risk of storm surges. The inaccurate data may further amplify the ambiguity of understanding the actual estimation of loss of lives and damage statistics. This may also result in over-estimation or under-estimation of the actual risk thereby, misleading the future adaptation and mitigation approach for storm surge risks.

Although, storm surge is generated predominantly from tropical cyclones, yet not all cyclones result in generating a storm surge. This not only increases the 'uncertainty' attributed to storm surge but also highlights the lack of possible data and emphasise the need to understand storm surges. When classifying the damage caused by a storm surge, the observations must be measured and recorded in a useful and understandable manner. This could be suggested as one of the future recommendations for storm surge data collection and monitoring.

3.4 Awareness and risk communication of storm surge

An interview given by the then director of National Hurricane Centre to the National Public Radio in 2018 stated that "*Most of the fatalities from these tropical systems is from water*" (NPR, 2018).

Storm surges are a complex seaborne hazard originating predominantly from key weather events such as tropical cyclones. But also, their sensitivity to react to the slightest change in the storm parameters retains its 'uncertainty factor' regarding why all hurricanes do not result in a storm surge and why some storm surges are anomalous to coast (NHC: NOAA, n.d.). Communication plays a critical role throughout the different phases of a disaster such as pre-disaster, during and post-disaster emergencies (Neussner, 2014; Jibiki, 2016). Cyclone Nargis was the first to make landfall in Ayeyarwady delta, the people from the Ayeyarwady delta had little or no awareness about the cyclones or storm surges (Fritz et al., 2009). The super-typhoon Haiyan brought a 20-ft (6.1 m) storm surge and caused a significant death toll of more than 6,300 people in the Philippines and the primary factor behind the loss of lives was inadequate storm surge communication and awareness (NDRRMC, 2015). The residents who on average experience 18-20 typhoons annually, suffered catastrophic damage and loss of lives because the residents were not communicated or interpreted regarding 'storm surge' and its effects and influences (Hernandez et al., 2015; Neussner, 2014). Many hospitals moved their patients to basements, had known little about the 20ft storm surge (Jibiki, 2016; Hernandez et al., 2015).

Typhoon Linda which made landfall in Can Tho, Mekong Delta in the year 1997 was a significant event of all the 228 storms which made landfall in the same location (Takagi et al., 2017). Regardless of the mangrove forest, the 6.56-ft (2.0 m) storm surge was able to inundate the city of Can Tho. According to Takagi et al., (2017), despite Typhoon Linda left a 'storm-memory' to the delta residents, only a few studies have been conducted on the storm surges in Vietnam. Fritz et al., (2019) underlines an article from The Washington Post, how a local county officer of Florida during Hurricane Florence (2018), mentioned that "*A lot of people did stay because the storm went down from Category 4 to a Category 2 and they think of that number as being the end-all*". This statement demonstrates the general awareness of tropical cyclone warning systems and storm surge awareness in developed countries like the USA.

Establishing accurate death and damage statistics from disaster events are often critical for governments and their authorities (Guha-Sapir D, 2018). The previous Section 3.2 discussed how the NHC's tropical cyclone report of Hurricane Maria (2017), stated the death toll as 65 that varied largely with the observed death toll from the study done by Milken Institute of Public Health -George Washington University. The new death toll which is 2,975 identified by the Milken Institute School of Public Health (2018) is 46 times greater than the number declared previously by the federal government of the USA.

The new statistics obtained were based on verified death certificates, clarifying the accuracy and precise death count from Hurricane Maria (Milken Institute School of Public Health, 2018). Despite the verified data, the federal agency has not considered revising the death toll. The observed variation between the earlier reports versus the new death statistics clearly shows the possibility of how inaccurate data is fed within disaster record management. This should be viewed as an action described by Guha-Sapir (2018) on how increased death or damage may expose the inefficiencies of the country's poor infrastructure or inadequate preparedness and responses to extreme weather events These inaccurate data may further lead to miscalculation of socioeconomic damage thereby resulting in underestimation of actual risk from storm surges for future mitigation.

According to the Annual Disaster Statistical Review 2016, the collective data as shown in Figure 3.8 indicates that every year from 2006 to 2015, the hydrological (flood) disasters have contributed to most disasters with around 177 events. Followed by this, the meteorological disasters (cyclones and storms) were identified with 96 events (Guha-Sapir et al., 2017). It is not clear on whether these flooding were caused by cyclones, storm surges, extreme rogue waves/high tides, or heavy downpours.

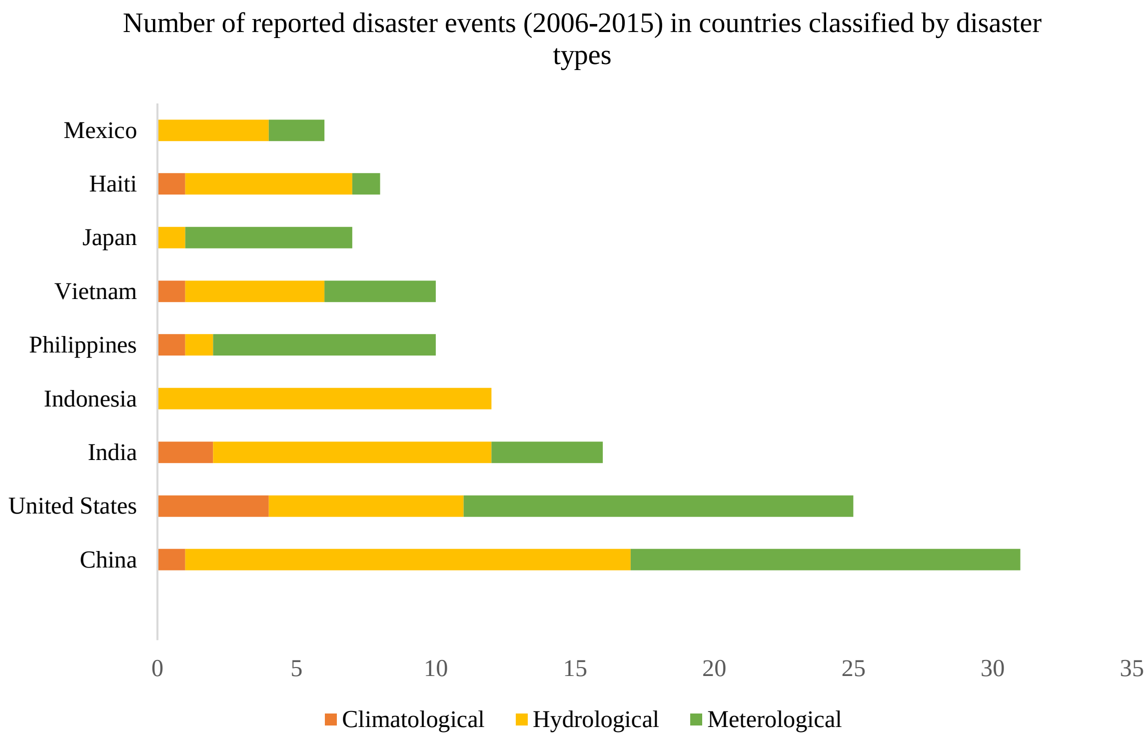


Figure 3.8. Annual Disaster Review 2016: statistics and trends for 2006-2015 [source: Guha-Sapir D (2017)]

Based on the indications from Figure 3.8 the number of reported hydrological and meteorological events is greater than that of climatological events. This implies the possibility that, storm surge events may have occurred under both these classifications. That is the hydrological disasters induced by meteorological events triggering storm surges inundating the city with coastal and induced river flooding.

In an interview to the NPR in 2018, a local resident said that, "*I have been living down here for a long time, so this one is OK*". The resident was identified to be in the path of Hurricane Florence (2018) and further added that the decision to stay back was based on the alert issued by NHC that the hurricane has now weakened (NPR, 2018). Despite NHC's alerts regarding possible storm surge inundations, the resident chose to stay back in a mandatory evacuation warned zone (NPR, 2018). As possibility is that the resident may have seen many hurricanes which had not brought any coastal storm surge in the past. This may have led to her decision to stay back. However, the then potential Hurricane Florence (2018) may or may not bring a storm surge which was unpredictable. The contradictory behaviour in coastal resident's decision to stay-back subsequently after the evacuation order, should be observed as 'lack of clarity' in emergency communication on behalf of the authorities or shallow understanding of storm surge threat on behalf of the resident.

During cyclone Nargis (2008), the death of 140,000 people was reported due to the failure of the early warnings and public awareness of the storm surge hazard (Fritz et al., 2009). The perilous condition post-cyclone Nargis made the country to be overwhelmed by the storm surge impact resulting in call for humanitarian assistance request (Guha-Sapir, 2018). Though communication has seen extensive improvements with the support of technology in developed countries, the performance of early warning system and risk communication significantly differ with developing and under-developed countries.

The general understanding and awareness of storm surge among different countries are observed to have considerable variations. These observed variations may be due to social inequalities between developed and developing countries. It also may depend on the economic capacity under which a country's exposure and their ability to cope under vulnerable conditions is also a determining factor. Lessons learnt from past events, and most-recent events highlight the significant gaps such as lack of implementation of the lesson learnt and lack of invest in protective infrastructure and resilience measures. In some developed countries, despite their adaptive capabilities to mitigate and cope with the risk, the countries continue to suffer the impacts that abounds with storm surge.

3.5 Storm surge measurement and current adaptation measures in practice

The first satellite images of the Atlantic tropical cyclones became active to forecasters in the year 1966. It is in this same year, the first observation and numerical tropical cyclone forecast models were introduced (Rappaport, 2014). National Hurricane Centre, the formerly known as Miami Weather Bureau communicated the information about hurricane Betsy (1965) to the public using television as the communication medium (Rappaport, 2014).

However, present-day weather prediction has improved considerably. The weather prediction models of National Hurricane Center (NHC) such as the Sea, Lake, Ocean, and Hurricane (SLOSH) and the European Centre for Medium-Range Weather Forecasting (ECMRW) were recognized for their accuracy in plotting the likelihood of the impending tropical cyclones. The NHC's SLOSH model simulates using 27 ocean basins along the U.S. east coast and Gulf coasts to predict the worst-case scenarios for every potential hurricane. The result of a sample simulation of SLOSH models suggest that is if a storm surge occurs with the highest category 5 hurricane, according to Saffir-Simpson Hurricane Wind Scale (SSWHS), over 16,000 km of evacuation route and at least 22 million people could be at severe risk and affected by storm surge and coastal flooding. As stated in the NHC's report of SLOSH model, it is identified that Maine, Massachusetts, New York, and New Hampshire do not have the FEMA recommended official evacuation routes (Zachry et al., 2015). Despite the results, suggested by the simulation states identified with no evacuation routes exposes the vulnerability of population directly leading to risk.

The track or the path of the tropical cyclone is termed as the 'cone of uncertainty', which is predicted five days in advance utilising the technical advancements and innovations in hurricane forecasting and hindcasting systems (NHC, n.d.). Due to this advancement in hurricane prediction, pre-planned and organised evacuations can be advised earlier protecting loss of lives. Although, the technical advancement may seem to benefit in decreasing the death toll in developed countries, but this can also aid to an overlooked effect as it is the only solution to mitigate this hazard. Also, the technical advancement and their results which may be achievable in developed countries may not be feasible in all the countries and the achievement of similar results could be lower in developing countries and even lesser for least developed countries (Bouwer & Jonkman, 2018).

Post-hurricane Katrina the storm surge measurement was removed from the SSWHS scale due to various criteria that contradicted the storm surge and hurricane is removed from this scale. In 2016, NHC issued the first storm surge flood hazard map and the first storm surge watch-warning was issued prior to Hurricane Matthew. The introduction of the 'storm surge watch-warnings' and the 'flood hazard maps' were issued to create awareness and understanding of storm surge. The risk hazard maps issued in the best interest to create awareness however it was issued only to certain locations to test the procedure. Other exclusions are levees, embankments, seawalls were excluded from the mappings due to their complexity in calculating the flooding and over topping levels. For locations with such a situation, the community residents were requested to check with local officials (NHC, 2016). Contemplating on the recurrence of Hurricane Katrina, and how levee failure resulted in catastrophic damage, the current flood hazard map estimated with levee exclusion, only highlights the increased likelihood of experiencing similar damage of Katrina.

Coastal Zoning is one of the popular systems in place to categories the coastal properties and communities according to low, medium, and high-risk zones. Most developed and some developing countries whose coastal communities and infrastructures exposed to hazards have ‘coastal zoning’ systems already in place as a step towards mitigating storm surge hazard. Nevertheless, even the low-risk coastal zones were trespassed by coastal surges. Inundations from storm surges and coastal flooding are identified continuously even during the most recent Harvey (2017) and Michael (2018).

Overriding of zoned systems, beyond their mapped areas shows the gap between mapping methods and actual observation post-surge events. This could be mainly from issues like the use of outdated maps, decades of gap in updated census records but also the sensitivity of storm surge to additional variants before landfall affecting mapped location (Bathi & Das, 2016). In early 2015, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) introduced colour code storm surge warnings (Flores, 2015). This type of colour-coded early warning system is introduced due to the result of damage incurred by Typhoon Haiyan (2013).

3.6 Challenges in storm surge tools, techniques, and existing gaps

Technical advancement has certainly improved hurricane forecasting and hind casting techniques to a high degree (NHC, n.d.). With the present-day forecasting techniques, situations like the 1900 Galveston hurricane which struck the Texas coast without any official warnings has been almost diminishing even in developing countries. However, certain factors such as hurricane intensity (Seo & Bakkensen, 2017), rapid intensification and re-intensification (Nguyen & Molinari, 2012), the size of the storm that influences the storm surge (Irish et al., 2008) calculations remain critical.

Hurricane intensity is one of the biggest challenges for the forecast and monitoring agencies like NHC. As the intensity of any hurricane is measured as highest sustained wind speed, and this measurement does not include information on storm surge or precipitation-based flooding. Both hazards are predominantly hazardous than the primary hazard which is the tropical cyclone themselves (Folger, 2018).

3.6.1 Traditional Methods

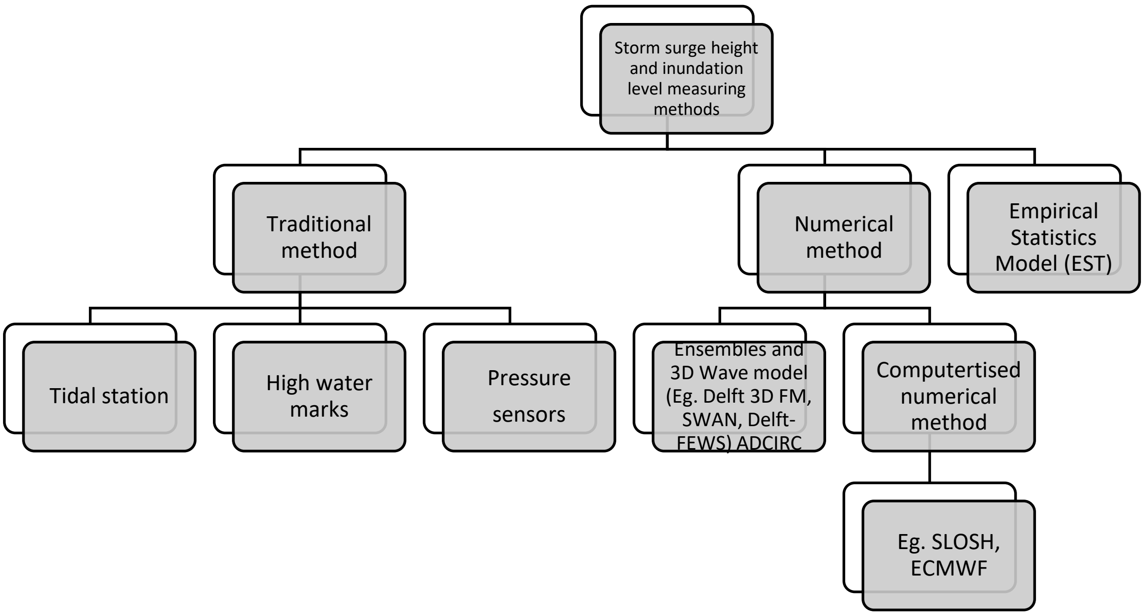


Figure 3.9 Illustration of storm surge measuring methods

Traditional storm surge measurement includes observations from the tidal station, high watermarks and pressure sensors as shown in Figure 3.9 (NHC, 2008). Storm surge recordings from tide stations are most accurate information, however, their distribution along the coastline is considered uneven (NHC, 2008). Also, the poor adequacy in the number of tidal stations limits the real-time validation of storm surges in most vulnerable areas. Moreover, majority of these tidal stations were being situated in North America and Europe further restricts the broad-scale global assessment of accurate storm surge measurement (Wahl, 2017). In line with Wahl’s statement, the Asian countries observed with shortage of tidal stations, underlines lack of storm surge measurement implements in developing countries.

Storm surge data has also been recorded using static Global Positioning System (GPS). Recording data by this method requires areas with no trees to return the accurate results and excluding the tress only compromises the accuracy of such systems and subjected to questioning. Although, these data are close to the accuracy they may lead to an underestimation or over-estimation of storm surge risks. After every hurricane event, the storm surge inundation levels and heights were measured for future reference. During such attempts, possible misinterpretations have and could occur. For instance, wave run-up or wave height or river flooding may have been captured instead of storm surge.

Another critical factor which affects storm surges is the cyclone intensity. Although, the expected track 'cone of uncertainty' (NHC, n.d.) is calculated with possible hurricane category, calculating the rapid intensification, or weakening of tropical cyclones remains critical still today (Nguyen & Molinari, 2012). The rapid intensification of the storms influences storm surge considerably. Understanding the factors that contribute to the sudden change in the strength or weakening of cyclones, characteristics of rapid intensification and re-intensification are crucial. In general, predicting the accuracy of intensification of cyclones and their re-intensification less than 24 hours is much more challenging than predicting their path. It is these dynamics which alter the storm surge characteristics significantly, yet a large portion of this area is yet to be investigated more (Nguyen, 2012; Irish et al., 2008).

3.6.2 Numerical methods

As discussed previously in Section 3.5, storm surges are currently estimated using the computational numerical models such as the SLOSH with 20% accuracy (NHC, n.d.) and ADvanced CIRCulation (ADCIRC) models in support of enhancing effective evacuation decision-making. Both ADCIRC and SLOSH models are water-surface outputs (Allen et al., 2013). Although, the NHC's SLOSH model simulates 27 basins along the U.S. east coast and Gulf coasts, it also has its limitation such as wave impacts, astronomical tide data, river flow data which are not fed into these models thereby limiting their accuracy. However, this is considered as one of the reliable methods by the NHC in storm surge prediction (NHC, n.d.). The ADCIRC model is considered as a better-quality model compared to SLOSH, as external factors such as winds, atmospheric pressure, tides, circulation of the basin, external terrestrial obstruction, were included within the simulation for improved results (Allen et al., 2013). The ADCIRC model greatly benefits by providing coordinated outputs from varied factors. However, ADCIRC model also has its limitation such as (*i)* dependency on former outputs for increased accuracy *(ii)* requirement of expert-level knowledge *(iii)* coordinated outputs of more than one modelling applications. In addition to this lack of water-level data in the selected area may also influence the accuracy of the results obtained (Allen et al., 2013).

Reiterating the discussion in Section 3.5, SLOSH model that has identified impact of the worst-case storm surge scenario with a possible category 5 hurricane according to the SSWHS, that could affect at least 22 million people and yet some evacuation routes were yet not determined. Maine, Massachusetts, New York, and New Hampshire not identifying a recommended evacuation routes in case of emergency leaves such innovation and its efforts ineffective (Zachry et al., 2015). Moreover, New York and Maine did not have their official recommended evacuation routes already-in-place, since the landfall of Hurricane Sandy (2012) further highlights lack of implementation of the lessons learnt, and poor usage of available resources. It is more likely that these cities would endure the same consequences faced during Hurricane Sandy's in case if the same is repeated in the future.

Satellite altimetry measurements is the more advanced technique used to explore the ocean dynamics, and changes in global sea-levels (Cipollini et al., 2017). However, these types of data monitoring and measurement that supports the estimation of storm surge are still in the development stage and require complex sequence of processing. Contributions to enhance and improve the altimeter data in understanding the ocean and the sea-level variability are in progress. Although, this is a welcoming effort, could not be considered for an immediate adaption and mitigation for storm surges, until fully studied (Cipollini et al., 2017).

3.6.3 Saffir-Simpson Wind Hurricane Scale

Tropical cyclones wind speed and their intensities are generally measured along the Saffir-Simpson Wind hurricane Scale (SSWHS) on a scale of 1 to 5. This scale is primarily used to estimate the level of property damage that can be caused by a potential hurricane (NHC, n.d.). Although, this scale provides the information of sustained winds speed, it does not provide any information about the storm surge associated with the cyclones (NHC, 2008). For example, a Category 1 hurricane does not disclose the details of the equivalent storm surge height or their inundation levels (NHC, 2008).

According to the National Hurricane Centre (NHC), the SSWHS included the hurricane and storm surge inundation levels and later the storm surge inundation height scale was removed from the original version (NHC, n.d.). This is due to the exemptions identified from various events which do not emphasise the requirement of storm surge scale to be correlated with hurricane scale. For instance, Hurricane Charley (2005), a Category 4 hurricane from SSWHS produced a storm surge of 6-8 ft (1.8- 2.4 m) and Hurricane Ike (2008), a Category 2 hurricane from the same scale produced 20 ft (6.1 m) storm surge (NHC, 2008). Although, NHC's viewpoint on removing the storm surge inundation levels was based on its non-correlation with the hurricane scale, the inclusion may rather have provided the likelihood of the inundation levels to a certain extent.

AccuWeather, a weather media company remarked that "*The current hurricane scale does not reflect the real impact of hurricanes*" (AccuWeather, 2019). The company contributes by maintaining a weather-related database and providing critical information on weather-related emergencies. To support the hurricane understanding, the AccuWeather RealImpact^{TM} scale for hurricanes was introduced in January 2019. The scale categorizes hurricanes on a six-point scale (AccuWeather, 2019). The new scale is said to have considered several other factors such as storm surges, flooding rain, high winds, total damage, and economic impact from the storm. The scale further remarks that SSWHS has categorized the hurricanes primarily based on the wind and does not include any factors (AccuWeather, 2019). The RI scale highlights how the Category 2 Hurricane Sandy would have been rated as RI_5 and the how Tropical Storm Allison which did not have a hurricane status as per SSWHS would have been rated RI_5 based on the additional factors (AccuWeather, 2019). The rating of the new Real Impact hurricane scale emphasises on the revision and reconsideration of the SSWHS according to the changing hurricane intensity and including additional influencing factors underlining that fact that the SSWHS does not wholly comprehend the severity of potential storms.

3.6.4 Return frequency analysis

Frequency analysis is often conducted to understand the return period of storm surges on the coast. Extreme sea levels with a certain probability of occurrence or how often an event is expected on average are calculated. This is estimated through an equation, by inputting the annual maximum water levels (AMWL) to estimate the likelihoods (Paprotny, 2014). This is termed the '1% annual chance flood' i.e., the level that is exceeded at this rate at a given point. If this level exceeds once in 100 years, then it is called the 100-year flood (FEMA, 2004).

The return frequency calculations are observed to have drawbacks. The primary drawback is that the 1% annual chance flood is not attributed to any specific event. The assumptions highlight that the AMWL produced can be from a similar wave or flood producing mechanisms such as a tsunami or a more intense storm located at a far distance can produce the same flood levels (Paprotny, 2014; FEMA, 2004).

3.7 Preliminary gaps from stakeholder's perspective

3.7.1 Insurance

Insurance being a key stakeholder in disaster risk management, they play a vital role in the response and the recovery phase of DRM during emergencies. The role of isnurance is also well-recognised for reuction of future risks. More than insurance pay-outs and financial restoration, their contributions by effectively coordinating the flood risk zones and possibly assessing the risk by catastrophic risk modelling support the government is observed in developed countries (RMS, 2015). In the USA, general home insurance does not cover the flood or wind damage created by a tropical cyclone. The 2017 Atlantic hurricane season left the country with various insurance related issues, especially during Hurricane Harvey. A Dutch-Texan team reported that Hurricane Harvey (2017) had flooded areas that were not within FEMA's mapped high-risk zones and most fatalities were recorded in these areas. As these were beyond the flood insurance covered and mapped zones, FEMA could not provide disaster aid, and no insurance claims could be processed through FEMA's NFIP (Science Daily, 2018).

The USA's National Flood Insurance Program (NFIP) is one for the strongest insurance providers for natural disasters particularly related to hurricanes and flooding. The NFIP which operates under the Federal Emergency Management Administration (FEMA) mandates all the properties within the Special Flood Hazard Areas (SFHA's) must have flood insurance (FEMA, 2004). The SFHA is mapped together with the Flood Insurance Rate Map (FIRM's) (Horn & Webel, 2019). FEMA through the NFIP provides the flood cover for properties in a 100-year flood plain which is referred by FEMA as Special Flood Hazard Area (SFHA) and it is mandatory for the homeowner residing to register under this program (Committee on Homeland Security and Governmental Affairs, 2006).

The insurance pay-out litigation and disputes in flood-insurance post-Hurricane Katrina and Hurricane Sandy underline how the insurance sector in developed countries suffers potential gap within (Committee on Homeland Security and Governmental Affairs, 2006; FEMA, 2017). Especially, Hurricane Sandy experienced significant litigation under the Write Your Own (WYO) insurance companies, which was contracted by NFIP under

FEMA. It was reported that Sandy's litigation costs were higher than the actual insured losses (FEMA, 2017).

Standardized insurance programs or policies were either not popular or not being commonly practised in few developing countries such as India, China, Philippines, and many in least-developed countries such as Haiti, Myanmar, Bangladesh (Ali, 1999) whose delta region is highly vulnerable to storm surge hazard. These countries after having faced significant cyclone events have not mandated individual flood cover or property cover to those residing in coastal flood risk zones (Wallemacq & Below, 2017). High population, lack of adopting protocols or procedures in creating stipulated flood insurance, illiteracy rates of these developing or underdeveloped countries could be a hindering factor in assessing individual property damage and insurance pay-out (Wallemacq & Below, 2017; Henson, 2008). Due to these drawbacks, developing and under-developed countries were often paid via general national disaster relief funds that cover only the basic emergency needs post hurricanes (CRED, 2018). In general, the USA's insurance policies do not appear to have incorporated the future forecasted sea-level rise 'the year 2100 scenario', further escalating gap in policies (FEMA, 2017).

3.7.2 Construction and housing

Private housing in most urban areas along the coasts and rivers was identified as most vulnerable, facing flood risk-prone future. Especially, the US was identified to have settled as multi-dwelling units (MDU) along the eastern shoreline. Figure 3.10 shows the most vulnerable cities of the USA and their exposed coastal population.

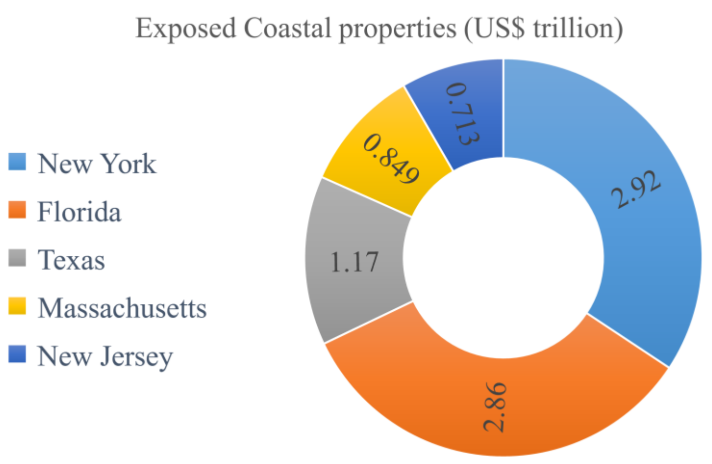


Figure 3.10 Most vulnerable cities of the USA and their exposed coastal properties [source: Smith & R.Katz (2013)]

In New York, above 70% of the multi-dwelling units were situated in floodplains and are already vulnerable to the 100-year floods[1]. Moreover, above 90% of those buildings were built before 1983, when the city's first floodplain map was introduced. Some cities which have never seen storm surges in the past were also counted as risk zone and expected to storm surges in the future due to the increasing sea-level rise.

This is also due to the change in coastal hydrography in recent years which tends to welcome inundation from future surges and the sea-level rise which sets a new baseline for storm surges (RMS, 2015; Smith & Katz, 2013).

3.7.3 Media participation in disasters management

Technology in media including electronic media (radio, television) or print media (newspapers, journals) play a prominent role in the acquisition and dissemination of emergency disaster information (Dave, n.d.). With the availability of the possible hurricane path or track from the weather prediction centres (NHC, n.d.), media play a vital role in creating the attention and significant storm surge awareness amongst the public (Dave, n.d.). The recent approaches of emphasizing the damage through before and after images, aerial view images and videos of overall damages have certainly improved the visualisation of the hazard and their impacts (BBC News, 2012). This also helps to visualize the socioeconomic damage and where does the country stand in hazard mitigation.

In addition to this, the usage of social media pages has changed the way risk is being communicated. They equally play a significant role in reaching the donors for funding globally (PEJ New Media Index, 2010). On the contrary, they also seem to have their own implications such as false news being circulated and spread, old news may still be circulating and all these may lead to unnecessary confusions (Wang & Zhuang, 2018). Persuasive attention from international media agencies such as BBC, CNN, The Guardian, Associated Press, Rigour, The Times were some of the trusted sources of web-based information which have drawn significant attention regarding the landfalling cyclones and their associated hazards (BBC News; Ofcom; Bakamo, 2019).

Media's prominence not only ends with the tasks of boosting the awareness but also supports the victims by gaining international attention (Dave, n.d.) and drawing requests from international humanitarian organization and their participation to instigate further

[1] The 100-year flood plain is the area in the plain at risk for the one percent chance of flood.

relief funds (Fritz et al., 2009). On the contrary, the media's interpretation can also lead to a deviation from the actual understanding of the problem (Searles, 2016). During Hurricane Katrina (2005), the significant socio-economic damage was primarily caused from storm surges straining the critical levee system (Committee on Homeland Security and Governmental Affairs, 2006). Even the USA's Department of Defence (DOD) relied on media for initial reports on the levee breaches in various areas (Committee on Homeland Security and Governmental Affairs, 2006). However, the media's entire attention highlighted in showing the storm hit areas and failed to focus on the federal failures. Moreover, the failure of the federal government in decision-making and evacuation of an ethnic minority were not highlighted by the local media and were only left for criticism (Holliday, 2006).

According to a study by Five Thirty-Eight's Dhrumil Mehta, published on 28 September 2017, it is observed that Hurricane Maria received less media attention relative to the previous hurricanes such as the Harvey and Irma which had its landfall in the US mainland (Centro, 2018). The Louisiana floods which occurred in 2016 was a '1000-year-flood-event' over two days and was officially recorded as the costliest disaster after Hurricane Sandy (2012) (Searles, 2016). Although, NOAA's weather prediction centre called it 'inland sheared tropical depression', which was less than a tropical depression status, a record 24+ inch rainfall was observed across various locations in Louisiana. While the world's media were focusing on the Rio summer Olympics (2016), and the national media were focusing on the 2016 US Presidential election. Little or no attention was given to the Louisiana floods which shows the priority of communications (Searles, 2016).

3.8 Global disaster frameworks, protocols, and agreements

According to Neal (1997) studies on various phases of disasters were originated, since the 1930's. The earliest disaster management cycle as proposed by Baird et al., (1975). Theoretical development of disaster research and the frameworks were essential to understand and organise the key findings (Neal, 1997). To address the existing climate-related risk and in support of future disaster risk reduction, an initial discussion of the protocol was held during the 1992 'Earth Summit' and the protocol was finalized in 1997 (Henson, 2008). The Kyoto Protocol emerged from the United Nations Framework Convention on Climate Change (UNFCCC) as a contribution towards reducing the

climate change impact through reduced global warming (UNFCCC, n.d.). The framework was designed to stabilize the rising greenhouse gas (GHG) emissions (Henson, 2008).
The USA is one of those industrialized countries whose GHG emissions were also identified as high from 1990-2012, denied their ratification and participated merely as an observing country. Due to this, there was a delay in the ratification process from the USA, which made the initially proposed Kyoto Protocol to be finalised in 1997 and the first commitment period started from 2008-2015 (Henson, 2008). Despite being a developed country, the USA's decision to not to ratify the Kyoto Protocol should be observed as a 'negligence of participation' from a stakeholder perspective. This may further lead to a non-cooperative behaviour from developing and underdeveloped countries towards a future initiation to mitigate climate-related consequences. This further leads to the key question on cross-country participation to address the present and future disasters and changing risks.

"The starting point for reducing disaster risk… lies in the knowledge of the hazards and the physical, social, economic, and environmental vulnerabilities ...and of how hazards and vulnerabilities are changing in the short and long term, followed by action taken based on that knowledge".

- Hyogo Framework for Action 2005-2015 (UNDP, 2010, p. 1).

In 2005, around 168 countries agreed to adopt a 10-year plan focusing on reducing the disaster risk and it is the Hyogo Framework for Action (HFA) with a goal period from 2005-2015 (PreventionWeb, n.d.). The framework was aimed at reducing the socioeconomic and environmental losses from natural disasters (UNISDR, 2007). Hare et al., (2013), highlighted "*The HFA prompted considerable progress towards a more proactive and holistic approach to DRR. Nonetheless, achievements are patchy across regions and unevenly distributed among the five priorities for action*", (p. 23).
"While the Hyogo Framework for Action is drawing to an end, having spurred some progress but unable to stop the rising trend of disaster losses and associated hardships, a renewed commitment is needed to drive international efforts in disaster risk reduction" (Hare et al., 2013, p. 23). In March 2015, the third UN world conference on Disaster Risk Reduction (DRR) held in Sendai, Japan. The framework is called the Sendai Framework for Disaster Risk Reduction (SFDRR) (Mysiak et al., 2016). This framework is the successor of the previous Hyogo Framework for Action (HFA). The SFDRR was aimed to insist the countries to develop plans for existing and new disasters through a strong

commitment from participating countries. The aim of the framework is to achieve the seven global targets through four main priorities (United Nations, 2015). Although, the SFDRR is a successor of the HFA it under-utilizes the lessons learnt from HFA's and rather it proposes a new set of targets and priorities (Oxley, 2015). One of the primary limitations of these frameworks is their non-binding agreement, which does not mandate the participating countries to implement the Priorities for Action (PFA) instead, it encourages voluntary implementation. Issues in implementing the DRR starts at this point where the priority is shifted from 'mandatory' to 'voluntary'. The other major drawback of these frameworks or approaches considered by the author is the 'time' and the hazards are imprecise or generalized approach to disaster risk reduction. Hazards such as climate change and sea-level rise take its course over a period, these frameworks are more suitable for the long-term hazards whose effects are not imminent and certainly inadequate for short term hazards.

Although, these global frameworks have certain disadvantages, the step to mitigate the DRM and DRR issues and achieving progress is very important. Every step-change in disaster risk reduction either becomes fundamental towards a successful future adaptation and resilience or predecessor of future DRR frameworks. Despite the availability of various international protocols, frameworks, and federated emergency management plans, the limitation of these global frameworks may provide insights into the future possible lessons learnt of the existing lessons learnt.

3.9 The Call for an action to mitigate storm surge

The IPCC in its annual report 5 (AR5) has stated that for a 2 degree Celsius of global warming the following impacts were observed:

- Sea level rise,
- The intensity of the tropical cyclone with a likely increase of 1-10%,
- The proportion of tropical cyclone with Category 4-5 will increase likely most likely.

The Geophysical Fluid Dynamics Laboratory (2019) emphasises the relationship of the increase in the intensity of hurricanes with the observation issued by the IPCC AR5. According to Bhatta (2010), the increase in urban development within coastal zones has increased the vulnerability and risk of exposure to coastal hazards. Sea level rise (SLR) is one of the direct consequences of climate change impacts and can alter the current and future storm surge hazard significantly (Wahl, 2017). NASA (2018) highlights the rising trend of sea levels observed from 1993- to the fourth quarter of 2019 as shown in Figure 3.11.

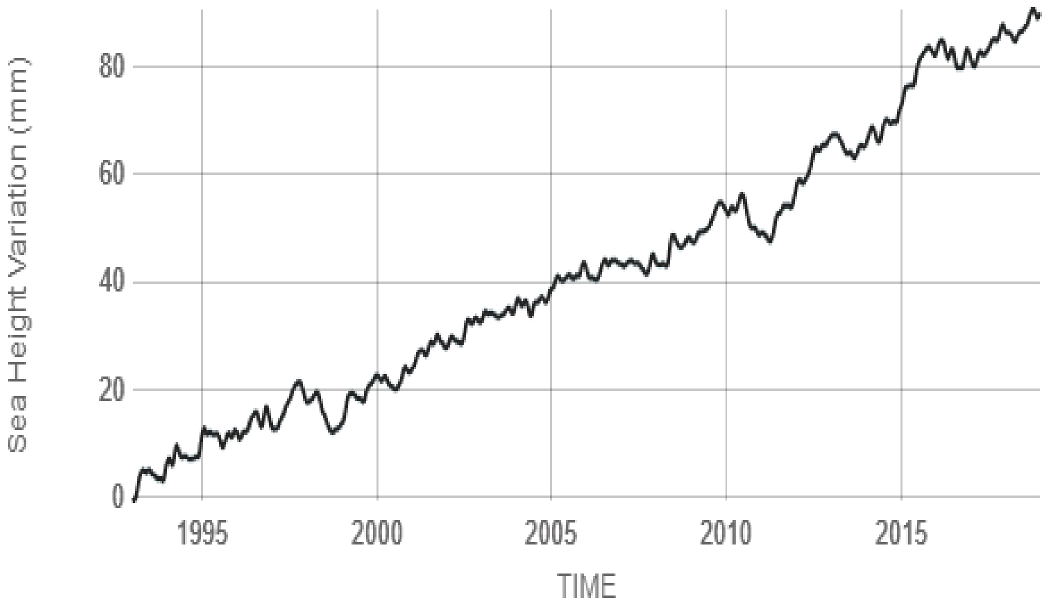


Figure 3.11 Satellite sea level observations from 1993- Q1 2019 [source: NASA (2018)]

The consequences from rising sea levels were not expected to be imminent rather, their increase will be gradual over a period. However, the gradual increase is projected to act as an 'elevated base' for extreme sea levels such as storm surges (Wahl, 2017). A further detailed discussion of the relationship between sea-level rise and storm surge is discussed in Chapter 2.

As highlighted by the (IPCC, 2015), the global warming contributes to ocean warming which further leads to the formation of tropical depressions and into hurricanes. Henson (2008, p. 145) stated that "*warm ocean waters help give birth to tropical cyclones and provide the fuel they need to grow*". The formation of a tropical depression in the warm ocean has more likelihood to be developed as a tropical storm thereby developing into a potential tropical cyclone (Henson, 2011).

The third most important factor is the increasing frequency of tropical cyclones. The recent Atlantic cyclones from 2016 to 2018 which includes storms such as Hurricanes Matthew (2016), Harvey, Irma, Maria (2017), Florence, Michael (2018) are notable events in the US hurricane history, particularly the year 2017 which involved a 'cluster of storms' (Faust & Boce, 2017). Figure 3.12 shows the socioeconomic damage of past significant events and their corresponding variations between economic damage and casualties. Figure 3.12 is compiled using the cyclone reports available from official government websites.

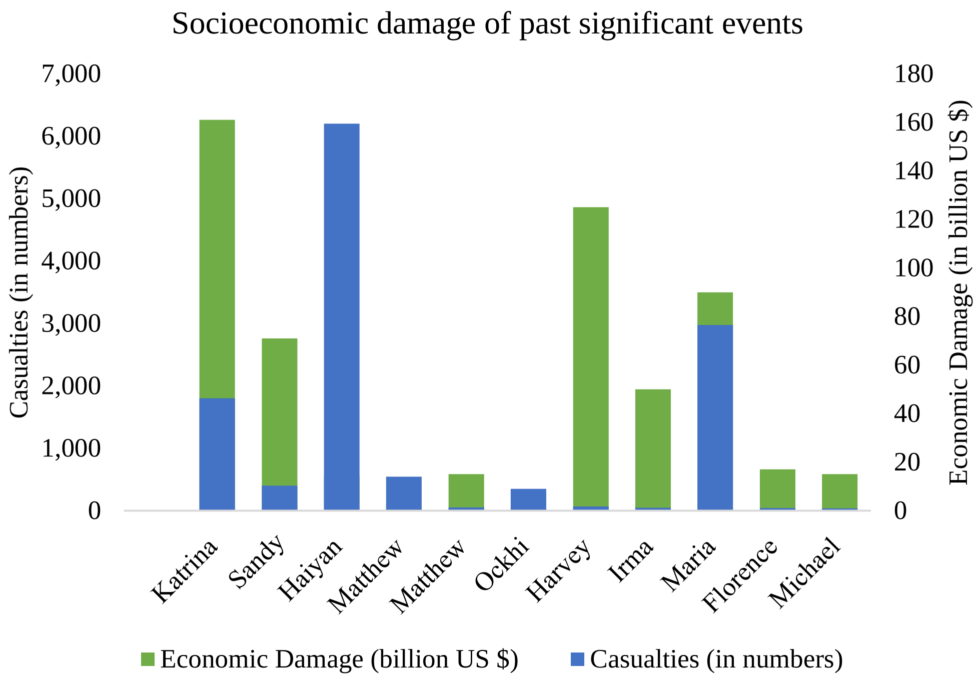


Figure 3.12 Socioeconomic damage of past significant events

The awareness of the storm surge impacts could also be understood from the point that, the adaptive capacity to disasters of the developing countries is comparatively less than the developed countries. All these storms which occurred in the Atlantic Ocean were major Category 3 and above storms with hurricane-force winds greater than 115 mph in SSWHS. The observation of recent hurricanes from 2016 to 2019 reveals the increase in the intensity and frequency of tropical cyclones.

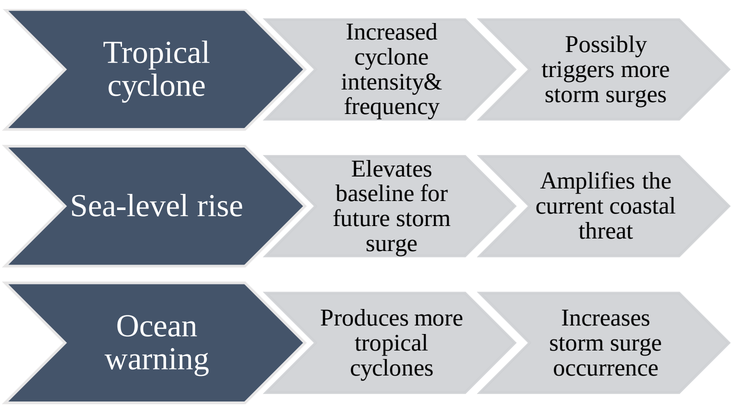


Figure 3.13 Direct and indirect external factors influencing the rise of storm surge hazard

Figure 3.13 shows the relationship between ocean warming, increasing sea-levels and tropical cyclones how they directly and indirectly result in bringing storm surge hazard. With a clear indication of various direct and indirect triggers of storm surge hazard, it is important to highlight that globally 2.4 billion people live within 100 km of the coastline and over 600 million people live within less than 10m above sea level (UNISDR, 2017). Significant weather events such as the Bathurst Bay Cyclone,1899 (Australia), the 1900 Galveston (USA), the 1953 Bristol storm surge (UK), the 1970 cyclone Bhola (India), to the 2019 cyclone Idai (Mozambique), emphasises on how storm surges are a constant hazard and their potential to occur in any of the tropical ocean basins. Also, the loss of 8,000 lives from the 1900 Galveston (NHC, 2008); 300,000 lives from the 1970 cyclone Bhola; 140,000 lives from the cyclone Nargis (Guha-Sapir, 2018) and 6,000 lives lost from typhoon Haiyan (Hernandez et al., 2015) indicate the severity of storm surge hazard. These events also prove how a storm surge (single event) can produce significant damage to coastal communities and infrastructure thereby directly impacting a country's socioeconomic growth.

It is also equally important to understand the changing risk from a tropical cyclone, and sea-level rise on storm surges as storm surges have a greater impact than the tropical cyclone or sea-level rise. An interconnected global approach is required to address the problem for the long-term. It is also essential to reassess the risks, changing risks, and vulnerabilities to develop innovative approaches, emphasizing adaptation and resilience with continuous development as a key priority (Wilson & Fischetti, 2010).

3.10 The requirement of a framework approach to mitigate storm surge hazard

According to Horn (2015), the physical causes of storm surges are well-known, and the models are increasingly effective in storm surge prediction associated with certain cyclone conditions. Despite this, the loss of life from storm surges remains critical. The reason for this being inadequate mitigation actions to reduce storm surge severity and adaptive capacity to storm surge risks (Ellis & Sherman, 2015). The continuous migration of people and coastal investments within LECZ's or cyclone-prone zones not only amplifies the vulnerability and risk of exposure but, also necessitates continuous monitoring and reassessment of risk (Bathi & Das, 2016). This instigates the continuity of research addressing increasing coastal extremities and analysis of strategies to mitigate future disaster risk.

The identification of the preliminary gaps in storm surge measurement within the current approaches, modelling techniques and with the uncertainty around the hurricane intensities amplifies the underlying storm surge risk from the tropical cyclone. It is important '*to know'* what is being done in the past and present to determine what '*to do*' for the future, and to fix the gap (Peffer & Sutton, 1999). It is, necessary to understand the key factors affecting vulnerability assessment, resilience, and adaptive measurements for re-assessment of existing technology and new findings. Assessing risk of a country to increase the adaptive capabilities and resiliency to EWE's is strategically important not only to a country's government but also to all the stakeholders involved.

The discussion and review of the identified gaps in the Chapters 2 and 3, not only highlight the gaps but also underline the critical importance of storm surge and the need to develop a fully operational framework to help mitigate storm surge within low elevated coastal zones (LECZ's). Being technically robust is not sufficient for the future adaptation and mitigation in the face of the predicted increase in sea-levels, extreme weather events and change in climatic conditions.

3.11 Summary

This chapter has explored previous publications, reports, approaches and media communications to understand the current background and approaches to understanding the importance and significance of storm surge. The findings from the previous papers such as by Bouwer & Jonkman (2018) and Rappaport (2014) have limitations and exclusions. Understanding the importance of storm surge is increasing following post-disaster reviews from Katrina and Sandy which have illustrated its significance. The literature review has identified a lack of data, reports, and publications in the subject field, especially in developing countries. The increased adaptive capacities observed in developed countries and their approaches may not be adaptable in the same way by the developing countries due to its limitations in resources and economic capacity. This chapter also identified gaps in the mitigation approaches and understandings of existing approaches and the requirement to create public awareness in all countries (with low elevated coastal zones) addressing the effects and the influences of storm surge. To fulfil these identified gaps and raise awareness, a non-structural or a non-engineered solution that is cost-efficient and cost-effective is considered. Such a solution only leads to a framework approach which can support the government and the communities for a long-term to mitigate and adapt to these hazards.

CHAPTER 4
RESEARCH DESIGN AND METHODS

The purpose of this chapter is to present the methodology underpinning the research, explaining the philosophies, strategies, analysis techniques and the procedures used to justify the research methodology and choices of methods adopted.

4.1 Research purpose: introduction

Creswell (2009) claims that qualitative research is a way of exploring and understanding the research problem. To retain the logic throughout this study, investigate and understand the research problem in-depth, this research follows the qualitative research design. According to Yin (2003), a case study research design has the potential to link the collected data to the research questions. In this research, case study methodology is applied to explore individual events because each disaster event includes a lot of parameters (key activities), that will allow us to understand the meaning, differences, and various aspects of the event. Among the three approaches, namely, explanatory, descriptive and exploratory qualitative research designs (Yin, 2003) this research deploys exploratory approach. The exploratory design operates with the need to familiarize the basic facts and concerns around the subject, formulating the research questions, and generating hypotheses. Following which the practicality of conducting the research is studied, and finally, the strategies for current and future data collection were determined and developed (Neuman, 2014). The choice of descriptive design provides an option to integrate various components logically where necessary thereby the research problems and questions are effectively addressed Mason (2002). Because the study revolves around a contemporary set of events, sandwiched choice of exploratory (majorly applied) and descriptive (selectively applied) research design approaches were considered.

4.2 Research design and methods

According to Neuman (2014), case studies are pervasive in providing in-depth knowledge and expands the understanding of the subject within social research set-up. Bryman (2012) stated that case studies provide a detailed and intensive analysis of a single event. Patton (2002) also suggests that case studies are an alternative method, that allows connecting with the decisions made in day-to-day life. This research incorporates study methodology to create coherence to the research subject and utilised the advantages listed by Patton (2002), Bryman (2012) and Neuman (2014). While highlighting the importance of case studies, Neuman (2014) also says that case studies can be criticised for not yielding a guaranteed result unlike an experimental or a quasi-experimental research. As per Yin (2014), different research methods can provide different insights into research. Furthermore, his statement details that in certain cases, the insights are the key to exploring the research and need not necessarily guarantee a result. This research primarily adapts the social science investigation for which case studies are considered appropriate to understand the subject of study and how it impacts the society. For instance, Scriven (2009), says that the astronomy in natural science does not rely on the experimental method. This suggests that different research methods fill different requirements for investigation. However, a simple rule of thumb is that the strengths and limitations of the research method should complement the research such that a potential outcome is attained (Bryman, 2012).

Table 4.1 Qualitative vs Quantitative research design [source: Neuman (2014) & Bryman (2012)]

	Qualitative	**Quantitative**
Approach	Inductive	deductive
Goal	Generate hypotheses	Test hypotheses
Setting	Natural	Experimental/quasi-experimental
Sampling	Purposive	probabilistic
Data	Words	Statistics
Data collection	Natural and rich	Shallow and broad
Analysis	Iterative interpretation	Statistical tests
Epistemology	Interpretivism	Positivism
Ontology	Constructivism	Objectivism
Value	Personal involvement	Detached involvement

Neuman (2014), states that qualitative methods are to be understood in contrast to a quantitative method and for this research, the qualitative method is considered as 'data-enhancers'. Key aspects of cases can be more clearly seen when data are enhanced. Table 4.1 was adapted from Neuman's and Bryman's qualitative versus quantitative research design to show the different approaches and their corresponding techniques, where appropriate, which fits this research method. The research emphasises more on the qualitative perspective to view the enhanced data to elevate the research and its scope of study in the subject field.

4.3 Research philosophy

According to Saunders et al., (2009), both qualitative and quantitative methods may utilize the research philosophies with the appropriate research paradigms to understand the research-development and for developing knowledge in the field of study.

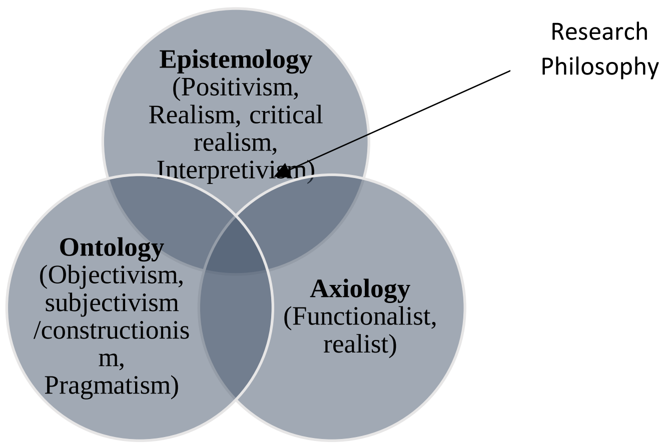


Figure 4.1 Relationship between research philosophies [source: Neuman (2014)]

The choice of research philosophy through their assumptions will guide the research underpinning the research strategy, the questions of methods, and how the collected data might answer the research questions (Saunders et al., 2009). Figure 4.1 shows the relationship between the different approaches and their assumptions in research philosophies and how they are influenced by practical considerations to a certain degree. Epistemology, ontology, and axiology are the three main ways of thinking about research philosophies Neuman (2014). Epistemology is, the factor considered as acceptable knowledge in the field of study (Bryman, 2012). Ontology is the way the nature of reality is considered (Saunders et al., 2009).

According to Bryman (2012), the research process in social science set-up is greatly influenced by the assumptions and the research view that is to be conducted. It is these assumptions that allows the researcher to determine the possibilities and generate a meaningful knowledge (Jackson, 2008).

Positivism, interpretivism and realism are the three main epistemological approaches. Realism is further classified as direct and critical realism (Bryman, 2012). This research embraced 'positivism' to develop the knowledge in the subject while applying the methods of natural science to study social reality. Furthermore, the study adopted 'interpretivism' when observing the social action of the individual i.e., understanding from the participant perspective. According to Neuman (2014), although, objectivism and subjectivism are the two common ontological approaches. Subjectivism can also be used as constructivism, which emphasises the nature of knowledge and their categories that are subject to constant revision or construction by their participants or social actors. This study embraced constructivism in the place of subjectivism to revise the subject constantly.

The following epistemological assumptions which were considered for this research to determine the research possibilities and to generate a meaningful knowledge:

- What are the possibilities to be studied to further understand storm surge phenomenon to adapt the best practices in disaster risk reduction?
- How a meaningful knowledge can be generated from the theoretical design of storm surge framework?

In line with Patton's statement that the epistemology and the ontology were designed in a way such that it justifies each other while maintaining harmony with axiology and defining the achievable, and this research follows the same strategy.

4.4 Theory development

Hamel et al., (1993) claimed that all social science research is expected to have a baseline theory and a theory validation of the study against the original propositions. According to Eisenhardt (1989), research is a process which can be based on theory development or a theory-testing process. Creswell (2009) claimed that theory within research is an 'orienting lens' that shapes the research questions informing how the research data should be collected and analysed towards the development of an action or change. Although, all these statements imply the importance of theory in research, these statements are very much applicable for quantitative approach and need not necessarily be followed by a qualitative research.

Yin (2003) argues that it is essential to strengthen the research design which is even more critical when conducting a case study research to determine what is being studied and what is to be studied. According to Bryman (2012), a deductive theory as shown in Figure 4.2 in which the theory guides the research, and an 'inductive theory' is the bottom-up approach of a deductive theory i.e., a theory as the outcome of the research.

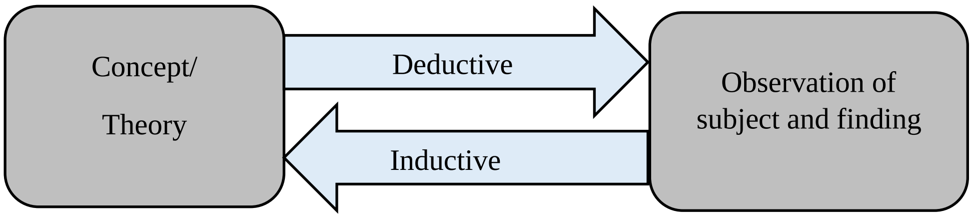


Figure 4.2 Relationship between theory and research through deductive and inductive approaches [source: Bryman (2012)]

Locke (2007) references how Sir Isaac Newton rationally used the inductive theory by explaining how all the previously prevailing theory of white lights were false, but only as a by-product of showing his experiment on white lights. In other words, Newton proposed his findings and observations by proposing a new theory of white lights. This bottom-up approach is called an inductive theory. The reference of Sir Isaac Newton suggests the relation between the theory and research is carried out by obtaining the theory (if any) as an outcome of the research.

According to Charmaz (2006), except for occasional studies, quantified theories were generally preferred before Glaser and Strauss (1967). Qualitative research and theories were relegated and were considered only as a precursor to rigorous quantitative research (Charmaz, 2006). It is Glaser and Strauss (1967) who argued how qualitative research could be viewed as science on its own and capable to generate theories and highlighted how theory and research can be two different pursuits Charmaz (2006). Creswell (2009) also reflected his thoughts that the process of qualitative research largely follows the inductive theory in which the researcher or inquirer tries to generate the meaning from the data collected in the field of study. Reflecting on Charmaz (2006) views about Glaser and Strauss (1967) that research and theory could be two different pursuits and research need not necessarily generate a theory, this exploratory research focuses on the research part as science on its own. Also, by following Locke's reference of Newton's approach, and Creswell (2009) this research will take up inductive approach with a literature search and data collection or observations available in the related topic as a foundation to explore if a theory is possible at the end of the research.

To elaborate this, the implementation of storm surge framework within DRM would require data around existing early warning systems, emergency communication, infrastructure adapted accordingly. The initial reflections were given as the potential gaps within the current disaster risk governance in different countries was highlighted in Chapter 2, Literature review. According to Yin (2014), generalization from case studies supports in the cross-case analysis. The reflection from the literature review, generalizations from case studies, findings from the cross-case analysis is expected to allow the researcher to identify if a theory is possible (Walker & Myrick, 2006).

4.5 Multiple case study design

Multiple-case studies are considered for this research. According to Bryman (2012), a single case study analysis although, could be effective in a different set-up, could provide a tunnelled vision in this research. Yin (2003) also states that multiple cases strengthen the findings from more than one case study. Therefore, the advantages of a multiple case study design are adopted for this research. Figure 4.3 shows the flow of multiple case study design.

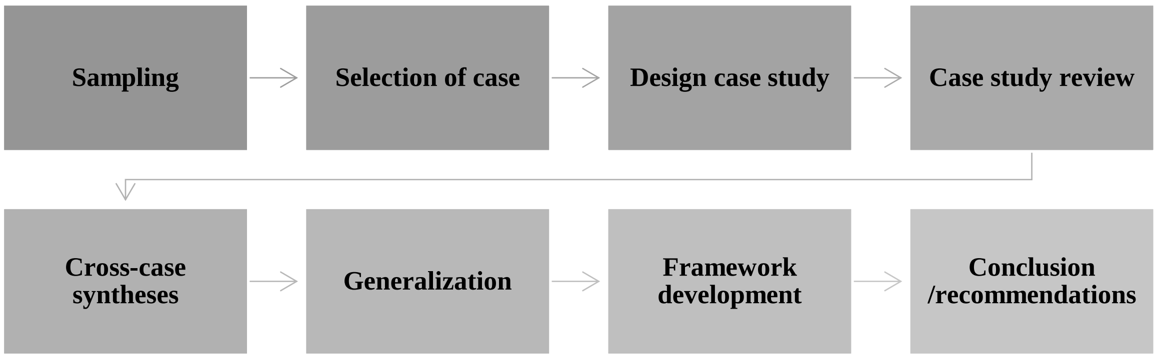


Figure 4.3 Multiple case study designs adapted from Yin (2014)

To highlight the seriousness of storm surge, it is essential to derive the output from a sequence of specific major storm surge events. Each case has its own set of information but consists of significant evidence of their effectiveness from storm surge damage, but also widely varied in their focus. This is mainly due to the different protocols such as the early warning systems, emergency communication, and evacuation techniques varies for country-to-country. Furthermore, multiple-case studies could provide a broadened vision to the series of events discussed (Yin, 2014). The rationale for a multiple-case study is to cover different cases which could be useful to draw a collective conclusion during the cross-case analysis. Therefore, multiple-case studies were considered as a suitable choice to gain the benefit of collective conclusion from various situations. The choice of multiple case studies also gave the convenience of generalizing different outcome from various cases and compare the same factor under different conditions, which provided in-depth understanding benefiting from the perspective of comparative advantage. This approach is 'analytic generalization' (Yin, 2003).

4.6 Initial population and sampling process

Unlike quantitative experiments, the 'sampling' process in qualitative research is not done with numbers and therefore, sampling in qualitative experiments is not straightforward. Furthermore, qualitative research needs a careful choice of sampling from the research population (Mason, 2002). This research mainly considered storm surges as primary focus, though they are the secondary hazard which cause more damage than the tropical cyclones, the primary hazard (Smith & Katz, 2013). All the 'cyclone triggered storm surge events' which had significant socioeconomic damage is the total research population. Sampling in this research is the process of selection of the 'case to be studied' further. According to Patton (2002) a purposive or purposeful (non-probability based) sampling is when a case or cases that are either selective or subjective to information-rich where possible or most effective where resources are limited or scarce. The sampling is done based on the choice of disaster events from different countries which are significant storm surge events. Creswell (2009) states that 'representative sample' which is a sample preferred more likely over another sample simply because, the preferred sample is a representative of the other similar sample. Such strategy stated by Creswell (2009) is also used in this research to choose the best-of-all sample from the total research population.

Appendix A includes the initial research population which includes list of tropical cyclone events across the Atlantic, Pacific and the Indian Ocean and details of profiled countries from which the following sampling criteria are applied to choose the required cases for this study.

- The first criterion is to identify the significant tropical cyclone-triggered-storm surge events from total tropical cyclone events (as highlighted in Chapter 2, not all tropical cyclones triggers storm surges). In other words, water-driven events were selected as a sample over an entirely wind-driven event. In some cases, both water and wind-driven were considered where the damage from the event is primarily from the water-driven event. For example, Hurricane Harvey (2017) was the second costliest tropical cyclone in the US history (NHC, n.d.). Though this is a significant event and triggered a 10 ft (3 m) storm surge, the primary damage was mainly due to heavy rainfall up to 60.58 inches and not due to the storm surge (Blake & Zelinsky, 2018). Therefore, this event is not considered for the case study.

- The second criterion is the time frame. The chosen sample should fall within the sampling time frame i.e., the tropical cyclone-triggered-storm surge event should have taken place or occurred between 2000 and 2017. This filter is applied with a notion to see the change in disaster management strategies and their adaptation over the given period. For instance, significant events which occurred before the year 2000, such as the 1953 North Sea great storm surge, 1970 cyclone Bhola, 1900 Galveston hurricanes were not included within the research population.
- The third criterion is the technique of filtering of the research sample based on being a representative case. The filtered sample is not necessarily an extreme or unique event rather it is filtered because it is an epitome of a broader category. For example, in the year 2017 Hurricanes Harvey, Irma, Maria, Jose were all significant events of the year. However, one significant event (in this research Hurricane Maria is chosen) which is a representative case over other similar events.
- The fourth criterion is to rely on choosing the 'most suitable case' which could provide and serve in achieving the research objectives.

Once the sampling is carried out, the cases chosen for the study have one factor in common which is all the samples are tropical-cyclone-triggered storm surge events. Additional factors that are considered during the sampling process particularly on the fourth criterion which is the choice of 'most suitable case' is the hazard, vulnerability and risk are considered as shown in Figure 4.4.

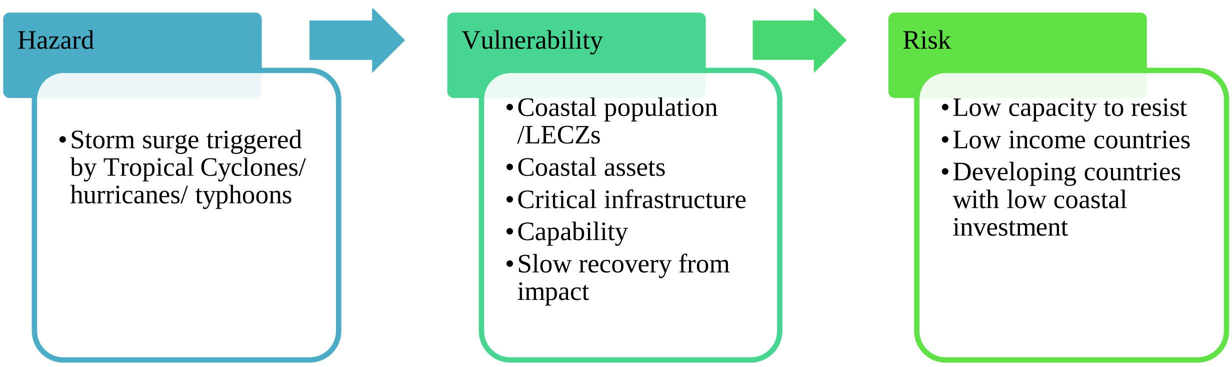


Figure 4.4 Selection criteria of 'most suitable cases' for study

According to the UNDRR terminology, a hazard means a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation. A country may even be subjected to multi-hazard situations i.e., cascaded, or cumulative hazardous events may occur simultaneously or sequentially (PreventionWeb, 2017). However, in this research hazard is typically tropical cyclone-triggered-storm surge event. Vulnerability is the susceptibility of an individual, a community asset, or systems to the impact of hazard (PreventionWeb, 2017). Country profiling is carried out from the research sampling. While carrying out the sampling, countries were profiled based on the selected case studies, and not vice versa.

The sampled case studies were further filtered based on their hazard, vulnerability, and risk exposure. The risk of exposure also considers population, economic costs of coastal assets and infrastructures exposed to storm surge hazard. Final criteria for the choice of case studies rely on the socioeconomic impact created by the hazard. The adaptive capacity of the country was also included while considering the vulnerability. For instance, the capability of a developing country (e.g., The Philippines) will vary with the capability of a developed country (e.g., The USA). The choice of considering different events from different countries provided further support during the cross-case analysis and further comparisons.

4.7 Identifying the causes and designing the case study

Yin (2014) says that a unit of analysis is defined as a major entity that is analysed in research which provides a boundary for the research. For this study, the unit of analysis is the 'events' which are catastrophic storm surge events triggered by tropical cyclones or hurricanes or typhoons. Variations in case studies were considered during cross-case analysis to derive the required outcome (Yin & Davis, 2007). According to Yin (2014) a case study research includes five components which are *(i)* a case study question *(ii)* the plan *(iii)* unit analysis *(iv)* the link between the data to the plan and *(v)* interpretation of the findings.

Although, the cases were not explicitly grouped, the cases were chosen to study the response of a developed, developing and Small Island Developing States (SIDS) to storm surge events which occurred between 2005 and 2017. Each significant events and case study chapters are supported by facts and figures. Each case studies indicates the various phases of disaster risk management implemented by the country, and the country's resilience measure taken post-event as an adaptation for future storm surge scenario. The following sub-criteria permitted the researcher to refine the sampling further narrowing down to the actual case study events. Those sub-criteria were as follows:

- significant death rate because of *the event*
- significant economic damage cost *by the event*
- Failure of national or regional governance *pre-event, during and post-event*

Table 4.2 shows the list of case study events chosen for study after applying sampling from the total research population.

Table 4.2 Selection of case studies after sampling

Event	***Year***	***Location***	***Selection criteria***
Hurricane Katrina	2005	USA	• *1,800 Loss of lives* • *economic damage worth US$ 160 billion* • *failure of the levee system, infrastructure*
Cyclone Nargis	2008	Myanmar	• *140,000 deaths* • *failure of disaster governance*
Hurricane Sandy	2012	USA	• *economic damage (Closure of New York stock exchange closed), 472 deaths*
Super-Typhoon Haiyan	2013	The Philippines	• *6,900 significant death, lack of storm communication, early warning system* • *failure of disaster governance*
Hurricane Matthew	2016	Haiti	• *1,000 significant death, lack of communication* • *failure of governance*
Hurricane Maria	2017	Puerto Rico	• *2,900 deaths* • *Power outage for more than 7 months*

4.8 Pilot case study

From the sampled case studies, as shown in Table 4.2, a single case is chosen as a 'pilot-case' is further chosen to determine the structure of the case. The chosen pilot-case is information-rich, allowing the researcher to design the case study structure and its protocol to be applied for the remaining cases. The protocol developed for the pilot-case with variable and themes is applied in a similar format for all the remaining case studies. Yin (2014) states that, when the same structure is followed for all the other cases, then this supports the cross-case syntheses with an opportunity of a comparing or even in some cases, possible pattern-matching. In this research, 'Hurricane Katrina' is chosen as pilot-case. This is because of the chronological year of occurrence is 2005, therefore, the event is an information-rich case in comparison with the other recent cases. This step was greatly beneficial in designing the structure of the case and further supporting the case study analysis, reporting and even during interpretation.

4.9 Case study structure

Every case study in this research followed identical structure so that similarities and differences across the case study events which took place in a different period are observed. By following a structure, the process of identifying the similarities and differences further supported during the cross-case analysis and generalisation from the analysis and the findings. The following case structure was adapted:

1. Origin and background of the case: this section describes the synopsis of the tropical cyclone's origin, landfall details, forecasted track, and timeline with key changes in the cyclone's structure.
2. The disaster phases of the case x: this section demonstrates the four main phases of the disaster management cycle.

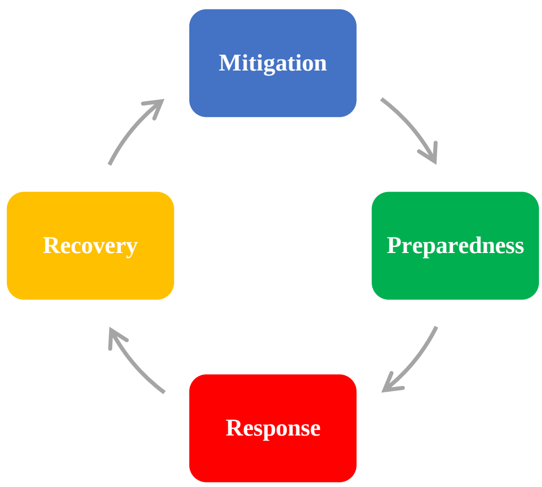


Figure 4.5 The four phases of the disaster management cycle [source: Baird et al., (1975); Neal (1997)]

Figure 4.5 is a typical disaster management cycle with the four main phases adapted according to the earliest version of disaster management cycle proposed by Baird et al., (1975) which was revised by Neal in 1997. The four main phases of a typical disaster management cycle are *(i) Phase 1: Preparedness (ii) Phase 2- Response (iii) Phase 3- Recovery (iv) Phase 4- Mitigation*. A colour coded scheme is used as shown in Table 4.3 to differentiate each key theme.

Table 4.3 Key themes and their colour code

Key theme	*Matching colour code*
Preparedness	
Response	
Recovery	
Mitigation	

Within each disaster phase, their corresponding list of key activities as shown in Figure 4.6 is identified both through coding search in the documents using Atlas.*ti* software and using the case study discussion. A possible set of predefined activities corresponding to the four phases of the disaster management cycle were listed in Figure 4.6.

Preparednes

- Forecasting
- Monitoring
- Early warning
- Emergency planning
- Response plan (national/local)
- Capacity building
- Telecommunication
- Training and exercise
- Prior connunity outreach
- Scenario planning
- Prior deployment of resources

Response

- Risk identification
- Risk analysis
- Evacuation
- Additional deployment of resources
- Communication
- Coordination
- Humanitarian aid
- NGOs,INGOs & volunteers support
- Incident stabilization
- Emergency shelter
- Mass care
- Transportation
- Logistics
- Power and utility

Recovery

- Damage assessment
- Rehabilitation
- Reconstruction
- Restoration
- Debris removal
- Insurance
- Improving livelihoods
- Organizationals capacities
- Temporary housing
- Health and social service

Mitigation

- Technical prevention
- Coastal protection
- Public education & awareness
- Sustainable infrastructure
- Future hazard assessment
- Implementation of lessons learnt
- Environment
- Strategic alternate approach
- Wetland mitigation
- Stakeholder involvement
- Future risk assessment
- Policy reforms
- Housing in LECZs
- Land use planning

Figure 4.6 List of key activities identified in their corresponding four key themes of the DRM cycle

The list of key activities corresponding to their disaster management phases was compiled using the case study events, data collected from various sources listed in Table 4.4. This process of filtering the key activities helped in reducing the deviated or raw data related to the documents.

3. Summary of key activities: The list of key activities observed in the four main phases of the DRM cycle are summarized based on the activities achieved or unachieved.
4. Physical damage and loss statistics: the overall losses and damages incurred from both the hurricanes cyclonic winds and storm surge flooding are discussed under this section.
5. Impact of storm surge: the effects and influences of the storm surge identified during the event occurrence are discussed in this section.
6. Adaptive measures taken post-event.

The above-mentioned structure is followed for all the six cases to maintain consistency and homogeneity. According to Scriven (2009), applying uniformity in structure, for all the cases, supports the identification of variations and commonalities which is also applied to the case studies.

4.9.1 Data collection techniques (Sources of evidence)

The research principally relied on the secondary data. Bryman (2012) claims that, the cost, time, and quality of the data are the prime benefits of secondary data. In addition to the benefit of secondary data illustrated by Bryman (2012) the advantage of using various sources of evidence is considered as a major strength of case study data collection and the same is followed in this research.

Yin (2014) outlines that data collected for any research follows four basic principles.

Principle 1: Pre-requisite for using multiple sources of evidence

Principle 2: Create a case study database.

Principle 3: Maintain a chain of evidence

Principle 4: Exercise care when using data from electronic sources

This research incorporates the four principles and the data for the research is collected through the following resources.

- ***Source 1: archived governmental documents and records***

Reliable data is collected mainly from the government websites such as the federal, state, and local governments, were retrieved from their database, and from the document sections. Table 4.4. shows some of the government websites accessed for data collection.

Table 4.4 List of government websites used for secondary data collection.

Country	Government website
USA	National Weather Service (NWS), National Hurricane Centre (NHC), National Oceanic and Atmospheric Administration
The Philippines	The Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA)
Haiti	Caribbean Disaster Emergency Management Agency (CDEMA)

Government documents were considered as an unobtrusive stable document and for broad coverage of the disaster for longer years particularly for disaster, events as the data are continuously reviewed and updated. Tropical cyclone report, case study reports were considered as a prime source of governmental documents.

In addition to the reports, emergency evacuation advisories, declaration of emergencies were also considered. Maps, before and after images, cyclone tracks and paths, hurricanes and storm surge watch-warnings, and all other emergency communication listed in the government websites were considered as the support source of evidence. Some government websites consist of disaster data however these data were available only in regional language which is one of the limitations within archived documents.

- ***Source 2: organizational reports***

Individual reports of events, risk assessment reports, case studies observed by NGO's and private organisations, participant-observations and surveys from private, public, and non-profit organisations were also considered as a source of evidence to build the case studies. Special reports such as surveys, focus groups collected by NGO's were also used as secondary data for this research to develop rigorous cases. Neuman (2014) remarks that the 'quality of data is high' in archived documents and provides a peer-reviewed style when used as a secondary data set. This is also reflected by Bryman (2012), who claims that company reports, documentation and archived records were the effective sources to develop the case study data. In this study, these types of reports and archived records were considered as quality and verified sources of evidence reflecting the key points stated by Bryman (2012) and Neuman (2014).

- ***Source 3: media sources***

During the occurrence of natural disasters, media plays a critical role in spreading the communication from authorities and emergency responders to local communities. Various media sources include news articles, photographs, before and after pictures, observations, interviews, and documentaries (Bryman, 2012). Online news from verified websites, are chosen as one of the sources of evidence for this research. Media broadcasts of catastrophic events, and their related articles have served as a link to objectify the event during the time of occurrence versus the government observed data (Newman, 2011).

- BBC
- Associated Press
- The Economist
- NPR (National Public Radio)
- Reuters
- The Wall Street Journal

Data relevant to case studies were carefully filtered using one or all the online sources where applicable.

- ***Source 4: Data from an electronic source***

According to Yin (2014), using data from social media and other open sources falls within the sources of evidence. He further claims that for some case studies the actual subject of study may even be an electronic source itself. As the acceptance of electronic source provided the liberty, this research considered a broad array of electronic sources. This includes contemporary electronic media, archived open-source documents of previous studies, reports, thesis, research, verified websites and web pages as electronic source of data collection.

Once various sources of case study data are collected, before proceeding, all the data were categorized and grouped for further cross-checking. For this, the case study protocol and annotated bibliography were carried out. When the collected sources are within the case study protocol and set limits, the final step of ‘convergence’ is carried. Because case study data encourages the usage of multiple sources of evidence, the case is now supported by more than a single source of evidence. The rationale for triangulation is that converging multiple sources of evidence which may lead to a unified conclusion from more than a single source (Bryman, 2012). It is to be noted that, when such multiple sources were analysed separately as a single source of evidence then the conclusion is not unanimous. Rather, it is the conclusion of separate sources denoting that no triangulation is carried out (Yin, 2014).

During data collection, access to data was limited in some situations. For instance, few government documents were in regional languages and no translated scripts were available to extract data. Also, collecting the same set of data that is required for all the cases was challenging as they have been also subject to changes and limitation. As such this this was observed as a limitation. Lack of disaster data may be a major limitation not just for data collection, but this may further pave way for underestimation or overestimation, of the underlying actual risk from storm surges. Therefore, in situations where no data is available, related data is considered i.e., ‘some data’ is better than ‘no data’ (Neuman, 2014).

4.9.2 Data analysis of case study evidence

Detailed analysis is discussed in Chapter 8, which examines the multiple case studies through the cross-case analysis to draw further conclusions. In this part, the secondary data is analysed using qualitative analysis techniques to effectively address the initial proposition of the research. The preliminary findings from the literature review that led to the identification of gaps further led to the proposition of inductive theoretical approach. Taking this approach on account, the data collection related to storm surge, focusing on case study data was carried out. Following the design of the case studies, the cross-case analysis is aimed to support the development of the DAMSS framework working on the case study data from ‘bottom-up’. The analysis and interpretation of the data highlights on the implications that if a framework is not in place within DRR or DRM to address the future storm surge hazard.

The most important analytic technique utilized is ‘cross-case synthesis’. According to Bryman (2012), multiple cases aid in comparative advantage and convergence of individual case study leading to the conclusion. Similarly, in this research, the display of data collected from each case study according to the same uniform activities lead to the comparison of individual processes. This further enabled the study, to draw cross-case conclusions about the events and their possible outcomes. At this stage, the analysis probed whether different countries adopted the same approach in addressing the emergencies highlighting the similarities and differences. Such observation raised the understanding of the 'typology' of individual cases, which was insightful. This approach allowed the research to cover issues on a broader perspective (Yin, 2003).

Repeated observation of same variables was an additional opportunity to the cross-sectional analysis in support of yielding the expected outcome. That is during the cross-case different events with the same characteristics over the period is analysed. As claimed by Hamel et al., (1993) the iterative nature of these two techniques for each case provided an opportunity to identify if there is any possible pattern by comparing the cases.

4.9.3 Coding

Coding is used as a part of this research analysis process and Atlas.*ti* (version 8) software is applied for a web-based qualitative data analysis experience. The software is equipped with the search tool that allowed systematic keyword search. The Coding (by activity) provided the opportunity to identify keywords or phrases which have appeared within storm reports, and other media to visualise and understand the modus operandi of how they operated and communicated information to communities and residents.

The following actions were carried out in determining the coding:

- Taking the DRM cycle as shown in Figure 4.5, a possible collection of key activity which is grouped under the four colour coded key themes as shown in Table 4.3 is identified. Each key activity identified from multiple data sources is coding. The identified set of key activities need not necessarily be the action that is carried out under four key themes. However, they are identified in many of the actions executed in these four phases within a typical DRM cycle.
- Around 300 documents were run with the keyword (key activity) search. In a situation, where the corresponding key activity is not identified in the document an alternative close-to-accurate keyword (by activity) is used for information searching from the data sources.
- Each identified key activity is assigned as coding and once all the possible coding was identified, they were grouped using 'code group' option available

in Atlas.*ti* (Refer Appendix C which shows how multiple codes were grouped under a key theme'.

Therefore, in further chapters when the term 'coding' is used it refers to a single activity listed in Figure 4.6. Furthermore, to the existing list of codes (activity), additional codes were also included for few cases. This action is apparent where the code is relevant and supported during the designing of the framework. A sample code report and key functions of the how the coding (key activities) identified during the cases in all the source documents and how it is utilised for this research is separately shown in Appendix C.

4.10 Data Interpretation

Interpretation of data means reporting the case study, its results, and the findings to closure. According to Yin (2014) reporting the case studies indirectly supports the process of creating a communication between the case studies. The case studies were reported in Chapters 5, 6, and 7. All the cases were reported, to create communication within and across the cases. Reporting the case studies supported data interpretation by communicating research-centred information about the phenomenon. In this case storm surge awareness, their disaster risk governance, adaptation, and mitigation strategies followed in different countries were cross communicated. In addition to this, the coding also supported during the data interpretation, not by directly suggesting the interpretations but by developing the interpretation using extrapolated information without losing the data to be interpreted. Chapter 8 (Table 8.1) is a cross-case synthesis which is extrapolated using both the case study reports and the grouped coding and their cross-tabulations. It is from this cross-tabulations, many layers of writing and thinking aided the interpretation outlined in Chapters 8 and 9 supporting towards the development of the DAMSS framework and the guidelines as best practices.

4.10.1 Structure of case studies

The case study primarily is grouped as events that took place in the Atlantic Ocean, Indian Ocean and in Small Island Developing States (SIDS). The case study period is from 2005-2017 covering the events chosen for the case study. As shown in Figure 4.5, the structure of the case studies was categorised as four key themes. This has an advantage where the structure allows to understand them before the occurrence of the event (early), during the event (middle) and post-event (late) phases of the disaster. This structure type further promoted the understanding of the overall knowledge regarding the evolution of disaster management over the given period for a specific country or within cross-countries. And because, this research is exploratory, the structure of the case studies led to the identification of the pre-requites of a storm surge framework with the final step discussing the value of further investigation required for this research.

4.10.2 A critical review of the methodology

The literature review in the subject field is limited in two contexts. For instance, the literature on hurricanes and storm surge modelling is vastly available over storm surge awareness and communication. According to Crotty (1998), in qualitative research, the sample size is determined based on the information and not on the statistics. This made the sampling of the research to be carried with six cases. Data saturation was considered to have an impact on the case studies of recent events. Past events were found to be information-rich compared to the most recent events. However, considering that the most recent events allow us to understand the progression within the DRM and the DRR strategies. Therefore, a mix-match of yesteryear's and the most recent year's significant events were chosen. Besides, lack of data also limited the access to the resources in some profiled countries. The other limitations identified while using the case study strategy is restrictions of languages between the event and context which was not uniform or contained information instantly. This was commonly observed in the Asian countries where different structures and styles were adopted in reporting a disaster event.

According to Neuman (2014), the two forms of knowledge which the social researchers produce are instrumental and reflexive. This research aimed to provide an instrumental knowledge in two approaches. One is by providing a new framework for the academic audience and accumulate new information on recent events. The other is through policies and general interests for a non-academic audience. However, gaining reflexive knowledge became unavoidable for the research as it is inclined towards value-oriented knowledge, reflecting the moral commitment of achieving results and improving the process of knowledge created.

Bryman (2012) says that ethnographies and participant observations usually require long periods of observations and requires significant investment in the field and those approached were considered as a substantial level of efforts. In other words, even if these approaches were adopted, still the potential scope of work will be considered only as a regional observation and incorporating global approaches are time-consuming. Therefore, a valid case study which does not solely depend on the participant or ethnographic data is considered as the best suitable approach for the research. To conclude, case study research may also be readily utilized to complement future quantitative, qualitative, and statistical methods.

4.11 Summary

In brief, this chapter provided the methods, approaches and techniques used to design the case study to make the choices, assumptions, and considerations coherent with the research. Beyond all the research dichotomies this research design and the methodology is developed based on (i) the knowledge the study creates (ii) the range of audience to whom this research is and will be useful (iii) who initiates policies, puts theory into practice and finally (iv) future researchers to whom the finding may provide additional support. Underlining the acute need of the research in developing a structured framework in the subject field, and from the literature review, it is hoped that similar research in developing a framework for storm surge in future particularly in qualitative standpoints should be encouraged.

CHAPTER 5

SIGNIFICANT ATLANTIC OCEAN STORM SURGE EVENTS

Case Studies: Hurricanes Katrina and Sandy

5.1 Introduction

This chapter discusses the two major events Hurricane Katrina (2005) and Hurricane Sandy (2012) both of which occurred during their corresponding Atlantic hurricane seasons. This chapter focuses on the disaster phases and protocols followed during the emergency by their corresponding authorities and governments.

5.2 Hurricane Katrina: origin and background

Hurricane Katrina was the twelfth tropical depression of the 2005 Atlantic hurricane season. The depression originated from the west coast of Africa on 11 August 2005. The depression slowly merged with the remnants of a previous tropical depression known as the ‘Tropical Depression Ten’ (Knabb et al., 2005). On 23 August 2005, 1800 UTC, Katrina changed its course and directed towards the south-eastern Bahamas. By 24 August 2005, 1200 UTC a tropical depression near Central Bahamas was observed.

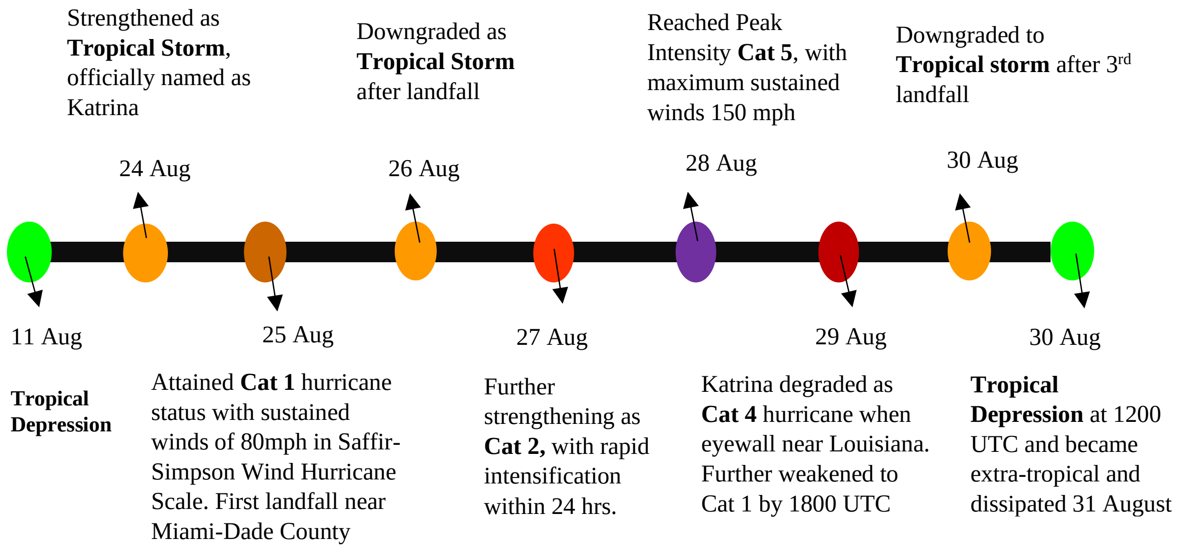


Figure 5.1 Timeline of Hurricane Katrina (11-31 August 2005) [source: Knabb et al., 2005]

The storm attained hurricane status as shown in Figure 5.1 on 25 August 2005, at 1200 UTC in less than two hours before its centre made landfall on the south-eastern coast of Florida. A convective asymmetric pattern in the system was detected when it crossed over southern Florida. Despite being asymmetric, Katrina sustained its field with the strongest winds causing heavy rains south and east of the centre in Miami–Dade County (Knabb et al., 2005).

Figure 5.2 shows the hurricane Katrina's projected path or track with colour coded hurricane categories. This version is adapted by the researcher using the original latitude-longitudinal data from NHC (Knabb et al., 2005). A further detailed structural change data of Hurricane Katrina, the projected pathway, and the hurricane watch-warnings issued by the NHC is included in Appendix B. These warnings included air pressure, wind field and strengthening or weakening of hurricane structure.

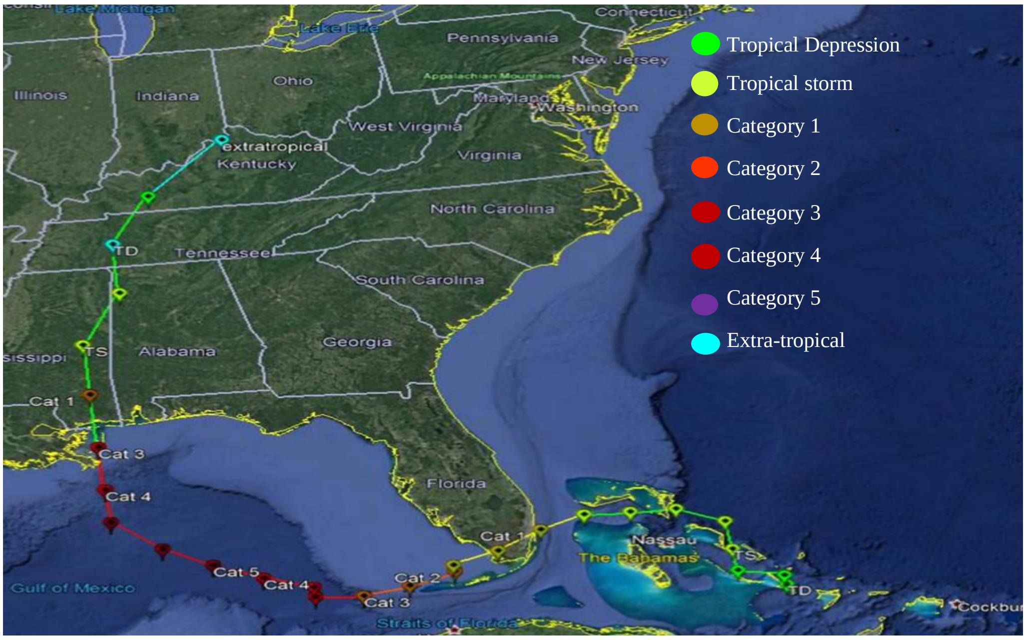


Figure 5.2 Hurricane Katrina's projected path with colour coded themes for different hurricane categories (version adapted by the author using Google Map)

After entering the Gulf of Mexico on 26 August 2005, Hurricane Katrina began to dominate the entire Gulf coast, undergoing two periods of rapid intensification, shown in Figure 5.2. Between these two intensifications, the size of Hurricane Katrina doubled on the 27 August (Knabb et al., 2005). Table 5.1 shows the landfall synopsis of Hurricane Katrina.

Table 5.1 Landfalls caused during Katrina's life cycle [source: (Knabb et al., 2005)]

Date	Time (UTC)	Landfall Location	Country	Category during landfall	Max. wind (knots)	Max. wind (mph)	Min pressure (mb)
25-Aug	2230	Border of Miami-Dade County & Broward County	Florida	1	70	80.64	984
29-Aug	1110	Buras, Louisiana	Central Gulf of Mexico	5	110	126.72	920
29-Aug	1445	Louisiana-Mississippi border	Northern Gulf Coast	3	105	120.96	928

According to Knabb et al., (2005), Hurricane Katrina holds the status of being one of the costliest hurricanes to-date, in US hurricane history with estimated economic damage of US$160 billion (inflation corrected to 2017 US$) with 1,833 deaths.

5.3 The disaster phases of Hurricane Katrina

5.3.1 Preparedness within the USA

During the monitoring of the approaching Hurricane Katrina, the risk was identified at an earlier stage by 11 August 2005. However, the early warnings were issued only after the 23 August 2005 in the USA twelve days later, followed by the warnings issued by the Bahamas (Moynihan, 2009). The dynamics of the storm was rapid, as hurricane status was attained quickly and made landfall in the USA on 25 August 2005. This allowed only two-days of preparation and evacuation time before landfall (Select Bipartisan Committee, 2005). The National Hurricane Centre (NHC) and National Weather Service (NWS) communicated the threat to FEMA, and their corresponding hierarchies, regarding the approaching hazard. NHC and NWS also warned that Hurricane Katrina may not be a 'typical' hurricane communicating the impending risks (Bea et al., 2006).

The State of Louisiana initiated the preparation by calling the National Guard troops on-duty ensuring the necessity of twice the workforce required in preparation for a significant evacuation within the shortest period (Committee on Homeland Security and Governmental Affairs, 2006). The City of New Orleans deployed its resources, Coast Guards were alerted on standby for a rapid search and rescue operation (Committee on Homeland Security and Governmental Affairs, 2006).

In Louisiana, the declaration of emergency was issued on 28 August 2005, which was 24 hours before the landfall (Select Bipartisan Committee, 2006; Moynihan, 2009). Moreover, this step was done only because of the then President Bush requested Governor Blanco to instigate a 'mandatory evacuation' in the Gulf Coast before landfall (Committee on Homeland Security and Governmental Affairs, 2006). Political let-downs such as lack of authority, negligence of responsibilities and lack of decision-making were exhibited during and post event.

Accuweather Inc, a private company, who issued a hurricane warning 12 hours before the NHC's first warning was issued (Select Bipartisan Committee, 2005). The delay in the issuance of early warning by NHC was criticised by the company, highlighting how vulnerable population were in the path of the storm without being warned earlier. The company further remarked that the warning would have aided timely evacuation in-advance prior to the landfall minimising the occurred loss of lives. According to post-disaster assessment report of Select Bipartisan Committee (2006), the close to accurate timelines of Hurricane's eye and its further forecasting and monitoring by the NHC and NWS were said to have prevented the extensive loss of lives (Moynihan, 2009). In contrary, the post-disaster report is inclined towards the achievement of some key activities while essentially ignoring the overall federal failures. Although, the failure of internal communication within the authorities was visible from the report, the failure of awareness regardless of assessing the risk should also be underlined.

While NHC was issuing hurricane watch-warnings and the advisories stated only minor changes in the pathway, intensity forecasters already warned that Katrina will be potentially a major hurricane at landfall (The US Department of Commerce, 2006). The Select Bipartisan Committee (2006) report states, that the lessons learnt were not reflected during Hurricane Katrina. The report discussed how the earlier experiences from previous hurricanes were not considered for evaluation and assessment, indicating the preparation for Katrina was inadequate (Select Bipartisan Committee, 2006). Learning the lessons from previous experiences is vital for future adaptation and mitigation of any hazard. This means a feedback loop of previous lessons learnt is essential to improve and create awareness and it is important that this feedback loop should also be continuously assessed. The outcome of this research partly creates such a feedback loop of the lessons learnt from the six different case studies to improve and create storm surge awareness.

The city of New Orleans is protected by a 350 miles of levee system due to large area of the city being below the sea level. It is to be noted that the levees and the flood walls designed by the Army Corps of Engineer were built to withstand a maximum of Category 3 hurricanes wind force (Seed et al., 2008; Marsh, 2015).

Figure 5.3 Aerial view of breached levees in New Orleans, during Hurricane Katrina (Source: NOAA Lib)

The flood walls along the Lake Pontchartrain were already identified with a crack from the force of the surging water which was a pre-existing condition before the landfall of Hurricane Katrina. This pre-existing condition caused two reactions which are (i) weakened the levee protection system and allowed the surging water to 'overtop' the levee and (ii) shallow landscape over which the levee was build caused subsidence of the levees as shown in Figure 5.3 (Risk Management Solution, 2005). A prior leak at two sites particularly in east and west bank crossing CSX rail line of the IHNC waterway was addressed previously during Hurricane Betsy in 1965. It was these same sites which were again breached during Hurricane Katrina. Though the storm surge from the Lake Borgne was responsible for the over topping of the water, the ignored previous crack in the levee protection indicates weak coastal protection system and failure of preparedness (Seed et al., 2008).

The USA, whose adaptive capabilities were higher than most of the developed countries faced criticism post-Hurricane Katrina. Few of the factors criticised includes delayed declaration of emergency, deployment of resources and evacuation, decision-making capacity that resulted in the loss of 1,800 lives and with an economic loss US $108 billion (2005) (Committee on Homeland Security and Governmental Affairs, 2006). The pre-existing conditions, and the levee cracks, evidently remark that the city has not rectified or repaired the coastal protection system and eventually confirms that the neither the federal nor the state government were prepared for the hurricane and failed to learn from previous storm surge experiences.

5.3.2 Response within the USA

As Katrina was approaching, watch-warnings for the hurricane were issued with a lead time of 20 to 32 hours in Florida, and 32 to 44 hours in Louisiana. As per Louisiana's Emergency Management team, the average evacuation time for the vulnerable residents in the coastal communities is typically 48 to 72 hours (The US Department of Commerce, 2006). The US Department of Commerce (2006) states that the national and local responders were neither prepared nor pre-planned, which further highlights the level of response followed during Hurricane Katrina.

The breach in the levee system which occurred from both overtopping water and subsidence of the levees continued, increasing the number of breaches at various locations. The breaches notably occurred on location such as the Industrial Canal (Inner Harbour Navigational Canal), 17th Canal Street, (Knabb et al., 2005) which are highly populated. Flooding from the storm surge inundated both the west and east sides of the canals faster than expected (Nelson, 2015). Moreover, the flood gates failed to work at the Industrial Canal, weakened the entire coastal protection system leaving the responders to rely on sandbags to seal the flood walls (Nelson, 2015). This observation exhibits poor planning and preparation executed by the state and federal governments relying on meagre measures as a response.

According to Neuman (2015), around 25,000 residents were identified as non-evacuees even after FEMA's official evacuation ordered was issued. Due to the swift dynamics of the storm surge, the non-evacuees were forced to resort to sheltering in their attics and rooftops and during the search and rescue operation, most non-evacuees were rescued from these locations. (Committee on Homeland Security and Governmental Affairs, 2006). The post-disaster analysis stated that the people who did not evacuate lived close to the Lake Pontchartrain and the canals in more deprived housing. Besides, many of these people did not have a vehicle or transport available to evacuate.

A key housing design and architectural technology consideration (whether for retrofit or new build) was the lack of attic roof light windows or roof hatches to exit from the attic zones. This led to delays in rescue but also tragically led to people drowning within their roof space or being trapped unable to leave or exit, waiting several days for waters to recede.

During a previous Hurricane Ivan (2004) a similar situation of non-evacuees was observed. Vulnerable residents such as elderly and disabled people stated that, the officials requested the people to evacuate but, they never instructed on the evacuation shelter locations or transport modes and routes. Many disabled and elderly residents stated that, they were issued with evacuation advisories, but they were not guided with the plan or procedures to follow. These were the observed as resident's opinion after Hurricane Ivan (2004) a year before Hurricane Katrina (Litman, 2006). The resident's opinion reflected on how key lesson learnt from the previous Hurricane Ivan was not reflected during Hurricane Katrina. Despite, being already aware of this prevailing situation of poverty and non-evacuation scenario in New Orleans, the officials continued to follow the same protocol, and no additional response were carried out.

Figure 5.4 Residents gathered in front of the Superdome emergency shelter after the landfall of Hurricane Katrina [source: Select Bipartisan Committee (2005)]

On identification of a large part of the population have not been evacuated, a make-shift response plan to set up Superdome as an emergency shelter was put-forth. When the storm made landfall at 6.00 am on 29 August 2005, the Superdome had already been set-up as 'shelter of last resort' for thousands of people, as shown in Figure 5.4. This clearly is a failure of planning and evacuation; however, this also showed failure to understand the emergency management process, and the roles and the responsibilities of the emergency responders within this process. The search and rescue operation further added tens of thousands of people into the process of moving them to safe grounds (Select Bipartisan

Committee, 2006). Airports in New Orleans were closed by 30 August 2005 and bridges of Interstate-10 (city's exit route) was destroyed impeding the already overdue evacuation. (Waple, 2005). The Louisiana Department of Transportation and Development's (DOTD) response during the evacuation was observed to be inadequate mainly due to the lack of prior transportation and evacuation plans which led to gridlock in many interstates entirely hampering the efforts (Committee on Homeland Security and Governmental Affairs, 2006).

Failure of evacuation, further led to extensive search and rescue operations, involving support from the army and many rescue operations were carried out by airlifting the victims. The US Coast Guard rescued around 30,000 local people, while the army supported airborne search and rescue (Committee on Homeland Security and Governmental Affairs, 2006). Volunteers joined the forces at a local and national level. Private organisations like Walmart assisted with their logistics and efficiency in getting the supplies into New Orleans days in advance to FEMA was an appreciated effort from ad-hoc stakeholder perspective (Birdsall, 2009).

Figure 5.5 Before (right) and after (left) image of the Superdome of Downtown, New Orleans post-Katrina [image source: AP Photo/David J Phillip, Gerald Herbert]

By 30 August 2005, 80% of the New Orleans city was underwater. All the locations at the 17^{th} Street Canal which were protected by sandbags failed to prevent the flood waters. The Superdome which was set-up as a makeshift emergency shelter was ordered to be re-evacuated again by 30 August 2005 (Bugliarello, 2006). Figure 5.5 shows the ripped-off rooftop of the Superdome which was built to withstand the wind force of the Category 3 and above hurricanes. Moreover, the hospitals in Louisiana were forced to evacuate after landfall, at very short notice due to the loss of power (Bugliarello, 2006). This step of re-evacuation at various locations was regarded as a clear indication of inadequate response plan exhibited during Katrina.

Around 2.5 million people were impacted with power outage in Florida (Energy.gov, n.d.) and 3 million affected from disconnected phone lines (Marsh, 2015). It took almost twelve days to restore the electric services (Bugliarello, 2006), resulting in an adverse impact of telecommunication lines.

The overwhelming impact of Hurricane Katrina with a massive 27 ft storm surge breaching the levees, affected the communication and coordination delaying the overall response. At this stage, the response of Hurricane Katrina was observed to be beyond what was planned by the federal, state, and local officials. FEMA's response to Hurricane Katrina was widely criticised particularly on the key areas such as the deployment of responders, communications, inefficient planning, ordering mandatory evacuations and search and rescue operations (Moynihan, 2009). The most efficient pumping system of the New Orleans, which could drain 300 million gallons of water a day, was submerged by the storm surge flooding. The primary motors and the power unit of the pumping system, which was located at the ground level, were fully inundated by surge water making the system inoperable and eventually leaving the city to remain flooded for more than two weeks (Schleifstein, 2015).

All these critical factors during the response stage led to the socioeconomic losses to exceed the actual loss imposed by Katrina individually (Neumann et al., 2015). The former 9/11 public disclosure project panel members criticized that "*failure in communication and lack of coordination costed lives*" thereby giving 'a failing grade' for US federal government's response to Hurricane Katrina (Committee on Homeland Security and Governmental Affairs, 2006, p. 21). Lack of implementation of previous lessons and failure of adaptation of evacuation plans to the current scenario was identified. Despite of early identification of hazard, inadequacy in decision-making for effective pre-emptive preparedness was observed.

5.3.3 Recovery within the USA

The officials from different emergency response departments from Louisiana and Mississippi collaborated and coordinated during the incident recovery phases and were identified to have coordination concerns. The lack of communication and coordination did not favour the situation and only prolonged the process of recovery phase (Select Bipartisan Committee, 2005). This was further confirmed from the post-disaster analysis report of the Committee on Homeland Security and Governmental Affairs (2006). Their analysis states that the search and rescue operations were successfully carried out in many areas while the coordination and communication between different teams lacked coherence. Many public services such as police stations and hospital were affected. Key workers and first responders themselves were found as victims further extending and delaying the recovery period for this major disaster (Select Bipartisan Committee, 2005).

Prior to the damage of the Superdome's roof as shown in Figure 5.5, mass medical relief support was provided in the Superdome as shown in Figure 5.6 (Rare News, 2015). Various health-related issues, sanitary concerns and increasing temperature inside the emergency shelter due to large population created further deterioration in public health. The shelter was identified as unorganised and further led to law-and-order issues. Medical facilities and personnel were deployed in delay and were generally considered to be only reacting to recover from the situation and were not pre-planned or pre-deployed (Committee on Homeland Security and Governmental Affairs, 2006).

Figure 5.6 Sheltering and mass care in the Superdome before re-evacuation
[source: Committee on Homeland Security and Governmental Affairs (2006)]

As the homes became uninhabitable, the American Red Cross deployed state emergency shelters and provided food, shelter and supplies to 146,292 people (Moynihan, 2009). The Department of Defence (DoD) remarked that Katrina's recovery phase was supplied with major military deployment not seen, since the civil war. In addition to the DoD, the Red Cross also provided services 20 times more than any of its previous missions during the recovery phase (Moynihan, 2009). Undoubtedly, these excess deployments of resources remark that the response exhibited was beyond the capacity of federal and state teams which complicated many of the activities of the recovery phase. According to the Federal Urban's search and rescue teams who had a previous experience during the 9/11 operations, and the California earthquake stated that, Katrina's response and recovery were beyond the expertise of even the knowledgeable professionals in term of managing the disaster (Committee on Homeland Security and Governmental Affairs, 2006). It took six months to recover the severely damaged Gulf Coast and the interstate bridges to become fully operational. Access to the I-10 Twin Span Bridge was limited even after two months, since Hurricane Katrina's landfall (Grenzback & Lukmann, n.d.).

According to the report of Marsh (2015), the insurance sector faced a crucial criticism during the recovery phase. Private insurance industries in the Bahamas, suffered a significant impact, as the state government did not support the private insurance companies. Insurers withdrew their protection cover for some of the areas, resulting in homeowners to self-insure or limiting the premium with exclusions. Eventually, this resulted in the property being abandoned and loss of mortgages. Problems were also identified during the damage assessment of these abandoned properties due to the disconnected coordination between state and local authorities (Committee on Homeland Security and Governmental Affairs, 2006; Marsh, 2015).

According to Towers Watson (2005) assessment report, ambiguity in assessing the wind-damage and water-damage from storm surge was identified during the recovery Phase. The US homeowner's policies covered the damage from wind and rain (wind-driven), but not from flooding (wind-driven) i.e., storm surge flooding was not covered. Because storm surge was classified as flooding, most of the claims were denied. Unless the homeowners had bought flood insurance in addition to their property insurance, they were generally not covered (Towers Watson, 2005). Once again, the limitations in insurance imply the poor assessment of the hazard which is one of the important key activities belonging to phase-1 preparedness but then impacting the phase-3 recovery stage.

5.3.4 Mitigation within the USA

The Red Cross, which worked closely with FEMA, acknowledged that 'it was not easy to coordinate with FEMA' emphasizing the issues faced in communication and coordination. They further highlighted situations where the Red Cross's request for food supplies on 1 September 2005 was cancelled by FEMA initially. The request was redelivered finally on 8 October 2005, delaying the pace of recovery, and challenged incident stabilization (Moynihan, 2009).

The levee protection system which was initially made up of the I-walls were reconstructed with T-Walls for future mitigation of storm surge or any other flooding hazard. Nearly after a decade, in 2015 reconstruction slowly kicked in the Lower 9th ward that is just in front where the levees were breached (Nelson, 2015). Criticism from various sectors urged FEMA to deploy the Mitigation Assessment Team (MAT) to investigate the performance of all the coastal buildings, infrastructures and re-evaluate the construction practices (Select Bipartisan Committee, 2006).

Figure 5.7 Comparison of base flood elevation level (BFE) designated by FEMA and actual flood level observed during Hurricane Katrina [source: Select Bipartisan Committee (2006)]

According to MAT's report, the advisory base flood elevation (BFE) maps issued were identified with buildings elevated as per the BFE levels but suffered storm surge inundation directly shown in Figure 5.7.

This observation led the assessment team to suggest a 1-foot freeboard i.e., a vertical step increase of 30 cm approx. above the standard BFE, for all buildings in hazard-prone areas (V, VE, V1-V30[2] zones) or LECZ's. However, looking at the BFE level and the actual flood level, as highlighted in Figure 5.7, clearly indicates that the 1-foot freeboard above the BFE is an inadequate mitigation mechanism. Post-hurricane Katrina, the Department of Homeland Security (DHS) and the US Department of Transportation (USDOT) conducted a nationwide assessment of emergency preparedness. The findings stated that

[2] According to Flood Insurance Rate Map, flood hazard areas are referred as Special Flood Hazard Area (SFHA), and residential housing were labelled as Zone A, Zone AO, Zone AH, Zone A1-A30, Zone AE, Zone A99, Zone AR, Zone AR/AE, Zone AR/AO, Zone AR/A1-30, Zone AR/A, Zone V, Zone VE, Zone V1-30.

the emergency preparedness plan for urban areas was partially sufficient in terms of specific and measurable requirements for a successful evacuation (Bea et al., 2006; Committee on Homeland Security and Governmental Affairs, 2006).

Hurricane Katrina's key lessons showed lack of understanding and the dispersion of role and responsibilities of various national and international actors. Capacity building became crucial when, FEMA failed to recruit and train enough personnel for operational tasks (Litman, 2006). Whilst they were senior decision-makers based within the authorities, staffing (such as field workers) was insufficient to execute the decisions and plans were insufficient. Integrating the response and recovery both effectively and efficiently for future disasters and emergencies also remained a critical factor of mitigation (Litman, 2006).

5.3.5 Summary of key activities and disaster phases during Hurricane Katrina

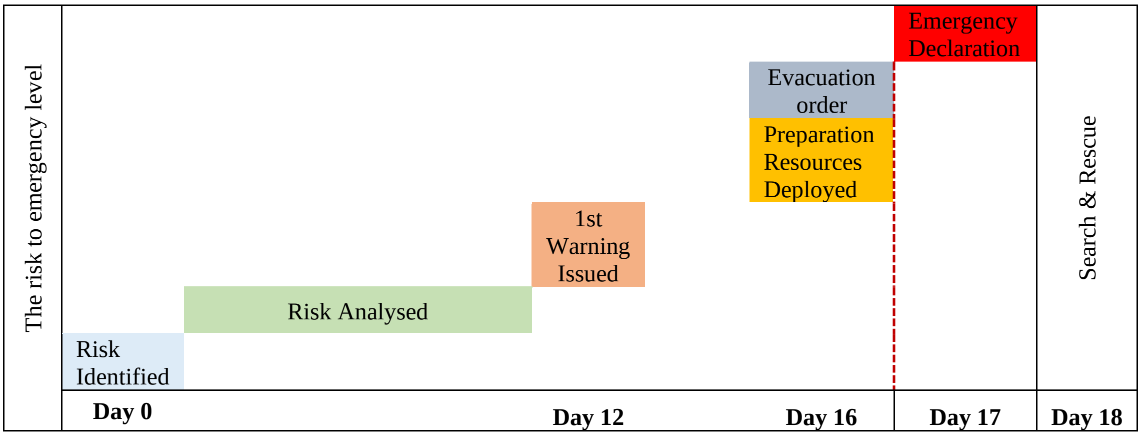
Summarising all the key activities observed in the four main phases of the DRM cycle, the following table 5.2 has been developed. The table provides an overall summary of all the actions as key activities measured both from coding and from the document sources.

Table 5.2 Summary of the key activities and their achievements observed from Case Study Katrina

	Preparedness	***Response***	***Recovery***	***Mitigation***
Activities Achieved	Declaration of emergency Forecasting Monitoring Risk identification Risk assessment Deployment of resources Early warning	NGO and volunteers Incident stabilization Evacuation Emergency Shelter	Reconstruction Rehabilitation Search & rescue Damage assessment Debris removal Health care Recovery Insurance	Coastal protection Technical prevention Multi-agency approach Lessons learnt Public education and awareness Capacity building
Activities unachieved/not identified	Technical prevention Capacity building Scenario planning Training and exercise Vulnerable population Hazard assessment	Community outreach Risk analysis Telecommunication Emergency planning Transportation Communication Coordination Power and utilities	Restoration Organizational capacities NGO and volunteers Improving livelihoods Infrastructure	Strategic alternate approach Wetland mitigation Stakeholder involvement Environment Scenario planning Land use planning Training and exercise

While observing the key activities, the following timeline gap was also observed as shown in Table 5.3. Between the first day of the risk identification and issuance of the first official warning, eleven days of an inactive period occurred, during which no preparedness activities were carried out. This suggests that if the key activities and the corresponding phases were initiated during this period, the possibility of the reduced deaths and economic damage may have been recognized.

Table 5.3 Overview of the timeline gap and risk emergency level observed during Hurricane Katrina



5.4 Physical damage and loss statistics

According to NHC, Hurricane Katrina remains the most significant event in the US hurricane history and continues to an exemplar case providing lessons particularly for future mitigation and adaptation (Marsh, 2015). The physical damage from Hurricane Katrina includes infrastructure damage, schools and hospitals, business interruptions, destroyed ports and cruise berths, and debris deposited on rooftops of single-story homes. The hurricane resulted in around 300,000 homes being uninhabitable (Committee on Homeland Security and Governmental Affairs, 2006) and around 2,000 cell phone sites damaged and lost services (Moynihan, 2009). More than 1,833 deaths were officially reported (Knabb et al., 2005). Table 5.4 lists the state-wise death toll from storm surge.

Table 5.4 Causalities from Hurricane Katrina [source: Knabb et al., (2005)]

United States	*Death Toll (numbers)*
Louisiana	1577
Mississippi	238
Florida	14
Georgia	2
Alabama	2

Modern engineered infrastructures built to withstand hurricane's heavy winds were observed to have failed to sustain the magnitude of the storm surge. Some infrastructures even failed to sustain Category 3 and above hurricane wind-speed and became a noticeable engineering failure (Select Bipartisan Committee, 2006). The US Army Corps engineered levee system; the Louisiana Superdome; i-10 Twin Span Bridge and the New Orleans pumping station were among those infrastructures (Moynihan, 2009).

The damage of the oil and gas refineries stopped the production of 91% of the domestic crude and 83% of the domestic natural gas production in southeast Louisiana and Mississippi (Risk Management Solution, 2005). Further, the delivery services were halted for several months resulting in a shortage of fuels affecting the economy (Risk Management Solution, 2005). Katrina's damage also included damage to the university, college, and private research centres, which prevented the continuation of further research and global investment and contracts being terminated or withdrawn (The US Department of Commerce, 2006).

According to the Committee on Homeland Security and Governmental Affairs' (2006) report, the overall damage in all the oil and gas refineries resulted in 24% of oil supplies being shut and 18% for gas production. Apart from the country's infrastructure damage, private housing, critical buildings, business firms and farmlands along the coastline suffered serious impact agitating the nation's economy (Committee on Homeland Security and Governmental Affairs, 2006). Several businesses were lost in Port Louisiana, New Orleans, and Mississippi because of major damage which impacted logistics. Furthermore, restoration and refurbishment cost in switching back to business was imposed (Grenzback & Lukmann, n.d.). Disruption in most of the public services not only impacted the population but also affected the environment, economy, and government function, ultimately delaying the process of recovery from the catastrophic damage. It took from several months to few years, for the residents to recover completely (Litman, 2006).

5.5 Impact of storm surge within the USA

According to the estimated storm surge levels observed by the NOC tide gauge and the USGS high watermarks, Hurricane Katrina was recorded with a 24-28ft storm surge along the coast of Mississippi as shown in Figure 5.8 (Knabb et al., 2005).

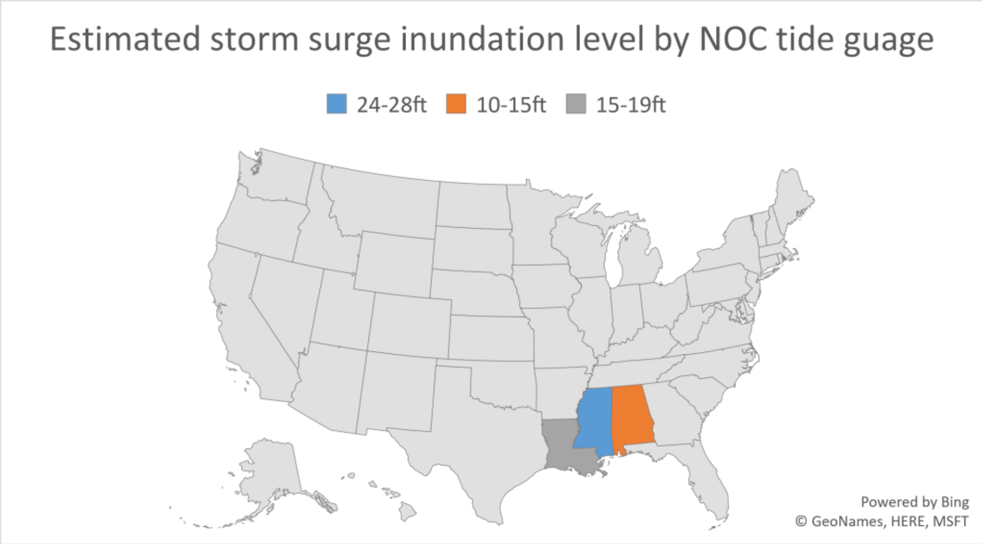


Figure 5.8 Storm surge inundation levels observed by USGS and NOS tide gauges [source: Knabb et al., (2005)]

The Gulf Port to Pascagoula, the eastern half of Mississippi coast was observed with a 17-22ft storm surge. However, as per the high-water marks, the maximum inundation was recorded as 27.8 ft at Pass Christian, east of St Louis Bay, Gulf Coast. Katrina was one of the highest recorded storm surges in US history above means sea level (Knabb et al., 2005). According to Knabb et al., (2005), the significance of this event relies on the factor that 51% of the City of New Orleans was already below 2 ft of mean sea level.

Figure 5.9 Storm surge from the Lake Pontchartrain breaching the levee in the City of New Orleans [Image source: Google Earth]

The report further adds that the poorly managed levees failed to withstand the magnitude of the storm surge directly contributing to the loss of lives. The levees were over topped from the funnel-effect of the storm surge from Lake Borgne and the Mississippi River Gulf Outlet reaching up to 15 ft above sea level. The storm surge triggered by the hurricane, forced the rivers and the canals breaching through the flood protecting levees as shown in Figure 5.9.

The Independent Levee Investigation Team (ILIT), assessed the post-event situation, reported that critical errors led to the levee failure, but the Inter-agency Performance Evaluation Task Force (IPET) strongly claimed that the force of the storm surge breached the levees causing catastrophic damage (Nelson, 2015). The debris from the storm surge inundation was observed for 90,000 square miles inland, which in comparison is the size of the United Kingdom (Grenzback & Lukmann, n.d.). The storm surge triggered by Hurricane Katrina was responsible for at least 10 oil spills, which was more than two-thirds the amount lost in various other oil-spills in the history of US disasters. Storm surge was directly responsible for the damage of 466 chemical facilities, destroyed around 170 drinking water facilities and wastewater treatment facilities, 31 hazardous waste production sites and 16 toxic waste sites (Birdsall, 2009).

5.6 Adaptive measures taken over post-Katrina

In 2014, the US Census Bureau estimated that population recovery in New Orleans has reached 79% of its 2000 population, particularly the urban population has increased by 94% of its 2000 population. However, areas directly impacted to the magnitude of the storm surge like Lower Ninth Ward were still recovering (The House Financial Services Committee's Democratic Staff, n.d.).

Despite, the criticism of the local and the coast guard teams were positively acclaimed for their response, the federal and the national response to Hurricane Katrina received wide criticism (Birdsall, 2009). This criticism eventually led from minor to major changes within several sectors including construction, insurance, and transportation. The National Weather Service (NWS) assembled a Service Assessment Team (SAT) to assess the performance of NWS and suggested identifying the best practices for future adaptation and mitigation to hazards (U.S. Department of Commerce, 2006).

The hurricane's aftermath also led to major policy changes (Bea et al., 2006). Post-Katrina Act was initiated to engage the changes in leadership roles and responsibilities within FEMA. The act further brought alterations in various components within the national emergency preparedness.

Some key mitigation actions and acts initiated were listed as follows:

- The Post –Katrina Emergency Management Reform Act of 2006 (in short Post Katrina Act)
- The security and Accountability for Every Port Act of 2005 (SAFE Port Act)
- The Federal Judiciary Emergency Special Sessions Act of 2005
- The Pets Evacuation and Transportation Act of 2006
- Louisiana Recovery Act 2005 (Venson, 2007)
- The Student Grant Hurricane and Disaster Relief Act
- The John Warner National Defence Authorization Act for the Fiscal Year 2007 (Bea et al., 2006)
- H.R. 1227 the Gulf Coast Hurricane Recovery Act of 2007 (The House Financial Services Committee's Democratic Staff, n.d.).

5.7 Hurricane Sandy: origin and background

Hurricane Sandy was a late-season hurricane which originated as a tropical wave in the west coast of Africa on 11 October 2012. The tropical wave travelled towards the southwestern Caribbean Sea and became a tropical depression on 22 October 2012, 1200 UTC. The depression further became a tropical storm within the next 6 hours duration (Blake et al., 2013). Hurricane Sandy, unofficially referred to as ‘Superstorm’ Sandy or ‘Frankenstorm’ Sandy was the eighteenth named Tropical Storm (Sopkin et al., 2014), which gradually became a fully developed hurricane on 24 October 2012, 1200 UTC exactly within 48 hours (NHC, 2012).

The storm made its first landfall in Jamaica as Category 1 on the 24 October 2012 as illustrated in the timeline shown in Figure 5.10. The structure of Sandy’s underwent a complex evolution and grew considerably in size over the Bahamas and continued to grow despite weakening into a tropical storm (Blake et al., 2013).

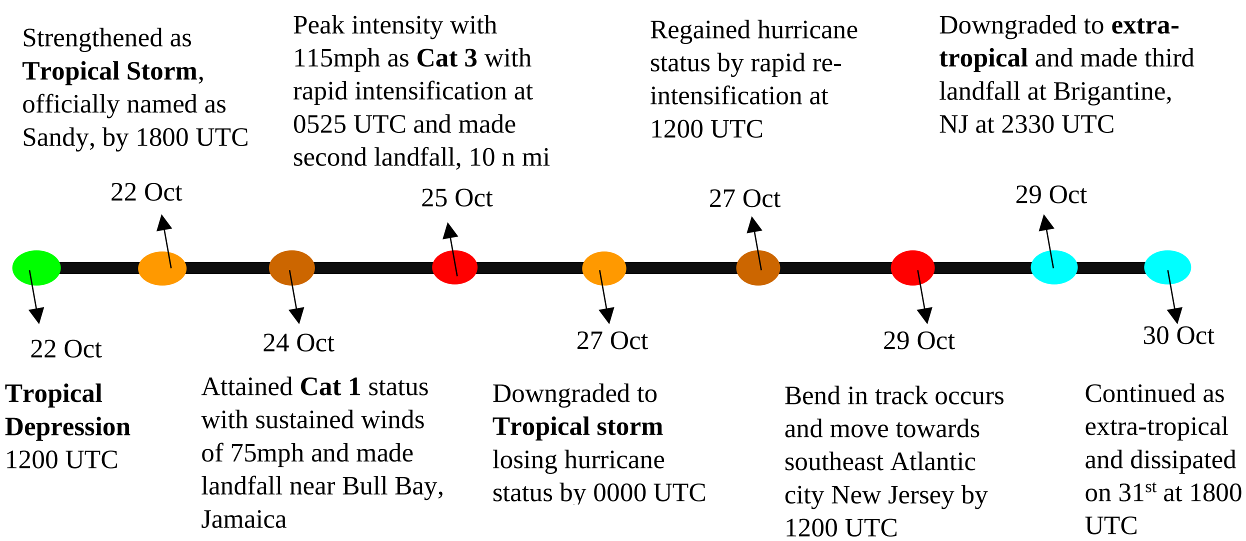


Figure 5.10 Timeline of Hurricane Sandy (2012) [source Blake et al., (2013)]

The storm was extraordinarily large as shown in Figure 5.11, a version adapted by the author using data collated from different sources such as NHC, NOAA, NASA and 'Weather underground' showing the comparison of Hurricane Sandy's radius with previous significant hurricanes in US history.

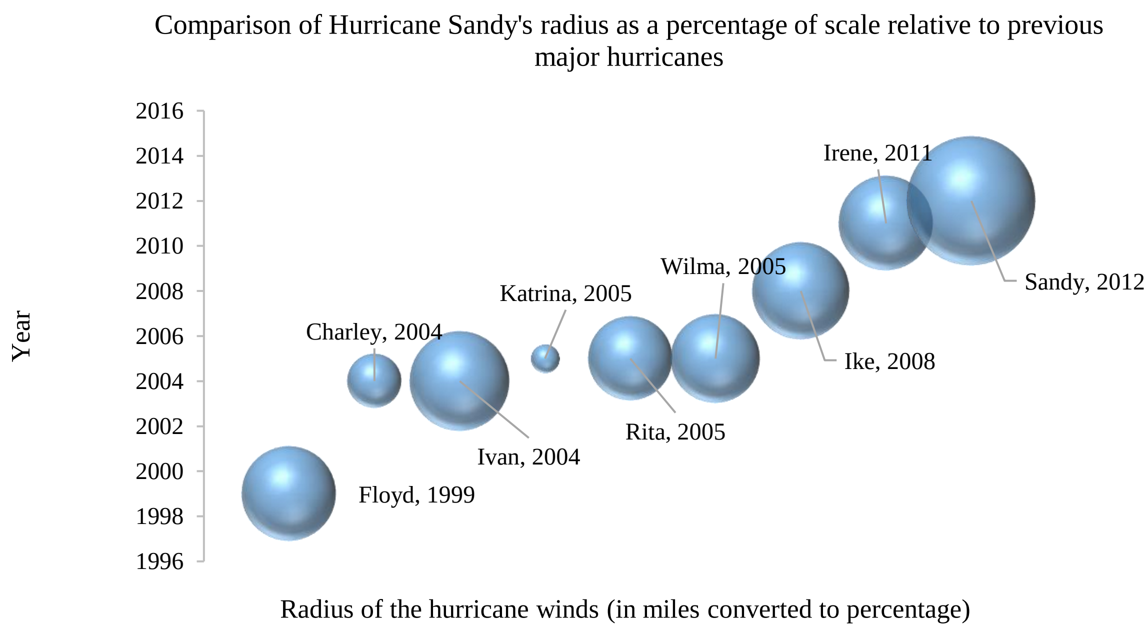


Figure 5.11 Comparison of Hurricane Sandy's radius with previous hurricanes [source: Blake et al., (2013)]

The storm continued to grow after crossing the Bahamas and until its final landfall as an extra-tropical cyclone along the mid-Atlantic coast. The change in its hurricane size (in radius) began to increase between 25-26 October over the Bahamas resulting in Sandy being the largest extra-tropical cyclone up to that period (Blake et al., 2013). The structure of the storm was quite unusual compared to other hurricanes. The size of the 'Superstorm' Sandy's wind field was a thousand miles end-to-end (NHC, 2012) and the interaction of Sandy with the northeaster or nor'easters (winds) before the landfall time which combined with the high tides to produce significant damage. Figure 5.11 also shows the size of Hurricane Sandy radius as a comparison percentage of scale relative to previous major hurricanes.

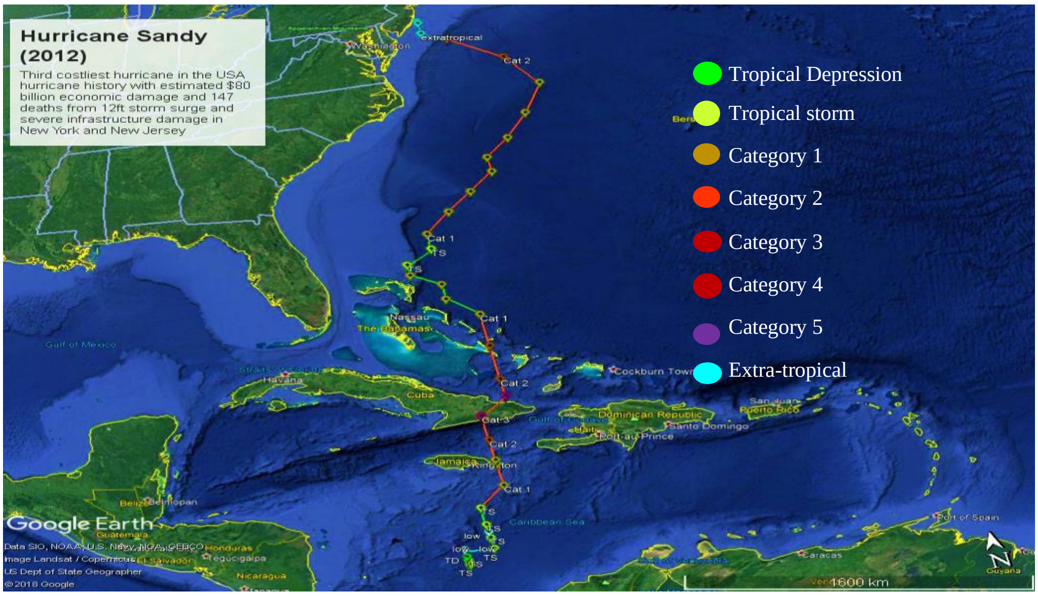


Figure 5.12 The hurricane path or track with colour coded themes for various hurricane categories (version adapted by the author using Google Map)

It is interesting to note that Sandy had a considerably larger radius than Katrina, but both hurricanes still resulted in considerable damage. In relative terms, the radius and the intensity of storm were key factors as Katrina was Category 4, but a smaller radius and Sandy was a tropical storm but with larger radius. Figure 5.12 shows how Sandy was travelling in parallel to the east coast of the USA and the sudden track change in the storm's path, moving towards the coast of New York and New Jersey. Hurricane Sandy affected the east coast of the USA from Florida to Maine making its final and primary landfall in New Jersey and the densely populated New York City (FEMA, 2013). The extra-tropical hurricane not only produced a storm surge of 12ft in various locations but also created a significant direct and indirect socioeconomic impact (Blake et al., 2013; NHC, 2013). Appendix B includes the author's version of the summary of Hurricane Sandy's predicted or forecasted pathway and the hurricane watch-warnings as issued by the NHC. These warnings include air pressure, wind field and strengthening or weakening of hurricane structure.

According to Blake et al., (2013), the number of direct fatalities from Hurricane Sandy was 147. However, a total of 233 fatalities were related with Hurricane Sandy in eight countries including Cuba, Jamaica, Haiti, USA, Canada, Bahamas, Puerto Rico, Dominican Republic (Diakakis et al., 2015).

The storm took the status of being the second-costliest hurricane with an estimated economic damage of US$ 71 billion (inflation corrected to 2017 US$) until 2017, which was replaced by Hurricane Harvey amounting to US$ 125 billion (NOAA Office for Coastal Management, 2019). It is to be noted that Hurricane Harvey was not a storm surge event, and the major loss was due to the heavy rain downpours. In terms of storm damage, and especially from the viewpoint of this research, Hurricane Sandy should be the second costliest hurricane in the US history excluding Hurricane Harvey as a rainfall event. The storm size was broad, being 1000-miles wide from end-to-end and when it made landfall near Brigantine, NJ was when Hurricane Sandy was a post-tropical cyclone (NYC, 2013).

Table 5.5 Landfall synopsis of Hurricane Sandy (2012) [source: Blake et al., (2013)]

Date	Time (UTC)	Landfall Location	Country	Category During Landfall	Max. Wind (knots)	Max. Wind (mph)	Min Pressure (mb)
24-Oct	1900	Bull Bay	Jamaica	1	75	86.4	971
25-Oct	0525	10 nautical mi	Cuba	3	100	115.2	954
29-Oct	2330	Brigantine	New Jersey	1	70	80.64	945

Table 5.5 shows the landfall history of hurricane Sandy with its maximum wind speed (mph) and minimum millibar pressure (mb) during its landfall. The wind speed during the final landfall was 70 knots (80 mph) but it is to be noted that the minimum pressure sustained was close to a Category 3 hurricane (FEMA-MAT, 2013). So, whilst Sandy was reported as an extra-tropical storm relative to the wind speed its sustained minimum pressure was equivalent of a Category 3 hurricane in the SSWHS.

5.8 The disaster phases of Hurricane Sandy

5.8.1 Preparedness within the USA

The lessons from the previous Hurricane Katrina were implemented during the response of Hurricane Sandy. The NHC's forecasters monitored the hurricane and the path called the 'cone of uncertainty' (Blake et al., 2013) and further provided earlier warnings about Hurricane Sandy's track change towards New York and New Jersey. Storm preparation protocols and emergency planning were initiated ahead. According to the Hurricane Sandy Rebuilding Task Force, (2013) the deployment of resources began corresponding to the emergency plans, setting up the emergency shelters, aerial patrols, qualified personnel, and field resources called on-duty and remained on standby to respond. The coastal power generating stations were shut-down as a precaution to avoid capacities-at-risk. More than 1,500 personnel from FEMA were called on-duty to be on standby along the East Coast (Hurricane Sandy Rebuilding Task Force, 2013).

By Monday 29 October 2012, despite 'Superstorm' Sandy having lost its hurricane status the collision with another weather system the nor'easters made it unprecedented and increased the complexity (Blake et al., 2013). Continuous monitoring did provide opportunities for forecasters to provide early warnings to coastal communities. Most importantly forecasters warned communities that the potential hazard from Hurricane Sandy has not lessened, even though it was no longer holding a 'hurricane' status. They further warned regarding the possibility of life-threatening storm surges approaching towards the coastal communities of New York and New Jersey (BBC News, 2012).

According to BBC News (2012), the New York city's authorities did consider the high tide and the combination of the approaching storm which could result in storm surges and storm tide flooding the Lower Manhattan and possibly flooding the city's underground transport system (BBC News, 2012). Around 6,700 National Coast Guards were made available on-duty to respond to the approaching landfall from Hurricane Sandy and around 140 helicopters were on standby to initiate the search and rescue operation as soon as landfall occurred (BBC News, 2012). The city of New York (NYC) and New Jersey provided the communities with hurricane watch-warnings along with the storm surge warning and ordered mandatory evacuation twice to the coastal communities communicating the approaching hazards. The NYC further deployed around 73 shelters throughout the five boroughs to host evacuees (NYC data, 2013). The general transportation services were halted and most of the subway stations were barricaded before the storm's landfall. New York City housing authority (NYCHA) liaised with

19,000 members to communicate and coordinate the response and prepare for the emergency (NYC, 2013).

As the storm was 800 miles from the coast for landfall and approaching with a wind speed of 90 mph, an estimated 50 million people were exposed or vulnerable to the storm with rain and wind. Most airline services were cancelled in preparation for the emergency by then (BBC News, 2012). The overall preparedness of Hurricane Sandy was observed to have implemented effective EWS, evacuation, deploying the resources with prior planning. This may also be observed as the implementation of lessons learnt from the previous Hurricane Katrina (2005).

5.8.2 Response within the USA

The federal response to Hurricane Sandy was activated even during the preparedness period. Hurricane Sandy affected 24 states across the northeast to the Mid-Atlantic. The potential physical damage from Sandy's landfall highlighted the city's vulnerability to storm surge flooding (Abramson & Redlener, 2013). The New York City hospitals moved their generators to higher grounds. Concreted walls protecting fuel pumps at ground level and response measures taken by health sectors to protect and prevent loss of lives during the approaching emergency. Benchmarked safety standards of the hospital and other key health-related fields were outdated which was observed and a reason to the failure of the federal and state government's response to Hurricane Sandy (Abramson & Redlener, 2013).

The city had restored wetlands and even had buildings elevated above the BFE levels mandated by FEMA's National Flood Insurance Program (NFIP) mapped with Flood Insurance Risk Map (FIRM) (FEMA, 2013). According to authorities of New York city certain resilience measures that had been invested to mitigate coastal flooding scenario, indeed performed well during Hurricane Sandy's response. It was the mechanical, electrical, and plumbing (MEP) systems which were situated on ground level not being elevated above the flood levels became a major disadvantage that was threatened by the storm's magnitude (NYC, 2013). In response to Superstorm Sandy, around 375,000 residents were evacuated and from the Lower Manhattan and other neighbourhoods in the New York and were safely moved to emergency shelters. In Delaware, around 50,000 were ordered to evacuate (BBC News, 2012).

New York city's oldest and well-interconnected power and utilities system faced a significant impact. The City of New York further found power outage was critical during the landfall of Hurricane Sandy (NYC, 2018). The power loss compromised the life support, heating systems, and various other critical systems resulting in a challenging situation (Abramson & Redlener, 2013). Although, the overall response was well-planned and organised during the beginning, the magnitude of the storm gradually deteriorated the systems consecutively resulting in substantial economic damage.

5.8.3 Recovery within the USA

Despite implementing the lessons learnt from the previous hurricanes and storm surge events, the efforts undertaken and, the process of response and recovery, were affected by various critical elements:

- While the recovery efforts were being initiated post-landfall, initial steps were significantly impacted by storm surge flooding and unavailability of roads for transportation and logistics of resources (NERC, 2014).
- The storm surge which flooded the New York's subway tunnels became a significant obstacle delaying the recovery, disconnecting the transportation and transits in the 100-year history since, built (Taylor, 2012).
- In some instances, e.g., where a substation exploded, restoration of power and recovery of utilities took longer than expected. It took 31 days for the restoration and recovery of power and utilities (NERC, 2014). However, it was also reported that some communities, which were severely impacted by the storm surge took months to recover from the lack of power (NYC data, 2013).

Figure 5.13 Oceanfront house in Rockaway NY, damaged during Hurricane Sandy [source: FEMA (2013)]

Coastline infrastructures and oceanfront buildings faced severe impact from the 12 ft storm surge as shown in Figure 5.13 (FEMA, 2013). The recovery of floating infrastructure was not as extensive as the fixed non-movable infrastructures (NYC, 2013). 95% of the New York City homeowners had home insurance, however, it was identified post-Sandy during its recovery phase that the majority did not have flood insurance (IBHS, 2012). As a result, thousands of properties were not covered by flood damage. Also, it was estimated that only 20% of the residential buildings were covered by NFIP (NYC, 2013). A similar 'ambiguity in insurance claims' was observed during Hurricane Katrina (2005) in Louisiana, was also identified during Sandy implying that lessons learnt from the insurance point of view were not implemented. In New York City, 70 % of the housing units in the flood plains were multi-dwelling units (MDU) which were built before 1983. Therefore, they were not covered by NFIP (NYU Furman Center, 2015; Furman Center & Moelis Institute, 2013).

During Hurricane Sandy, despite some properties being well elevated above the base flood elevation (BFE) levels, their MEP systems were still severely impacted. As per the estimation of the New York City Housing Authority (NYCHA), loss from storm surge not only included the property being damaged or destroyed but also included loss of MEP systems. Hurricane Sandy also damaged NYCHA's thirty-five multi-housing developments which were in the process (at that time) of receiving resiliency funding from FEMA (NYC, n.d.). Although, the developments were compensated, the recovery took seven years. This is a factor that is suggested to be minimised in the future.

5.8.4 Mitigation the USA

The NYHCA has 176,066 public housing units in 326 developments throughout the five boroughs which are Manhattan, Brooklyn, Queens, The Bronx, and Staten Island. These locations were the most severely damaged locations during Hurricane Sandy. Around 700 apartments in the Bond Street had their MEP systems severely impacted due to Sandy. More than 200 developments and around 60,000 houses were damaged and were without power for more than two weeks. However, only immediate repair works were done post-Sandy, and the actual resilience works did not begin until late 2016 (NYCHA, 2017). Hurricane Sandy was termed as a watershed event for industries such as building, transportation, construction, power, and utilities (Lacey, 2014).

During the restoration phase flood gates were installed as shown in Figure 5.14(a) & (b) (WNYC, 2016) in front of the buildings to reduce flood waters damaging the power and utility systems as a mitigation measure future the storm surge scenario (NPR, 2017).

Figure 5.14 (a) Floodwall with several 20-pound panels (left) (b) flood wall with type 2 panels covering the basement window(left) [source: (WNYC, 2016)]

FEMA which operates with international Write Your Own (WYO) insurance companies, which are contracted under the NFIP faced litigation, post-hurricane Sandy. In 2017, FEMA reached out to all the 144,000 NFIP policyholders who filed insurance claims and requested to apply for a review if the policyholders thought they had been underpaid or their claim was denied previously. It was also reported that Sandy's litigation costs were higher than the actual insured losses (FEMA, 2017).

After Hurricane Sandy, the Insurance Institute for Business & Home Safety (IBHS) examined the building codes in New York and New Jersey and outlined the critical situation and the vulnerability of the existing infrastructure. Their recommendations suggested that any habitable place and utilities should be at least 3 feet above the 'base flood elevation' (BFE) levels mandated by the National Flood Insurance Program (IBHS, 2012), which is one of the lessons learnt from Hurricane Sandy. Their suggestions further mandated to increase the resilience of the buildings by highlighting the vulnerability of roofs observed during the debris removal post-Hurricane Sandy (IBHS, 2012).

The Rockaway Boardwalk, which was destroyed during 2012, had their reconstruction work carried out and after six years, since Hurricane Sandy and was completed in 2018. The previously used wooden slats were replaced with concrete pilings (Rosenberg et al., 2018). Hurricane Sandy reinforced various mitigation measures to be adopted to survive a future hurricane however their sustaining capacity will only be known when faced with another hurricane in the future.

5.8.5 Summary of key activities and disaster phases during Hurricane Katrina

By reviewing all the key activities observed in the four main phases of the DRM cycle, the following Table 5.6 is generated. The table provides an overall summary of all the actions as key activities measured both from coding and from the document sources.

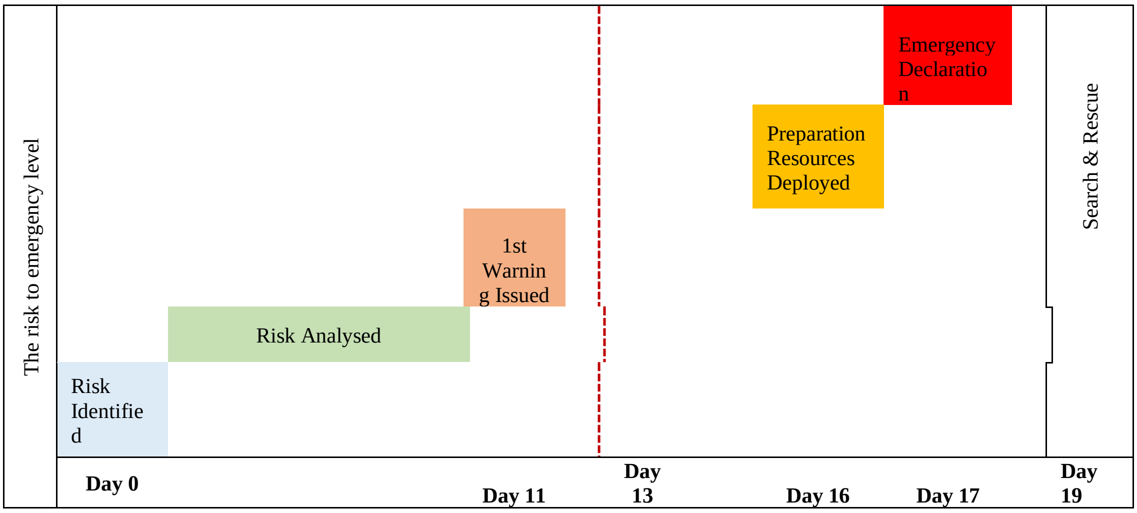
Table 5.6 Summary of the key activities and their achievements observed from Case Study Sandy

	Preparedness	***Response***	***Recovery***	***Mitigation***
Activities achieved	Risk identification Forecasting Monitoring Early warning Risk analysis Declaration of emergency Evacuation Emergency shelter Deployment of resources Hazard assessment Capacity building	Emergency planning Business interruptions Incident stabilization Media influence Communication Response plan Hazard assessment	NGO, INGO, and volunteers Rehabilitation Debris removal Restoration Health care Humanitarian aid Search and rescue Damage assessment	Public awareness & education Stakeholder involvement Land use planning Lessons learnt Technical prevention Multi-agency approach
Activities unachieved/not identified	Coastal protection Technical prevention Community outreach Scenario planning	Vulnerable population Transportation Power and utility Coordination Telecommunication Construction Infrastructure	Reconstruction Insurance Recovery Power and utility	Environment Vulnerable population Multi-agency approach Wetlands Coastal protection Infrastructure Transportation

As mentioned previously, although, the overall key activities were followed corresponding to their disaster phases, key activities could not sustain the magnitude of the storm surge. This implies that though protocol and procedures were followed their sustaining factor was underestimated paving the way to inadequacy at various levels particularly impacting the infrastructure and housing.

Table 5.7 shows the list of major activities carried out as a response during Hurricane Sandy. From the figure, a time delay of eleven days was observed as in-active period but, Sandy was relatively a slow-moving hurricane and this inactive period did not have an impact.

Table 5.7 Overview of the timeline gap and risk emergency level observed during Hurricane Sandy



However, if an earlier change in the hurricane's pathway had occurred, resulting in an earlier landfall, this would have reduced the inactive period (reducing warning time, evacuation, and readiness) could have imposed a severe impact resulting in further possible loss of lives. This should be considered for a future scenario for storm surge adaptation and mitigation.

5.9 Physical damage, market uncertainty factors and loss statistics

The high tides which combined with the extra-tropical hurricane not only produced a storm surge of 12 ft in various locations but also created a significant direct and indirect socioeconomic impact (NHC, 2013; Blake et al., 2013). Some substantial damages created by the storm surge triggered by Hurricane Sandy were the subway system damage as shown in Figure 5.15 (NHC, 2012; NHC, 2013).

The New York Stock Exchange and Nasdaq remained closed for two days. Figure 5.16 shows the image of over a hundred homes that were destroyed by the fire from a short circuit in Breezy Point substation, Queens, one of the New York boroughs (NHC, 2012).

Figure 5.15 Storm surge flooding in New York subway station [source: (NHC, n.d)]

Figure 5.16 Fire explosion which destroyed houses in Breezy Point, NY [source: NOAA/NHC (2012)]

Figure 5.17 Blackout in the Lower Manhattan areas of NY [source: NHC

Figure 5.18 Damaged road on NC12, Rodanthe, NC [source: (NHC (2013)]

Significant explosions at Manhattan power plant, during Hurricane Sandy, destroyed at least half a dozen houses and left millions of New York residents without power (NYC, 2013; Hurricane Sandy Rebuilding Task Force, 2013). Figure 5.17 shows the image captured during the complete 'black-out' of Lower Manhattan's power outage with only the Empire State Building still lit at the upper floors (NHC, 2012).

Figure 5.18 indicates the compounding multi-asset risks and damage that can occur to the exposed assets such as roadways which are crucial transportation routes both in terms of rescue and recovery (NHC, 2013).

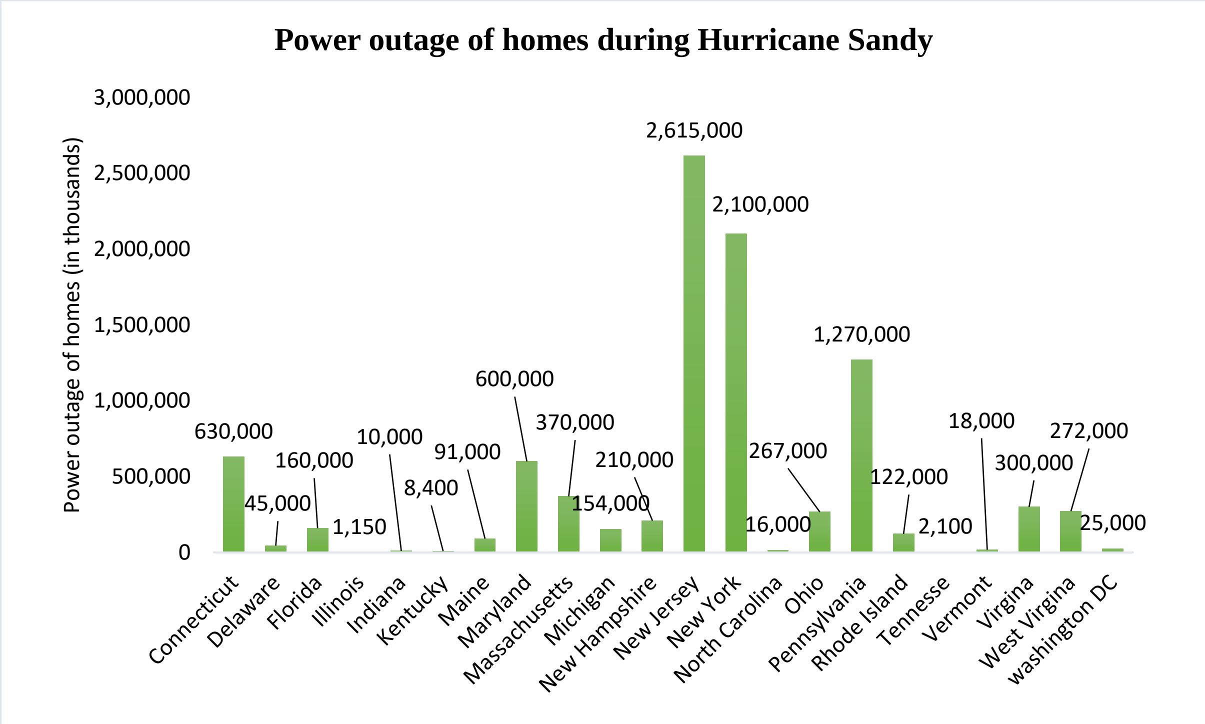


Figure 5.19 Power outage of homes during Hurricane Sandy (2012) estimated by AON Benfield

Figure 5.19 shows AON Benfield's estimation of a power outage during Hurricane Sandy (2012). The power outage led to 50% shutdown in New York and 80% shut down in New Jersey, further delaying the process of pumping out the water from the city (Plett, 2012). The NERC report, claims that approximately 8.35 million people were impacted by the power loss immediately after the landfall on 29 October 2012 (NERC, 2014) Around 650,000 homes were damaged or destroyed (Hurricane Sandy Rebuilding Task Force, 2013) and more than 23,000 businesses and 245,000 non-profit employees were affected by Hurricane Sandy's flood (NYC, 2013).

5.10 Impact of storm surge within the USA

Hurricane Sandy was not the most expensive nor did it lead to the most fatalities in the US hurricane history. However, its significance relied on the convergence of various factors which made the hurricane an extreme weather event.

The storm surge from Hurricane Sandy affected the U.S. coastline from northeast to Mid-Atlantic region including North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York. Figure 5.20 shows the maximum storm surge inundation ranges along the east coast of the USA (Blake et al., 2013). The coastal surge further pushed the water into New York Bay and up the Hudson River, causing substantial flooding in the New Jersey City (FEMA, 2013).

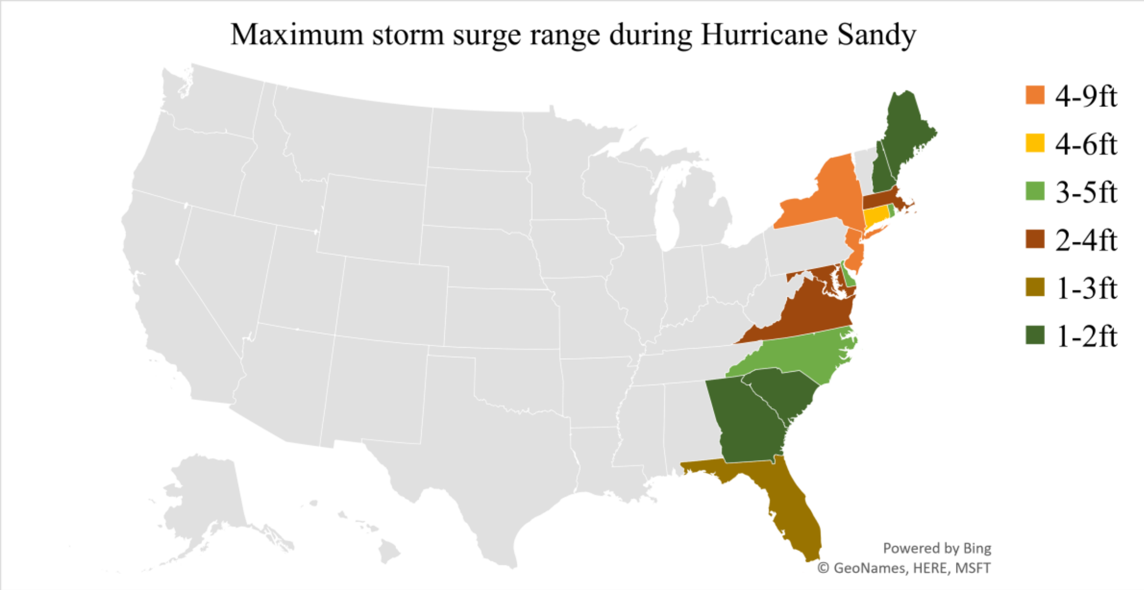


Figure 5.20 Maximum storm surge inundation range (in ft) observed by USGS and NOS tide gauges [source Blake et al., (2013)]

The flooding along the New York Bay inundated thousands of the houses across the boroughs of the New York leaving the city's housing infrastructure either severely damaged or destroyed (Lacey, 2014). Again, residents had to take refuge in attics due to rising waters and insufficient exit or escape routes from attic spaces. There were no in-built support rails or safe location zones on roofs for residents to locate to or hold onto, whilst waiting for rescue.

BoatUS estimated that Sandy destroyed more than 65,000 boats and caused marine-related damage of about $650 million to New York, New Jersey, and Connecticut (Leonard, 2013). Many of the coastal barrier islands further increasing the vulnerability of exposure to future storm surge events (Sopkin et al., 2014). Finally, the extent of the storm surge damage left the Federal teams with lack of capacity in resolving insurance claims which continued for five years after Hurricane Sandy (FEMA, 2017).

5.11 Adaptive measures taken post-Sandy

Post-Hurricane Sandy, the New York City authorities started to implement building and coastal zoning codes for many types of structures including buildings, raised mechanical-electrical-pumping (MEP) systems, apartments, and businesses (NERC, 2014).

Though the city is preparing for the future storm surge flooding or hurricane hazards, new developments were still encouraged both in Brooklyn and Manhattan (NPR, 2017). New York is currently working on improving the livelihood as steps toward mitigation to future storm surge and general flooding scenarios (NYC, n.d.).

- East Side Coastal Resiliency proposed action plans and mitigation measures for future sea-level rise and storm surges.
- 1,511 New Yorker's were provided with jobs again.
- 99% of the city-managed construction was complete (as of September 2019),
- The Rockaway Beach boardwalk reconstructed (NYC, n.d.)

To mitigate the future hurricanes and storm surge threat and in response to Hurricane Sandy, the Army Corps of Engineers considered various technical and coastal preventions. This includes the proposal of New York-New Jersey Harbour and Tributaries (NYNJHAT) coastal storm surge barrier. The construction cost is estimated at around US$ 10-50 billion and the maintenance cost US$ 100 million to 2.5 billion every year (RiverKeeper, 2018).

The T-Groin project in Sea Gate which involved a partnership between the New York City and the Army Corps of Engineers with a budget of US$ 28 million was completed in 2016 as a protection to the Brooklyn communities, one of the five New York boroughs (Rosenberg et al., 2018). Several other projects have also been initiated which includes the 'BIG-U' project constituting Lower Manhattan and East Side Coastal Resiliency projects. Living Breakwaters an architectural design proposed to improve the resiliency in Staten Island. The Red Hook Integrated Flood Protection system, Hunts Point Lifelines, Bullet project in Midland Beach were various projects considered and proposed to improve the city's resiliency toward storm surge and extreme weather events (Rosenberg et al., 2018).

5.12 Additional observations

Some additional observations made during both Hurricane Katrina and Hurricane Sandy which is worthy of mention:

- Design and construction technology whether of new build housing or retrofit measures did not cater for residents requiring exiting via attic zones due to rapidly rising water levels,
- Roofs were not designed or retrofitted for 'safe-haven' zones whilst awaiting rescue or for awaiting waters to recede,
- Building codes were insufficient both for structural requirements as resilience to storm surge and buildings and their roof integrity,

- Location of power utilities or in supporting continuity of power was insufficient to cope with flooding and storm surge, not only impacting during the storm but significantly impeding the recovery phase,
- The design, location and construction of water treatment services did not have sufficient resilience to cater for flooding and storm surge and prevent contamination of water due to flood overflow,
- There appears to be a dislocation between the planning and authorisation of homes in certain areas which could be prone to such flooding and the insurance coverage available.

5.13 Summary

This chapter discussed two significant events and studied various key activities corresponding to their disaster risk management phases. The case studies Hurricane Katrina and Sandy highlighted how developed countries such as the USA is not exempted during emergencies and exhibited basic issues such as the poor dissemination of early warning systems, lack of coordination and communication. Observations during Katrina especially the evacuation, early warning, failure of communication and coordination directly resulted in the loss of 1,800 lives. Failure of the pumping station which left the New Orleans city being flooded was a clear outcome of poor regulation and preparedness. Despite the economic growth or technical resources, developed countries were not exempted from the overwhelming effects of storm surge damage and loss of life. Instead, they endured severe infrastructure damage and failed during situational awareness highlighting the underlying potential issues for developed countries. This emphasises how a framework, if put in place, could potentially have supported the scenario planning, ensuring stakeholders involvement including government, regulators, and communities. Further analysis of the key activities from coding observed is discussed in Chapter 8 which is supported for the DAMSS framework development.

CHAPTER 6

SIGNIFICANT PACIFIC AND INDIAN OCEAN STORM SURGE EVENTS

Case studies: Cyclone Nargis and Typhoon Haiyan

6.1 Introduction

This chapter examines the disaster phases and the impacts caused by two of the most significant tropical cyclones which occurred in the North Indian Ocean and North West Pacific Ocean. The first case discusses Cyclone Nargis which occurred during the 2008 Indian Ocean Cyclone season. The second case examines the Super-typhoon Haiyan regionally named as Typhoon Yolanda, which was the twenty-third officially named typhoon of the 2013 Pacific typhoon season.

6.2 Cyclone Nargis (2008): origin and background

On 27 April 2008, the Indian Meteorological Department (IMD), identified a low-pressure system gradually forming to a tropical depression (Hurricane Science, 2008). At this stage, Burmese government received a weather warning from the Asian Disaster Preparedness Centre (ADPC) (Suwanvanichkij et al., 2009).

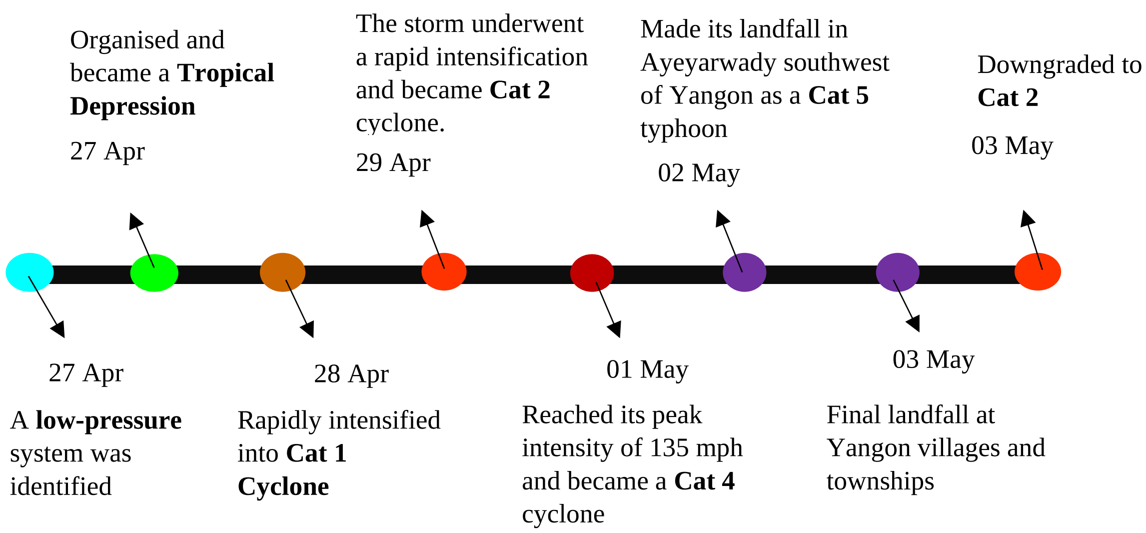


Figure 6.1 Timeline of Cyclone Nargis (27 Apr- 03 May 2008) [source: Hurricane Science (2008)]

This warning was received in addition to the warning issued by the IMD. On 28 April 2008, the depression was observed near the centre of Bay of Bengal and strengthened to an equivalent of Category 1 cyclone in the Saffir-Simpson Wind Hurricane Scale

(SSWHS) as shown in Figure 6.1 (Fritz et al., 2009). Despite the storm's movement being almost stationary over the warm waters of the Bay of Bengal, but continued to intensify and by early 29 April, the storm upgraded to a Category 2 cyclone with 161 km/h (100 mph) sustained wind speed (Hurricane Science, 2008). The first rapid intensification of the cyclone took place on the 01 May 2008. As the storm was heading towards the east of Burma, peak intensity of 217 km/h (135 mph) was reached, which is equivalent to a Category 4 in the SSWHS (Hurricane Science, 2008).

The cyclone made its landfall from 02-03 May 2008, in the Ayeyarwady (Irrawaddy) delta, approximately 250 kilometres southwest of Yangon (Rangoon) as a Category 3 cyclone (Tripartite Core Group, 2010). The cyclone then began moving inland and reached Yangon where the cyclone downgraded further to Category 1 after 12 hours, since the first landfall (Fritz et al., 2009). Final landfall at the Yangon villages as Category 1 cyclone affecting almost 50 townships particularly impacting Yangon and interior

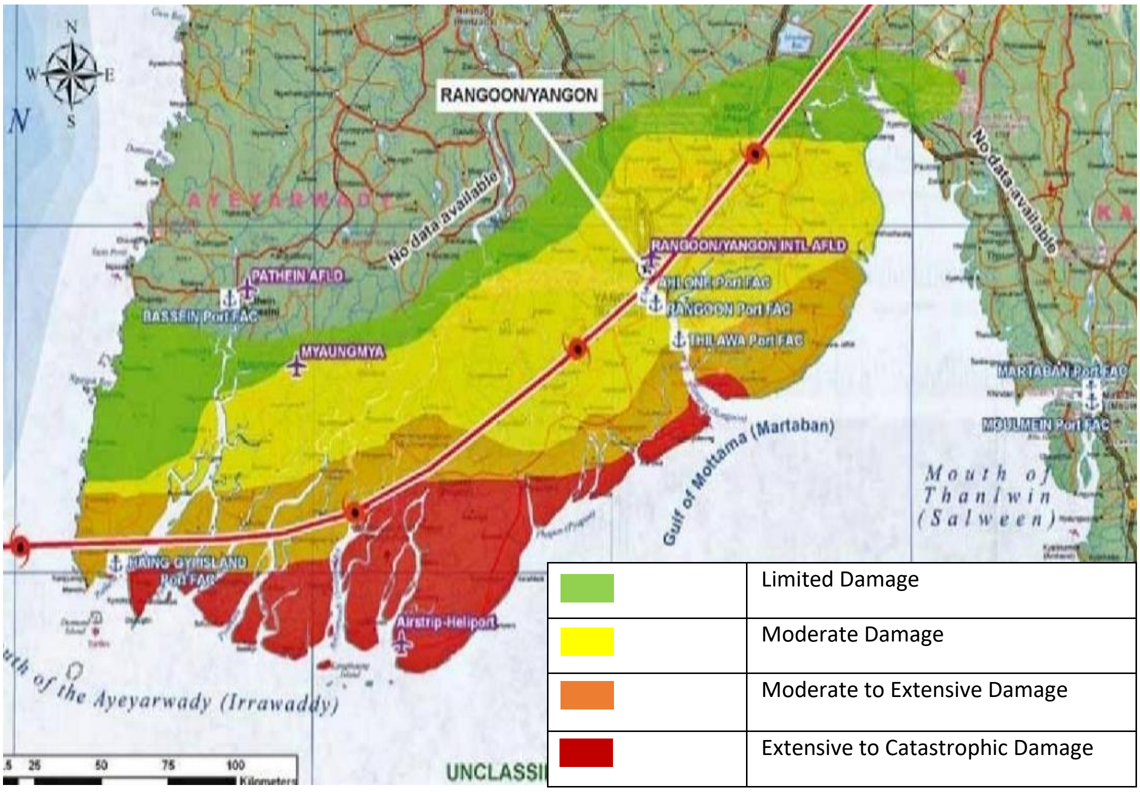


Figure 6.2 Landfall of Cyclone Nargis in Myanmar [source: Relief Web (2008)]

divisions of the Ayeyarwady delta as shown in Figure 6.2 (ReliefWeb, 2008; Martin & Margesson, 2008). The intensity of the storm was shown in Figure 6.2 using a colour coded scheme affecting various locations of Myanmar. From Figure 6.2, the impact of the storm surge inundation, which had reached several miles inland is noticeably impacting the delta regions and demonstrates their vulnerability. Appendix B includes the author's summary of Cyclone Nargis's predicted path and the structural changes of the cyclone.

6.3 The disaster phases of Cyclone Nargis

6.3.1 Preparedness within Myanmar

International forecasters, IMD, ADPC and Joint Typhoon Warning Centre (JTWC) alerted Myanmar regarding the approaching storm and its development as a potential risk. The alerts were communicated to the Myanmar authorities a week in-advance of Cyclone Nargis's landfall (Orozco, 2017). Despite being alerted by various sources of forecasters, no prior warnings were issued immediately by the government of Myanmar. A warning was finally issued in less than 24 hours before the landfall. But neither the emergency shelters were set-up nor instruction on moving to safe higher grounds were issued in preparation for the approaching hazard (Fritz et al., 2009).

Figure 6.3(a) Damage in the Ayeyarwady Delta Division in Myanmar [source: Zaw (2009)]

Due to the lack of awareness of the hazard, the coastal communities were reported to have ignored the final warnings issued by the officials just before the landfall (Fritz et al., 2009). This clearly highlights how a lack of awareness about the storm surge hazard was observed not only among the victims but also among the officials and emergency responders. Negligence of the early warning system (EWS) and evacuation to its entirety was observed (Orozco, 2017). As such the population in the path of the cyclone were highly exposed and vulnerable and the severity of the impact on these communities is shown by the example image as shown in Figure 6.3(a).

Habitat sites near the coast within low elevated coastal zones, where the landfall occurred, were initially observed to have fewer fatalities than that observed further inland (Fritz et al., 2009). This was noted as a possible result of the 'funnel-effect of storm surge'. As discussed in previous chapters the funnel-effect is caused when the storm surge enters the delta estuaries and rivers and with the narrowing of the river width with increasing distance from the coast, the storm surge increases in height, volume intensity, speed, and strength.

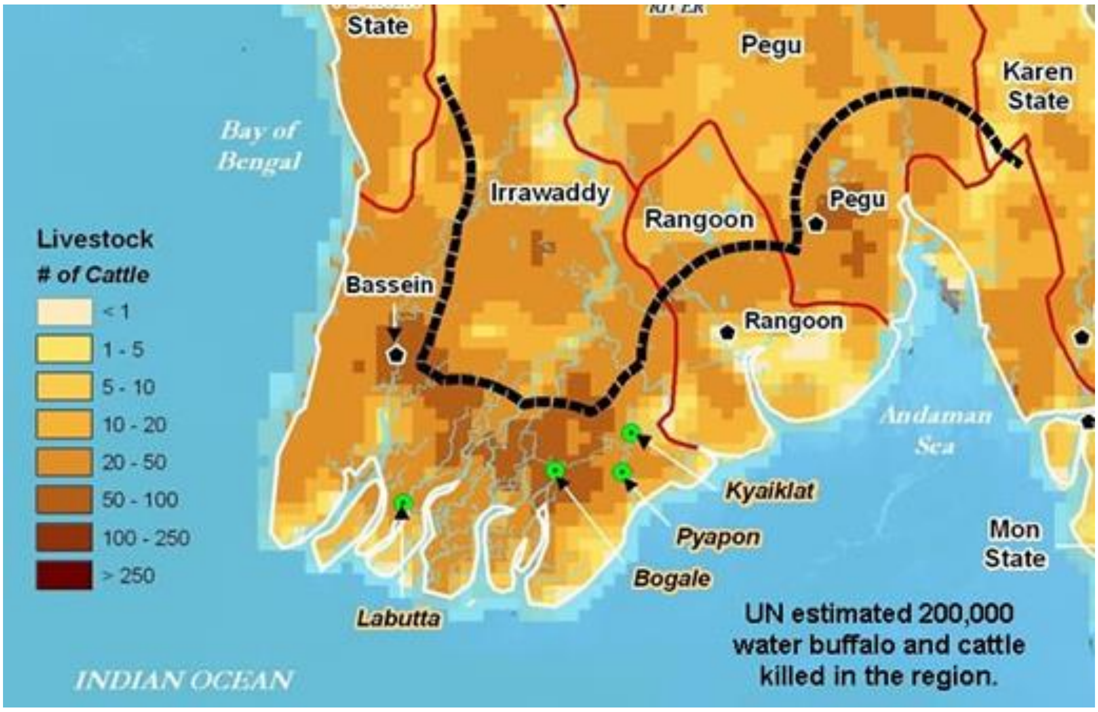


Figure 6.3(b) Livestock damage from Cyclone Nargis [source: Shean (2008)]

Figure 6.3(b) displays the impact on cattle and water buffalo deaths near internal townships e.g., Bogale some 30-50 km from the ocean coastline due to funnel-effect of the storm surge. The neighbouring region of the Irrawaddy delta were impacted by the Indian Ocean Tsunami in 2005 and the aftermath of the tsunami led to the initiation of two emergency shelters in operation and general awareness of the coastal extremities. However, in the Irrawaddy delta region, Nargis was the first cyclone to make an impact and hence the population in this delta region had no previous experience (Suwanvanichkij et al., 2009). This resulted in the lack of knowledge of the potential storm surge hazard. It was identified that only two emergency shelters were in operation, since the previous tsunami impact, but these were located far from the Irrawaddy delta region.

Telecommunications infrastructure was very limited in Myanmar even before the occurrence of Cyclone Nargis. The Burmese military junta had imposed strict restrictions on the usage of communication devices in general and usage of satellite phones were considered illegal and residents were penalised for illegal possession of satellite phones. Additionally, the usage of mobile phones was considered as an expensive expenditure by most of the Burmese residents. In this manner, the residents were generally isolated from mobile phones and were left with limited communication options. Moreover, the delta region had even fewer telephone lines, and general commodities including the newspapers or periodicals would reach the delta town only by canoe and boats from Central Yangon (Mohammed, 2009; Suwanvanichkij et al., 2009). These restrictions on the usage of communication devices barred the flow of communication, leaving the residents to solely rely on a single communication mechanism from the government for any announcements or warnings (Suwanvanichkij et al., 2009). This situation depicts the pre-existing regional conditions and the limitation in the Irrawaddy delta which was exacerbated by the landfall of Cyclone Nargis while highlighting the absence of strategic emergency response plans, lack of preparedness and public awareness of such hazards.

6.3.2 Response within Myanmar

According to Post Nargis Joint Assessment (PONJA), the officially confirmed death toll was 84,537; around 53,836 were displaced and 19,359 were injured. (Turner et al., 2008). Whilst the government's negligence and lack of pre-emptive response were exhibited in phase one (preparedness stage), the emergency relief and recovery assistance were provided by the government immediately after the landfall of Nargis. The Myanmar Red Cross Society (MRCS) worked as auxiliary support to the government's response teams (Red Cross Society, 2009).

According to the Tripartite Core Group (2010), the degree of the impact made by Cyclone Nargis was beyond the adaptive capacity of Burmese government (Red Cross Society, 2009), and therefore, a decision was made by the government towards requisition of international and local humanitarian assistance. Despite, the request for international assistance was initiated in a briefing with the United Nations on the 5 May 2008, no additional steps were taken to communicate or coordinate the visa procedures allowing the international organization to access the cyclone impacted areas. The combination of lack of organisational capacities within the government officials and authorities of Myanmar; and the lack of experience in negotiation and coordination issues with the international agencies complicated the Phase-3 recovery stage (Office of the Coordination of Humanitarian Affairs, 2008).

Figure 6.4 Satellite images of Myanmar village taken in 2002 (left) and same village after the storm surge (7 May 2008) (right) [source: NASA's satellite image]

Figure 6.4 shows the extent of the damage to a village within the Ayeyarwady delta in comparison with the previously taken image in the year 2002 before Cyclone Nargis. The government was overwhelmed in providing immediate assistance for the impacted communities.

The international non-governmental organisations supported with 56% of aid deliveries and the local non-governmental organisations supported with 19% of aid deliveries to the affected victims. A further 16% of aid deliveries were supported by private multifaceted international organisations with remaining being covered by the government (Tripartite Core Group, 2010). The extended support from various international and local NGO’s and contribution of the organisations showed the capacity of stakeholder involvement and the benefits of establishing multi-agency approach in supporting emergency, especially for developing and least-developed countries (LDC).

The City of Yangon, which is the largest city in Myanmar, was directly hit with a 200 kph (124 mph) winds causing adverse damage such as shutting down the city’s power entirely, obstruction of roads and hampering the already limited telecommunication system. But the storm surge flooding was primarily responsible for extensive loss of lives, inundation of farmlands, and a further saltwater intrusion into most freshwater sources leaving the delta region in destruction. The debris further truncated communication and power lines delaying the recovery (Office of the Coordination of Humanitarian Affairs, 2008; IFRC, 2010). Temporary operational hubs were set-up in six of the locations including Yangon, to expedite the search and rescue, and communicate, coordinate the relief supports from various sources (Office of the Coordination of Humanitarian Affairs, 2008). The US Department of Defence (DOD) assisted in arranging the emergency transportation and logistics of relief supplies during response and recovery phases. The DOD which operates aircraft between Thailand and Burma provided further emergency relief supplies such as food, water, and emergency shelter kits (GAO, 2011). According to the report of ALNAP (2008), an international humanitarian network system, the restriction, and limitations of access to resources existed throughout the response phase of Nargis. The international and local capacities who operated in the field, organising the resources, identified that the request for resources was scattered whilst the disbursal of resources was narrowed to filtered victims (ALNAP, 2008). Although, this may be an effect of the country's bureaucracy and military governance, but when viewed in terms of incident management this indicates negligence in response.

On 05 May 2008, the Burmese authorities announced, that the previously scheduled referendum would continue to take place as planned, regardless of the landfall of Cyclone Nargis on the 02– 03 May 2008, and amid the relief works being carried out (Martin & Margesson, 2008). It was observed that this referendum impacted the entry and exit to the region making the recovery an even more challenging process. Many international and national agencies who extended their support with relief-aids were stopped and, in some cases, were deported (Martin & Margesson, 2008; Tripartite Core Group, 2010). Media reporters of international news networks who were reporting the situation from the field were also deported (Humanity House, 2017).

The Burmese authorities further restricted the access to international disaster assessment teams, including the UN relief planes which landed in Yangon. Due to these restrictions, the UN and other international agencies and organisations were not able to assess the preliminary damage to further disburse relief-aid or funds to the victims (Suwanvanichkij et al., 2009). The first US plane allowed was on the 11 May 2008 and even at this point, the US aid workers were still restricted access (Suwanvanichkij et al., 2009). The Ayeyarwady delta which functions as the country's core and the rich agricultural economy was also considered as one of the least developed regions in Southeast Asia. The rich agricultural economy was damaged from the storm surge inundation and the recovery process of reviving from this crucial damage, improving the livelihoods, and rehabilitating the agricultural resources became a predominant key focus of this phase (ALNAP, 2008).

6.3.3 Recovery within Myanmar

The delta region was one of the hardest-hit areas in Myanmar yet access to these areas was granted between 09-23 August 2008 for the detailed damage assessment. The access for further recovery purposes was gained only after three months, since the landfall of Nargis (Fritz et al., 2009). After gaining access to the delta region, the recovery and relief support was delivered by various local and international NGO's (Government of Myanmar, IRP & ISDR, 2008).

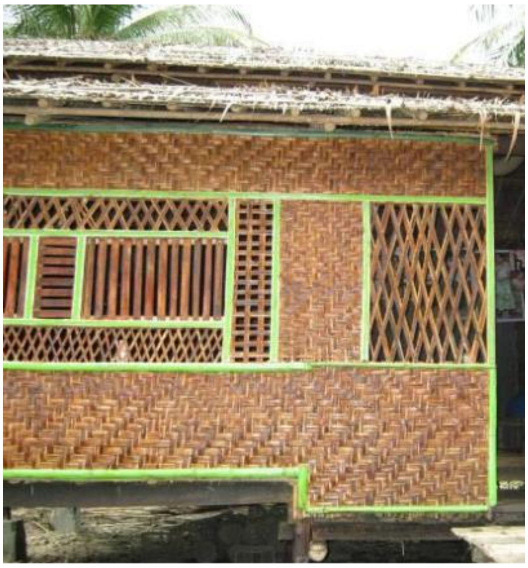


Figure 6.5(a) Temporary shelter of 16,264 houses built for families living in sub-standard shelter Photo: Yin Yin Myint MRCS [source: IFRC (2011)]

Figure 6.5(b) Image showing timber-framed housing with corner-bracing [source: IFRC (2011)]

The International Federation of Red Cross (IFRC) and Red Crescent Societies assisted in various areas such as improving livelihoods, health and sanitation, psychological support to expedite the recovery phase. These were fulfilled through nine hubs across thirteen cyclone-affected townships and temporary shelters for those victims were provided by the IFRC (Red Cross Society, 2009) as shown in Figure 6.5(a). Figure 6.5(b) shows how enhanced timber used with corner-bracing (IFRC, 2011) for better building. According to the UN, the overall response by the government of Myanmar was observed to be slower, by stating that, 'out of 2.4 million survivors only 500,000 had received the international assistance' which is just one-fifth of the survivors being provided with relief (McCurry, 2008). This was observed due to the various intervals of the restrictions imposed on both international and national relief workers, to assess and access the affected areas, which had a substantial impact on recovery phases. The Red Cross societies which provided immediate relief support working in correspondence with the government were restricted access at a later stage (Red Cross Society, 2009). As per the Red Cross, this may be possibly due to the attention these international organisations get from the media, who were reporting the field-situation of the massive death toll and the government's response and recovery, which was not welcomed by the government (Red Cross Society, 2009). The significance of the media and their role in post-disaster communications to inhabitants and externals is vital and this is an area of recommendation for the future, to enhance the stakeholder participation of media.

The Burmese authorities also imposed restrictions on NGO and organisations who had established prior relationships and access in various places within Myanmar. This was experienced by an UK-based aid organisation, who had previously established collaborations with local authorities of Myanmar for fourteen years, were comprehended, that their previous associations failed to work post-cyclone Nargis (McCurry, 2008). Similar issues were also faced by the United Nations, who stated that 'they did not have an easy-going relationship with the Government of Myanmar and their authorities. However, they had the advantage of being less restricted compared to other international organisations. In addition to the internal restrictions, the external pressure from the governments of western countries led to ongoing negotiations to gain access, further hampered the recovery activities (Fan, 2013).

According to the report of Shelter Organisation, the participation, and the involvement of the communities during the recovery, reconstruction, and rebuilding phase favoured phase 3-recovery stage. They further participated in various upgrading projects such as rebuilding roads, footpaths, restoration of coastal flood protection dykes, embankments, and pavements. The communities together with the support of local NGO's, constructed small bridges and their renovations (Shelter Org, 2010). Positively, key activities such as community outreach and community participation were recognized during the recovery phase. Community-partnered recovery efforts continued for two consecutive year supporting with the assistance required, while enhancing public awareness, capacity building and developing community resilience for a future scenario (IFRC, 2010).

The United Nations High Commissioner for Refugees (UNHCR) and the United Nations Human Settlements Programme (UN-HABITAT) supported the communities affected by Nargis during their recovery stage (Government of Myanmar, IRP & ISDR, 2008). The land emergency planning experts and the land use planners together worked on with the UNHCR and UN-HABITAT's joint public awareness campaigns on new settlements in the delta region. Around 3,000 displaced families benefited from this combined effort.

They further focused on the employment opportunities in the new settlement areas as a measure towards improving livelihoods (Government of Myanmar, IRP & ISDR, 2008).

6.3.4 Mitigation within Myanmar

After the landfall of Cyclone Nargis, the ASEAN communicated and coordinated the response and recovery between the Government of Myanmar and other international organisations. The Tripartite Core Group (TCG) was developed and brought into enactment to follow the response of the Cyclone Nargis. The prime aim of the TCG was to improve the logistics, policy, and governance of humanitarian response in the Ayeyarwady delta region (Kurtzer, 2009).

Post-cyclone measures to mitigate future scenarios were carried out in the affected communities and villages. The TCG observed that these communities were offered with training, provision of equipment such as loudspeakers and flags to raise alarm signalling the intensity of cyclones (Tripartite Core Group, 2010). TCG also emphasised that, out of forty villages affected by the Cyclone Nargis, only six villages have been equipped with multi-purpose emergency shelters. These shelters were designed to operate as schools and clinics during non-emergency situations and act as evacuation shelters during emergencies. Although, the shelter set-up was considered as a step to progression, the re-enforcing measures along the delta were less effective than required and were observed to be at a minimal level even after two years, since the landfall of Nargis (Tripartite Core Group, 2010).

The ASEAN remarked that the humanitarian missions in Myanmar following Cyclone Nargis was challenging. Difficulties in liaising between the government and the ASEAN committee was also observed. This was especially affecting the 'build back better' scheme, which was aimed to ensure the request of developing 'new humanitarian partnership models' particularly for Southeast Asian countries which are prone to disasters (Fan, 2013). The US Government of Accountability Office (GAO) evaluated the reports of various national and international NGO's, and the UN agencies. The outcome of the evaluation addressed the challenges in key thematic areas such as coordination, implementation, access to NGO's, resources, and capacity building (GAO, 2011).

The GAO (2011) further remarked, key lessons learned from Nargis should be considered as useful insights for future mitigation. Observing various phases of Cyclone Nargis, more than the existing conditions such as poor infrastructure, limited telecommunication services, lack of experienced professionals, those interim restrictions complicated the response and recovery phases. The poor construction of the housing units across the entire delta region, was not only highlights the lack of protection, but also shows how debris from destruction of so many homes also further impacted the recovery.

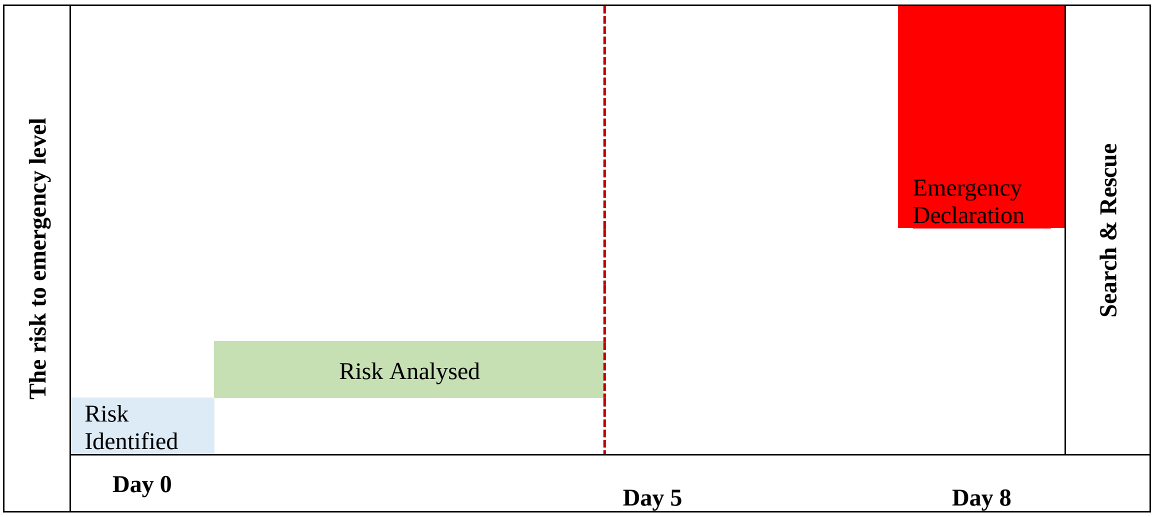
6.3.5 Summary of key activities and disaster phases during Cyclone Nargis

Table 6.1 Summary of the key activities and their achievements observed from Case Study Nargis

	Preparedness	*Response*	*Recovery*	*Mitigation*
Activities achieved	Monitoring Declaration of emergency Early warning	Humanitarian aid NGO and volunteers Power and utility Transportation Search and rescue	Damage assessment Health care Improving livelihoods Rehabilitation Restoration	Land use planning Lessons learnt Training and exercise Public awareness and education Community outreach Hazard assessment
Activities unachieved/not identified	Risk identification Emergency planning Coastal protection Communication Community outreach Deployment of resources Public awareness and education Evacuation Training and exercise Technical prevention Risk analysis Scenario planning Risk assessment	Emergency shelter Incident stabilisation Communication Coordination Telecommunication Vulnerable population Coastal communities Evacuation Construction	Organisational capacities Infrastructure Reconstruction Recovery	Environment Capacity building Communication Coastal protection Stakeholder involvement Strategic alternative approach Multi-agency approach Technical prevention Vulnerable population Wetland mitigation

The key activities observed in the four main phases of the DRM cycle were summarised based on the activities achieved and those not achieved as listed in Table 6.1. Observation of the key activities was derived from the coding and document sources. The key activities that are not achieved as shown in Table 6.1 are due to lack of early warning system, evacuation plans, poor communications, and unawareness of the hazard. The political instability and the restrictions imposed by the military Junta rule hampered many of the emergency management protocols from being executed. This became the primary cause for the failure of many key activities from being achieved within the DRM phases. The key activities shown in Table 6.2 are generated to understand if there were any identified delays during the disaster phases. As illustrated previously in Figure 6.1, the timeline diagram of Nargis, it is evident that storm risk was detected eight days in-advance, and they only had five days between risk identification and landfall as shown in Table 6.2.

Table 6.2 Overview of the timeline gap and risk emergency level observed during Cyclone Nargis



The dynamics and intensity of the cyclone was low-level intensity at its beginning. Within a very short period, the storm intensified significantly (partly due to the warm Indian Ocean). The intensification over the river deltas then created a strong funnel-effect which increased *(i) the volumetric force* and (ii) the *velocity of the storm surge*. Both the effects did not provide the residents with sufficient time to react. This implies that return of the similar cyclone in the same delta region in the future, without having mitigated the currently identified gaps, then the country would suffer significant impacts much worse than that happened during Cyclone Nargis.

6.4 Physical damage and loss statistics within Myanmar

The cyclone affected 2.4 million people (Government of Myanmar, IRP & ISDR, 2008) in Myanmar and was estimated to have caused economic damage of US$ 10 billion (2008 USD) (Hurricane Science, 2008). According to the estimation provided by the IFRC Societies, referring to the data collated from various other aid organisations, the death toll was higher than 128,000 people. But the assessment done by the Australian Government (2011), estimated that at least 140,000 people along with the coastal communities Ayeyarwady (Irrawaddy) Delta and southern Yangon Division were killed. Figure 6.6 shows the aerial view of the major agricultural damage by the 16.4 ft (5m) storm surge flooding.

Figure 6.6 Agricultural damage in the Ayeyarwady delta region post-Nargis [source: Humanity House (2017)]

The rapid increase in the price of water and the increase in the price of rice by 60% in three days from landfall are some immediate aftermath effects (ALNAP, 2008). Around 42,194 houses in the Dedaye Township were destroyed from Cyclone Nargis (Shelter Org, 2010). A further 160,000 people were affected in the Dedaye Township. Roughly 800,000 houses were either destroyed or suffered severe damage, and more than 1,400 schools were destroyed and around 783,000 hectares of farmland was flooded (Government of Myanmar, IRP & ISDR, 2008).

6.5 Impact of storm surge within Myanmar

The storm surge of 16 ft (4.9 m) was funnelled through most of the creeks and channels that stretched further inland in the Ayeyarwady delta region when Cyclone Nargis made a landfall. The high-water marks of the storm surge in certain locations were observed to have surpassed even the tsunami wave run-up levels within Myanmar (Fritz et al., 2009). The storm surge flooding inundated the city of Yangon with an estimated range of 40-50 km inland (Hurricane Science, 2008). Saltwater intrusion encroached around 43% of the freshwater bodies (Mohammed, 2009). Farmland in the coastal communities around 38,000 hectares of natural and replanted mangroves was destroyed and around 63% of the paddy fields were inundated as shown in Figure 6.7.

Figure 6.7 Saltwater intrusion from storm surge flooding during Cyclone Nargis [image source: Evan Schneider]

The structures in the low-lying delta region suffered 90-95 % of damage due to coastal surge (Office of the Coordination of Humanitarian Affairs, 2008). According to the Forest Resource Environment Development and Conservation Association (FREDA), the delta region was observed with 75% of loss in the mangroves, which would have possibly acted as a natural buffer in storm surge attenuation, before the landfall of Cyclone Nargis (Mohammed, 2009). The loss of mangroves observed in Myanmar emphasises the diminishing focus on the wetland mitigation exhibited by these developing countries. Despite the country's adaptive capacity, the wetland mitigation should be considered for a natural and cost-effective mitigation measure for storm surge attenuation in the future. Moreover, public awareness on increasing the wetland mitigation for storm surge should also be recommended for future storm adaptation and mitigation.

6.6 Adaptive measures taken over post-Nargis

The Government of Myanmar through its National Disaster Preparedness Central Committee (NDPCC) activated the 'Programme for Reconstruction of areas affected by Cyclone Nargis. Further, the implementation plans for future preparedness and protection from future natural disasters were also outlined (Mohammed, 2009) The Post-Nargis Recovery and Preparedness Plan (PONREPP), together with the Myanmar Government and the international communities issued a three-year framework to support the recovery efforts post Cyclone Nargis. The framework aims to cover three key themes mainly productive lives, healthy lives, and protective lives as a complete approach towards improving livelihoods (Government of Myanmar, IRP & ISDR, 2008; Mohammed, 2009).

Even after the Indian Ocean Tsunami which impacted Myanmar in 2005, the land use planning divisions continues to have many settlements still in the low coastal elevated zones (LCEZ). However, post-Cyclone Nargis and due to the extensive death toll, the planning division focused on building new villages, advising relocation of affected communities where necessary. As most of the resettlement works were regulated by the Government of Myanmar, they partnered with international planning agencies and adopted their already established plans and practices for new settlements in LCEZ's (Government of Myanmar, IRP & ISDR, 2008).

As a positive outcome, women participation was majorly observed during the recovery and the rebuilding phase and played a vital role in supporting restoration activities. During the reconstruction activities in most of the villages, the involvement of the women taking up various roles such as treasurer, procurement of transportation and construction materials, supervisor and monitoring processes, funds management were widely recognised by the local and international NGO's. The combined community support contributed towards the improvement of livelihoods, mental health, and wellbeing of the communities through enhanced public participation (Shelter Org, 2010).

6.7 Super-Typhoon Haiyan: origin and background

A low-pressure tropical depression originated in the Pacific Ocean, from the east of Micronesia on the 02 November 2013 and was confirmed by the Japan Meteorological Agency (JMA) on the 03 November 2013. As it approached the Philippines (NDRRMC, 2015), on the 06 November, the storm was officially named as Typhoon Haiyan (regionally referred to as Typhoon Yolanda) by the Philippines Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). Typhoon Haiyan was the 23rd officially named storm of the 2013 Pacific typhoon season. On the 08 November at 2040 UTC, the typhoon made its first landfall over Guiuan, Eastern Samar region. The second landfall took place over Tolosa, Leyte at 2300 UTC (NDRRMC, 2015). The total duration of the typhoon lasted for 30 hours in the Philippines while making all its consecutive landfalls within short intervals. The PAGASA observed a maximum of 312 km/ph (194 mph) during its landfall (PAGASA, 2013). The timeline of Super-Typhoon Haiyan as indicated in Figure 6.8 shows the constricted rapid intensification and the magnitude that was maintained during the peak four days with six landfalls at various islands in the Philippines.

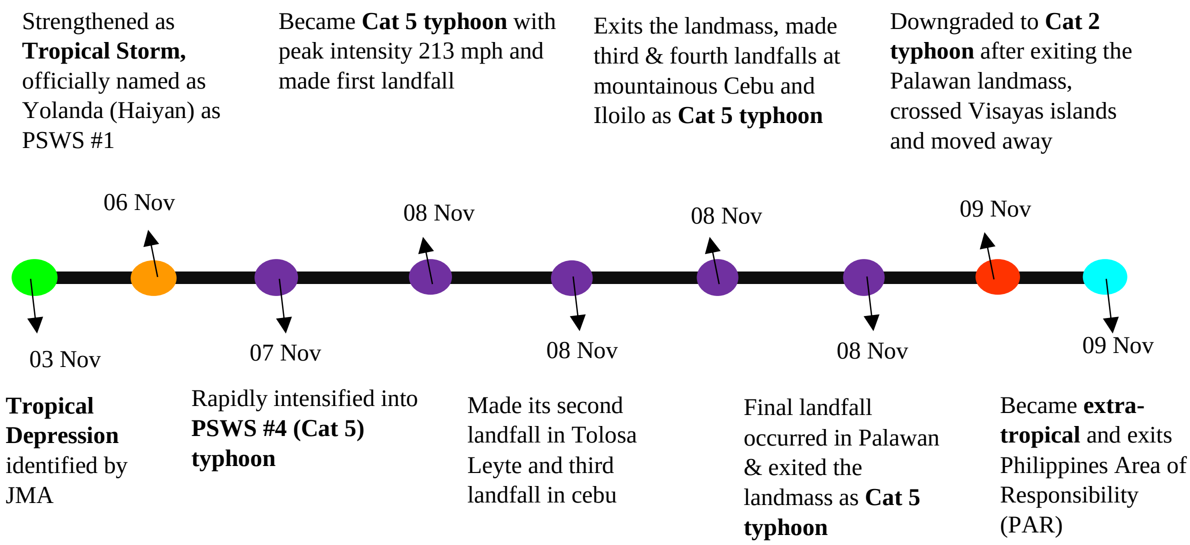


Figure 6.8 Timeline of Super Typhoon Haiyan (03-09 November 2013) [source: NDRRMC (2015)]

Figure 6.9 shows the forecasted path of Typhoon Haiyan in the Philippines obtained from the Office of the Presidential Assistant for Rehabilitation and Recovery (PARR). Table 6.3 (a) lists the landfall history of Typhoon Haiyan.

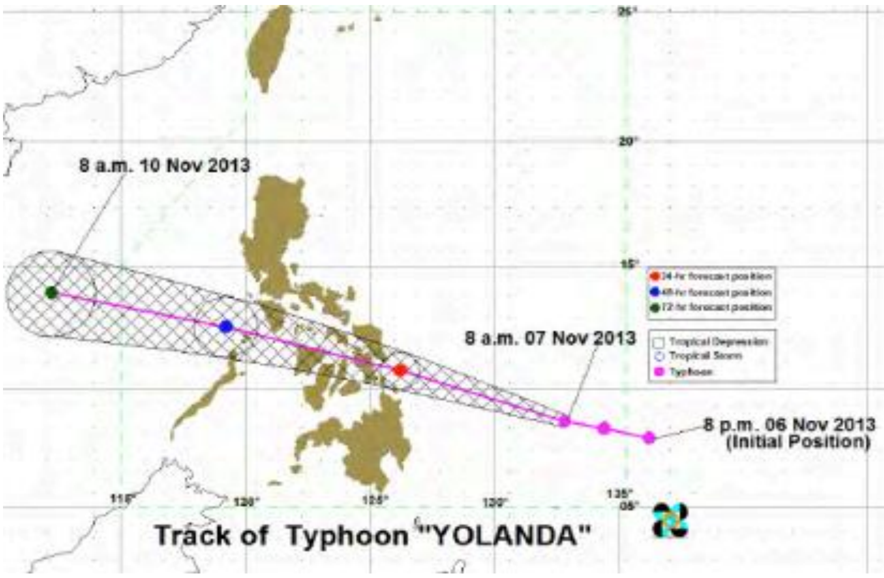


Figure 6.9 Super-Typhoon Haiyan predicted track in the PAR (2013) [source: PAGASA (2013)]

The Public Storm Warning Signals (PSWS) is a scale ranging from PSWS (#1 - #4) listed in Table 6.3(b) and is used by PAGASA to communicate the typhoon strength and wind speed. The scale is similar, like the National Hurricane Centre's (NHCs) Saffir-Simpson Wind Hurricane Scale (SSWHS) (NDRRMC, 2015).

Table 6.3(a) Landfall synopsis of Typhoon Haiyan (2013) [source: NDRRMC (2015)]

Date	**Time (UTC)**	**Landfall Location**	**Country**	**Category during landfall**	**Wind Speed (mph)**
08 Nov	4.40 am	Guiuan, eastern Samar	Philippines	PSWS#4 (Cat 5)	185
08 Nov	7.00 am	Toloso, Leyte	Philippines	PSWS#4	
08 Nov	9.40 am	Daanbantayan, Cebu	Philippines	PSWS#4	165
08 Nov	10.40 am	Bantayan Island, Cebu	Philippines	PSWS#4	
08 Nov	12.00 pm	Concepcion, Iloilo	Philippines	PSWS#4	155
08 Nov	8.00 pm	Busuanga, Palawan	Philippines	PSWS#4	145

Table 6.3(b) The Public Storm Warning Signals (PSWS) scale utilised by PAGASA [source: PAGASA (2013)]

Category during landfall	**Wind Speed (kmph)**	**Wind Speed (mph)**	**Expected time before landfall (in hours)**
PSWS#1	30-60	18 -37	36
PSWS#2	60-100	37-62	24
PSWS#3	100-185	62-115	18
PSWS#4	>185	>115	12

Appendix B includes the author's summary of super-typhoon Haiyan's predicted or forecasted path; typhoons structure changes adapted from PAGASA's report. As claimed by PAGASA, Haiyan was possibly the most powerful Category 5 typhoon in the Saffir-Simpson Wind Hurricane Scale (SSWHS) with 251 km/h of sustained winds ever recorded in the Pacific region (The U.N., 2013). The Japan Meteorological Agency (JMA) had measured a one-minute of sustained wind speed at 315 km/h (195 mph) which further confirms the possibility of Haiyan being one of the most powerful storms recorded (Neussner, 2014; NDRRMC, 2015).

6.8 The disaster phases of Super-Typhoon Haiyan

6.8.1 Preparedness within the Philippines

The Joint Research Centre of the European Union warned PAGASA, days in-advance before the landfall date, 06 November 2013. Red alert status areas were monitored closely, and weather bulletins as early warning were issued continuously to alert the residents about the typhoon's path, intensity, and predicted areas to be impacted (NDRRMC, 2014; PAGASA, 2013). The Philippines government's national and local response teams initiated emergency protocols by taking pre-emptive measures and setting up 109 evacuation centers across 22 provinces. The emergency responders evacuated around 125,600 people to these emergency shelters which were deployed in-advance including relief supplies (The U.N., 2013). As Typhoon Haiyan was developing into a major Category 5 storm, the country's readiness was critically challenged during the preparedness stage which is the initial phase within disaster management. The responders had to use force in some coastal communities where the residents did not follow the evacuation orders (NDRRMC, 2014).

Neussner (2014) stated that the official storm surge hazard map used by PAGASA for forecasting, was an underestimation of the surge inundation areas. The map further did not include surge heights of 22.9 ft (7 m) and therefore, correlation error occurred in the predicted surge levels and reliability inaccuracies were identified. As per Neussner's claim, PAGASA and the NDRRMC gave greater emphasis to rainfall, flooding and mudslides and issued warnings correspondingly and gave lesser importance to storm surge warnings (Neussner, 2014). With risks being identified and analysed days in-advance, the emergency responders failed to communicate and warn the residents about the magnitude of the storm surge. This may be because either the risk was underestimated, or it was not understood properly and interpreted to the residents in their local language (dialect). According to NDRRMC's (2014) report, the team members of PAGASA and its emergency responders themselves did not evacuate the high-risk zones and stayed nearshore despite the warning and became victims themselves. Both the coastal residents and the emergency responders acknowledged that they were not familiar with the term 'storm surge' communicated by the authorities (NDRRMC, 2015; Jibiki, 2016).

6.8.2 Response within the Philippines

During Typhoon Haiyan, the dynamics of the typhoon was rapid, and responders had limited time from the date of declaration of emergency (NDRRMC, 2015). Of the total seventeen administrative regions, nine were affected which includes 12,122 villages known as barangays, with 44 provinces and 591 municipalities and 57 cities which were entirely affected by Typhoon Haiyan (CDAC, 2014). Figure 6.10 shows the before and after image of the damage inflicted on the City of Tacloban and the magnitude of the storm surge, which affected around 3.4 million families across the 139 coastal villages (The U.N., 2013).

Figure 6.10 Before and after-images of the City of Tacloban (2013) [source: (PAGASA, 2013)]

One of the key challenges that were identified was that the residents did not understand the term ‘storm surge’, communicated by the Philippines Weather Authority (PAGASA) during the preparedness stage of Super-typhoon Haiyan. Observations shows how residents were prepared for typhoon’s heavy winds and were least informed of the severity of water damage that a potential storm surge could cause (Center for Excellence in Disaster Management & Humanitarian Assistance, 2014). Lack of awareness of storm surge hazard and related communication failure resulted in many residents, to consider basements as their safe grounds (CDAC, 2014). The public unawareness guided the residents to disregard pre-emptive evacuation orders directly resulting in the significant death toll, displaced, and affected population (Jibiki, 2016; Hernandez Jr, 2015).

The island of Tubabao, Eastern Samar, highly populated with farming families was another majorly impacted area by Typhoon Haiyan. Despite being severely impacted, these families received only limited assistance due to their remote location from the mainland. The responders found it difficult to reach these locations with relief support (FAO, 2015). The National Grid Corporation of the Philippines (NGCP) stated that 1,959 transmission facilities were adversely damaged by Typhoon Haiyan as of 22 November 2013 (NDRRMC, 2014).

The devastation created by Typhoon Haiyan in five major islands demanded a major response and relief support. The PASAGA's weather station was destroyed in Tolosa near Tacloban area during the typhoon and was later replaced with automatic weather systems (IRIDeS, 2016). It was beyond the National Response Team's (NRT) incident management levels; thus, leading to the requisition of national and international humanitarian assistance by the Philippines government (Dy & Stephens, 2016). This emergency was communicated across 57 countries and 29 militaries globally and humanitarian assistance from various agencies was provided to support the emergency response (Tiller, 2014). The Armed Forces of the Philippines (AFP) and USAID responded to request by initiating their internal contingency plans. Furthermore, the team facilitated in clearing the transportation routes and recovering halted logistics. This was considered as one of the key actions of humanitarian assistance, emergency relief support in regaining access to the airports and roadways to speed up the process of response and recovery (Center for Excellence in Disaster Management & Humanitarian Assistance, 2014). The US Department of Defense (DOD) furthermore, facilitated the response by providing naval, air and marine corps to the affected areas to support with search and rescue operations, transport relief supplies, assisting in road and debris clearance. The DOD personnel extended their support in assisting the situation with humanitarian assistance in the south of Tacloban and the Leyte Gulf areas (Lum & Margesson, 2014).

Lack of resources and the nation's constrained budgets resulted in significant reductions of prior investment in the deployment of resources, which also critically reflected the lack of adaptive capacity during the response phase of Haiyan (Dy & Stephens, 2016). The Local Disaster Risk Reduction and Management Council (LDRRMC) did not have enough resources or capacities for effective decision-making. Moreover, the local authorities, who directly liaised with the coastal community residents further lacked in capacity building and training on crisis management and familiarization with international humanitarian organizations. From 13- 18 November 2013, the national and international media criticized the country's response and relief support to be observed as slow despite the magnitude of the destruction (Dy & Stephens, 2016). By observing how the risk was identified in advance, and the aftermath that it created, the risk was supposedly either underestimated or served with inadequate response.

6.8.3 Recovery within the Philippines

The infrastructure of the country was severely damaged which includes the public and the private buildings, transportation, seaports, airports, power and utilities, water supply and drainage systems. Public buildings such as hospitals, health facilities and schools experienced significant damage hampering safety shelters which are alternative to evacuation centres (NDRRMC, 2014). Humanitarian agencies such as the International Federation of Red Cross (IFRC) were already grounded in the field, for the recovery of a previous earthquake which struck the Philippines in 2012. The existing teams were grouped again with new teams for phase 3- recovery of Typhoon Haiyan (IFRC, 2016). The Red Cross and their partnered teams activated their emergency relief support to respond and recover from the damage incurred. According to the IFRC, shelter repair assistance was provided to a total of 75,973 households (IFRC, 2016). Three months after the landfall of Haiyan the U.N. reported that the recovery operations were prolonged due to the lack of availability between the transitional and permanent shelter for both the evacuees and for the displaced population (USAID, 2014). This is a key area to be focused and included for future mitigation.

The USAID in collaboration with the Office of the U.S. Foreign Disaster Assistance (OFDA) initiated a team called, Disaster Assistance Response Team (DART). The DART team in correspondence with the US-based Response Management Team (RMT) further coordinated with the Philippines government to deploy the resources. Deployment of resources from this collaboration commenced on the 09 November 2013. The team also liaised in assessing the damage, humanitarian assistance, and search and rescue post-landfall of Typhoon Haiyan (USAID, 2014).

The IFRC emphasised on the fact, that though the international response was quick, yet it experienced substantial difficulty in synchronising the transition between local responders and international communities. This is mainly due to the prolonged existence of an international emergency team in the field than the time planned by the Philippines government (IFRC, 2016; IRIDeS, 2016). A contradictory viewpoint during the recovery phase was observed by the government and the international organisations. The Philippines government expected the international organisations to assist with the response to Haiyan stating the possibility of a quick recovery. This was challenged by the international response communities who envisaged that recovery phase was projected to continue anywhere between six months to a year (Dy & Stephens, 2016). As per the IFRC's report, the long-term recovery continued for 3 years till 2016. The city of Tacloban, whose infrastructure suffered significant damage (NDRRMC, 2014) focused primarily on the recovery of housing and power. The residents whose houses were destroyed were moved into bunkhouses and shelters constructed by the Government of the Philippines (GPH) as a first stage recovery (USAID, 2014).

Figure 6.11 Temporary shelters provided by NHA post-typhoon Haiyan [source: Estifania et al., (2016)]

The National Housing Authority (NHA) further assisted the second stage recovery process by constructing houses for the victims who were already provided with temporary shelter houses as shown in Figure 6.11 (Hernandez et al., 2015). NDRRMC reported that by January 2014, the power supply was restored in 1,243 affected households (NDRRMC, 2014).

6.8.4 Mitigation within the Philippines

The Government of the Philippines (GPH) launched a program called Reconstruction Assistance in Yolanda (RAY), as a four-year programme to operate from 2013-2017. The primary aim of the RAY was to support rehabilitation by rebuilding the coastal communities and areas affected by Typhoon Haiyan (Lum & Margesson, 2014). On 04 July 2014, the GPH declared that the humanitarian phase is over, and RAY will be replaced by the Comprehensive Rehabilitation and Recovery Plan (CRRP) (Shelter Cluster, 2016).

To improve the lives of victims, livelihood assistance was provided to 63,221 households (IFRC, 2016). The temporary shelters and homes were rebuilt using alternate practices such as the ‘build back safer’ techniques which includes solid foundation, bracing, roofing, joints, and other quality local construction materials. One of the significant mitigation measures as observed by the IFRC was the government’s mandated the ‘no-build zones' for areas vulnerable to hazard such as storm surge, coastal flooding and landslides (IFRC, 2016). It is to be noted that although, the 'build back safer' (BBS) technique primarily focused on the materials, the understanding of this term is widely interpreted differently by different actors resulting in lack of limited expertise to implement the safer rebuilding techniques were observed (Fernandez & Ahmed, 2019).

After two years of the landfall of Haiyan, around 1,600 families were found living in temporary housing provided either by government or through their collaboration with international NGO's (IRIDeS, 2016). The lessons learned from the devastating impacts of Typhoon Haiyan led the country to focus on the actions as soon as the emergency relief work was partially completed. However, due to various restricting factors and the adaptive capacity of the country the action taken was slow, relative to the catastrophic impact.

6.8.5 Summary of key activities and disaster phases during Typhoon Haiyan

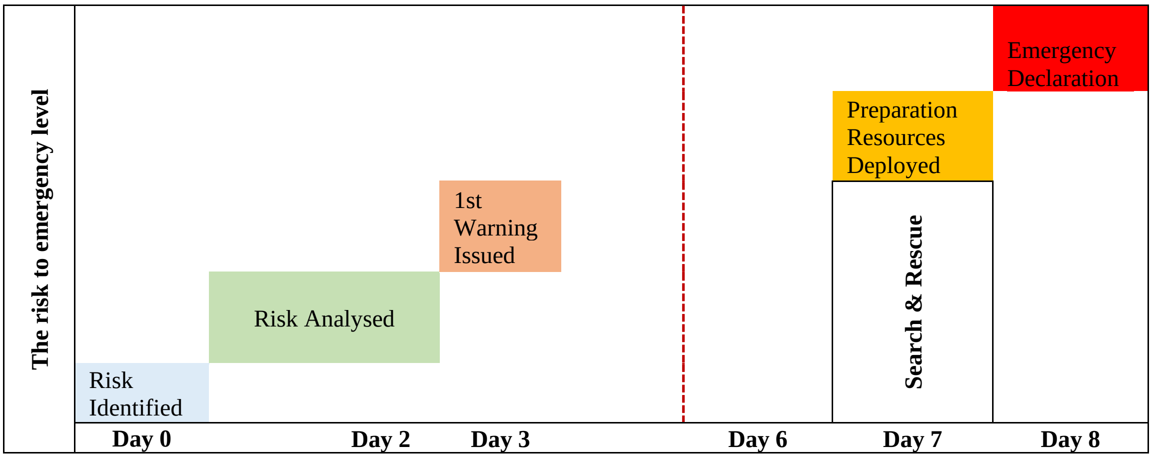
The list of activities achieved and unachieved in the pre-impact, post-impact and during the landfall of Super-Typhoon Haiyan was summarised in Table 6.4.

Table 6.4 Summary of the key activities and their achievements observed from Case Study Haiyan

	Preparedness	*Response*	*Recovery*	*Mitigation*
Activities achieved	Declaration of emergency Early warnings Forecasting Monitoring Risk identification Emergency shelter Evacuation	Involvement of NGO, INGO, and volunteers Search and rescue Emergency shelter Humanitarian aid	Community outreach Debris removal Reconstruction Relocation Damage assessment Health care	Improving livelihoods lessons learned Construction Telecommunication
Activities unachieved/ unidentified	Risk analysis Hazard assessment Technical prevention Deployment of resources Public awareness and education Scenario Planning Capacity building Training and exercises	Decision making Vulnerable population Communication Coordination Logistics Transportation Emergency planning Power and utility Incident stabilization	Organizational capacities Lack of Resources Stakeholder involvement Rehabilitation Restoration	Coastal protection Multi-agency approach Land use planning

The table provides an overall summary of all the actions as key activities measured both from coding and from the document sources. Based on the initial rapid assessment of the damage the President served the 'declaration of calamity' as presidential proclamation, on 11 November 2013 (NDRRMC, 2014). The unachieved key activities within the DRM phases were mainly due to lack of awareness of the storm surge hazard by both the emergency responders and the authorities themselves resulting in the lack of clarity at various levels. Table 6.5 also emphasises the observed delay in the declaration of emergency and deployment of resources as one of the key factors to be considered for future mitigation measures.

Table 6.5 Overview of the timeline gap and risk emergency level observed during Super-typhoon Haiyan



6.9 Physical damage and loss statistics within the Philippines

The final updated report of the NDRRMC, confirms that the total death toll was 6,300 (NDRRMC, 2015). Around 16 million individual people were affected 28,689 who were identified as injured by Typhoon Yolanda. A further 4 million people were displaced and 1,785 still missing. The total estimated cost of the damage was US$ 864 million (McPherson et al., 2015; Center for Excellence in Disaster Management & Humanitarian Assistance, 2014). The magnitude of Typhoon Haiyan resulted in a severe impact on the islands of the Philippines. The government of the Philippines (GPH) estimated around 1.1 million homes were affected of which approximately 600,000 were supported by GPH and the remaining were requested for humanitarian assistance. The storm further destroyed around 100,000 small-scale fishing boats across the coastal communities, whose prime resources for a living was fishing (USAID, 2014). Many critical infrastructures in the path of Typhoon Haiyan were damaged. This includes the educational facilities consisting of 3,200 schools and day-care centres which were either adversely damaged or destroyed (IFRC, 2016). Around eleven weather stations, many meteorological instruments and buoys were damaged leaving little or no data of storm surge inundation and heights (Kubota et al., 2013).

Table 6.6 shows the estimated total households recorded in 2010 versus the affected household in 2013 within the Cebu communities, where 90% of the households suffered severe damage or were destroyed completely (Marfil, 2013).

Table 6.6 Total households versus affected households in the communities of Cebu during typhoon Haiyan [source: Marfil (2013)]

Cebu communities	*Total household estimated (2010)*	*Affected household (in 2013)*
Bantayan	16,258	14,632
Madridejos	7,588	6,829
Santa Fe	5,928	5,335
Daanbantayan	16,282	14,654
Medellin	10,880	9,792
San Remegio	11,173	10,055
Bogo city	15,198	13,678

6.10 Impact of storm surge within the Philippines

The victims and the residents addressed the storm surge flooding triggered by the Super-Typhoon Haiyan as a tsunami or a tsunami-like event on various occasions (Morgerman, 2014). This might be possibly due to the facts (*i*) that pattern of reverse storm surge behaviour exhibited or (*ii*) the rapidity and magnitude of the storm surge as experienced by the victims. The victims of the coastal communities who witnessed the storm surge reported that the water receded exhibiting a basic pattern of a tsunami. They further added that immediately after the ‘surge recession’ of water had taken place, the magnitude was sudden, and they did not have enough time to react, as the water was funnelled into the city’s landscape (Morgerman, 2014).

Although, the size of the cyclone was small, the intensity of the storm surge was observed to be rapid (McPherson et al., 2015). As per German Aid Agency for International Cooperation’s (GIZ) estimation, 94 % of the causalities from Tacloban, Palo, and Tanauan was solely due to storm surge (Neussner, 2014). Figure 6.12 before-image shows the city of Tacloban, which was developed on the San Pedro bay (on the left) and an after-image shows the city’s exposure to storm surge > 19.7 ft (6 m).

Figure 6.12 Before and after image of the City of Tacloban post-Haiyan [source: BBC News (2013)]

The term ‘typhoon’ was never a strange word for the residents of the Philippines who are exposed to approximately 20 typhoons on average a year. The communities stacked their emergency supplies and stayed indoors knowing a typhoon would be imminent. Their focus was on high wind damage and flooding (from rain) and remained unaware of the approaching storm surge. The storm surge funnelled the water through the neck of the San Pedro Bay about 30 km until Leyte. The water funnelled hundreds of meters inland into the city and completely levelled most of the critical infrastructure situated nearshore (Galvin, 2014). Most of the measuring instruments were damaged directly and indirectly by damaging or destroying completely leaving little or no ground to be collected post-typhoon event. In Tanauan and Palo towns within the City of Tacloban, storm surge levels were estimated between 7.5- 16.4 ft (2.3-5 m) (Galvin, 2014). The storm surge damaged the PASAGA’s monitoring systems, measuring instruments, resulting in little or no ground data with the telecommunication system being toppled by the storm’s magnitude.

Table 6.7 Predicted storm surge issued by project NOAH [source: Neussner O. (2014)]

Province	*Location*	*Storm surge + tide in ft(m)*
Eastern Samar	Matarinao Bay	17.4 (5.3)
Biliran	Poro Island, Biliran Str	15.4 (4.7)
Leyte	Tacloban, San Juanico Str	14.8 (4.5)
Quezon	Port Pusgo	14.4 (4.4)
Eastern Samar	Andis Island, Port Borongan	14.1 (4.3)
Quezon	Santa Cruz Harbour	13.8 (4.2)
Palawan	Port Barton	12.8 (3.9)
Iloilo	Banate	12.8 (3.9)
Leyte	Palompon	13 (4.0)
Leyte	Ormoc	12.5 (3.8)

Table 6.7 shows the storm surge prediction levels issued by the project NOAH. These predicted measurements were later confirmed by PAGASA as near accurate values (PAGASA, 2013). The predictions given by Project NOAH was considered as near accurate. Because PASAGA's estimation excluded inundations beyond 22.96 ft (7 m), they underestimated the actual risk thereby, implying that storm surge is less severe than the other hazard such as rainfall and landslides. Table 6.8 shows the actual storm surge levels observed at three main locations severely impacted by a 16-23 ft (5-7 m) storm surge range.

Table 6.8 Actual storm surge measured in mainland Philippines post-typhoon Haiyan [source: PAGASA (2013)]

Location	*Storm surge inundation height in ft (m)*
Guiuan to Hernani	20-23 (6-7)
Tacloban to Palo	16-20 (5-6)
Basey	16-20 (5-6)

The coastlines across these three main locations were completely devastated from the inundations, destroying most of the homes near the coast, which were built with wooded exterior and glass roofs (PAGASA, 2013).

6.11 Adaptive measures taken post-Haiyan within the Philippines

By the end of November 2013 when the disaster relief was still carried out with milestones to reach, the President of Philippines initiated the Presidential Assistant for Rehabilitation and Recovery (PARR) to unify rehabilitation and recovery efforts (Dy & Stephens, 2016). On 16 December 2013, the National Economic Development Authority (NEDA) enforced the 'Reconstruction Assistance on Yolanda's: Build Back Better' guidance for rehabilitation plans. Followed by the guidance of the document in September 2014, 'Reconstruction Assistance on Yolanda's: Implementation of Results' on reconstruction plans and projects which were initiated (Dy & Stephens, 2016). Many of the grounded National Societies, non-profit organisations and NGO's reported that the recovery and rehabilitation works are expected to continue beyond 2018 (IFRC, 2016). The Office of Civil Defence (OCD) issued the Post-Disaster Needs Assessment in April 2014 (Dy & Stephens, 2016). Several international partnership agencies extended their organisational capacities supporting to improve the livelihoods of the victims during the post-recovery and mitigation (Philippines Humanitarian Country Team, 2013).

- The International Labour Organization
- United Nations Development Programme (UNDP)
- United Nations Children Fund (UNICEF)
- Save the Children, Oxfam
- United Nations High Commission for Refugees (UNHCR)
- International Organization for Migration (IOM)
- UN Office of the Coordination of Humanitarian Assistance (OCHA)
- World Food Programme (WFP)
- World Health Organization (WHO)
- UN Human Settlements Programme (UN-Habitat)

6.12 Summary

The case studies of Nargis and Haiyan have highlighted the intensity of storm surge hazard and the relative damage that could be to their coastal communities for not knowing or understanding the term ‘storm surge’. Whilst new legislation and guidelines may have been published, since these major events, today in 2020 there is still recovery work ongoing, despite being 12 years and 7 years since the event occurrence. The lessons learnt from the case studies also provide insight into how countries like Myanmar and the Philippines could suffer during the recovery stages if proper adaptation plans were not in place. Areas inundated further inland from the coasts underlines the influences of ‘funnel-effects’ of storm surges. Scenarios such as seeking shelter under the basement when a 20 ft (6.1 m) storm surge is approaching the coast, not only shows the lack of hazard awareness but also shows the ignorance of the authorities to leave the communities at greatest risk to life. This chapter also highlighted how high-risk ocean basins such as the Indian Ocean, Bay of Bengal whose deep warm waters could inflict catastrophic damage by becoming a rapidly intensified cyclones within a shorter span of their origin. Observing these case studies, it is evident how early warning systems is critical in saving lives during emergencies especially to those countries with the limited (restricted) resource. Well-planned and coordinated DRM and DRR strategies could benefit countries like Myanmar and the Philippines directly reducing the mortality rate. These statements further underline how the potential DAMSS framework approach together with the guidelines as best-practices could enhance the resilience of the coastal communities for developing countries.

CHAPTER 7

ISLAND STATES AND STORM SURGE EVENTS

Case studies: Hurricanes Matthew and Maria

7.1 Introduction

This chapter examines two significant hurricanes which occurred in the Atlantic Ocean. The cases are perceived from the perspective of responses exhibited by Small Island Developing States (SIDS) such as Haiti and Puerto Rico. The first case discusses Hurricane Matthew from the 2016 Atlantic hurricane season which made landfall in Haiti and the USA. However, the response is majorly discussed from Haiti's point of view and discussed in comparison to the USA. The second case examines Hurricane Maria from the 2017 Atlantic hurricane season and the case is discussed from Puerto Rico's perspective in comparison to the USA.

7.2 Hurricane Matthew: origin and background

Hurricane Matthew originated as a tropical depression on the west coast of Africa on 23 September 2016 and entered the Atlantic Ocean. The tropical depression moved rapidly along

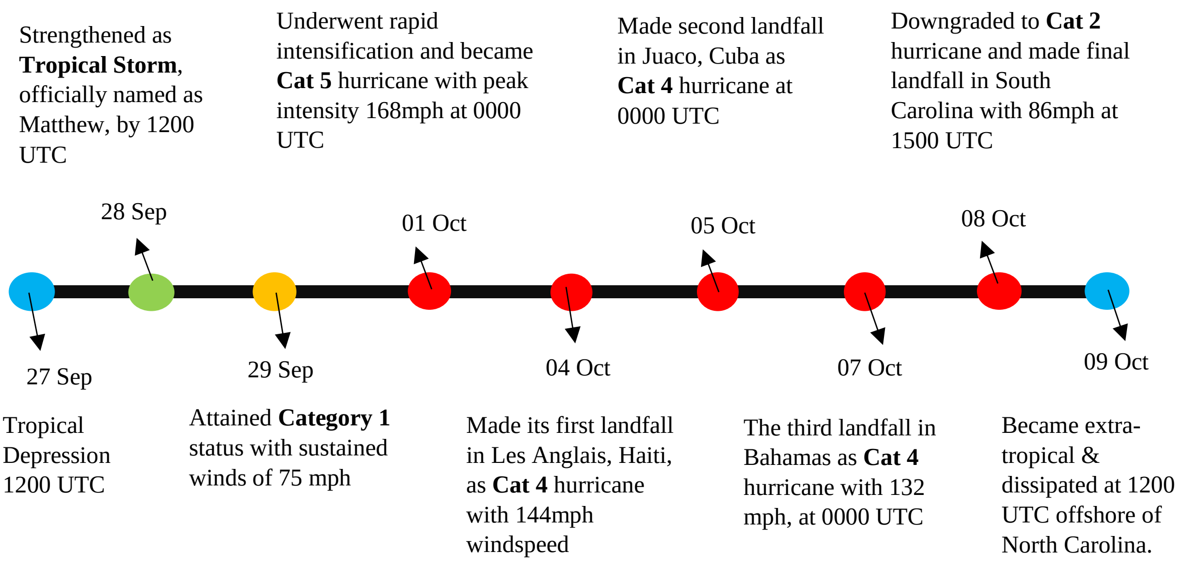


Figure 7.1 Timeline of Hurricane Matthew (27 Sept -10 Oct 2016) [source: Stewart (2017)]

the equatorial Atlantic following which an organised pattern was confirmed on 27 September 2016. The depression quickly picked up the storm elements becoming a tropical storm around 1200 UTC 28 September as shown in Figure 7.1 and gained its official name 'Matthew' (Stewart, 2017). With an unusually large wind field the storm moved fast over the warm Caribbean waters and rapidly intensified to reach hurricane status by 29 September 1800 UTC, within 24 hours after reaching storm status. Matthew underwent an extraordinary strengthening (over 2 days) from 75 knots to the peak intensity of 145 knots and became a Category 5 hurricane on the 01 October 2016, at 0000 UTC (Stewart, 2017).

The storm system quickly weakened back to a Category 4 hurricane in less than six hours and continued its course for the next two days until the first landfall occurred on 04 October 2016, 1200 UTC at Les Anglais, Haiti as a Category 4 hurricane. Hurricane Matthew was the first Category 4 hurricane after Hurricane Cleo to hit Haiti since 1964 (Hersher, 2016; Stewart, 2017). Figure 7.2 shows Hurricane Matthew's projected path with colour coded hurricane categories. This version is adapted by the researcher using the original latitude-longitudinal data from NHC (Stewart, 2017).

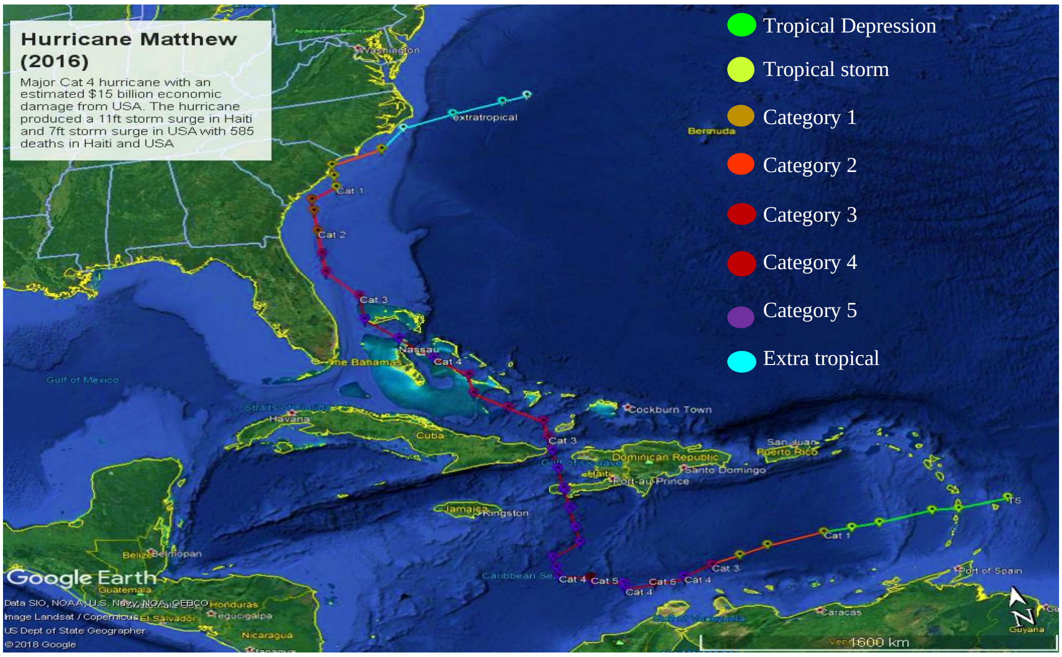


Figure 7.2 Hurricane Matthew's projected path with colour coded themes for different hurricane categories (version adapted by the author using Google Map)

A sustained wind measurement of 45 knots was reported at Toussaint Louverture International Airport in Port-au-Prince, Haiti. No specific wind reports were observed when Matthew made the landfall as a Category 4 hurricane. Table 7.1 lists the second landfall occurred in Juaco, Cuba 0000 UTC on 05 October and the Bahamas on the 0000 UTC 07 October 2016 as a Category 4 hurricane.

Table 7.1 Landfall synopsis of Hurricane Matthew (2016) [source: Stewart (2017)]

Date	**Time (UTC)**	**Landfall Location**	**Country**	**Category during landfall**	**Max. Wind (knots)**	**Max. Wind (mph)**	**Min Pressure (mb)**
04-Oct	1100	Les Anglais	Haiti	4	130	149.76	934
05-Oct	0000	Juaco	Cuba	4	115	132.48	949
07-Oct	0000	West-end, Grand Bahama Island	Bahamas	4	115	132.48	937
08-Oct	1500	5n mi of McClellanville	South Carolina	1	75	86.4	963

On 08 October at 1500 UTC, Matthew reached the coastline of Georgia, and then weakened and downgraded to a Category 2 hurricane and made its final landfall at South Carolina (Miller et al., 2018). The storm further weakened and became an extra-tropical cyclone after its final landfall, as it moved away from North Carolina as shown in Figure 7.2. Matthew broke the records of many previous hurricanes and became the record-breaking longest Category 4 hurricane for five continuous days in the Atlantic Ocean (Gilbert, 2018). A further detailed structural change assessment of data, for Hurricane Matthew, including its projected pathway, the hurricane watch-warnings issued by the NHC is included in Appendix B. These data warnings included air pressure, wind field and strengthening or weakening of hurricane structure.

7.3 The disaster phases of Hurricane Matthew

7.3.1 Preparedness within Haiti

Haiti was in the path of Hurricane Matthew and was predicted to be the first landfall location of Matthew. The Haitian government in partnerships with NGO organisations initiated their Phase 1- preparedness by activating the emergency response plans (Miller et al., 2018). Factors such as the economic capacity, the country’s political instability together with the lack of resources majorly hindered the preparedness activities. This further complicated the succeeding activities and left the country exposed to the approaching hurricane (Howe, 2016). The country’s vulnerability to disasters was well-interpreted from a previous earthquake event which occurred in 2010. A colour coded alerting system was in practice in Haiti to alert the population. On 02 October 2016, this colour code was modified from orange to red indicating the increase in the hurricane's strength. In Cuba, around 1,079,000 people were evacuated from six eastern provinces of the country (GRID, 2017). Once the storm crossed Haiti with severe damage the second and third landfall occurred in Cuba and in the Bahamas and advanced towards the east coast of the USA (Stewart, 2017). By this point of time, the USA had already initiated their preparedness procedures. All the residents in the predicted path of Hurricane Mathew along US Coastline of from Florida, Georgia, North, and South Carolina were ordered evacuation. In Florida, 147 shelters in 33 counties were set-up for the evacuees (Howe, 2016).

Various precautionary measures were initiated parallelly. Two of the major nuclear reactors in Florida, which were already facing issues regarding sea encroachment, was anticipated in Matthew's predicted path and flood proofing works were carried out (The USNRC, 2017). The authorities of the Nuclear Energy Institute ensured that 'the reactors in Florida were safe, flood proofed with emergency preventions'; and all the nuclear plants were safe under the Nuclear Regulatory Commission's (NRC) new rule'. The NRC new rule was imposed to improve the safety standards related to decommissioning after the Fukushima disaster (Nunez, 2015). Nevertheless, as an added precaution both the power reactors were shut down with severe warnings issued by NRC during preparedness for Hurricane Matthew (The US NRC, 2017).

The phase 1-preparedness between the USA and Haiti clearly shows the difference of approaches adopted by these two countries. While the USA had already evacuated its coastal residents ahead of time, Haiti had only embraced partial evacuation leaving many of its residents exposed. Also, being a small island state, and with restricted capabilities, and geographic limitations Haiti faced issues regarding availability of sheltering opportunities.

In the USA, before Matthew's arrival, FEMA had 444,000 litres of water and 513,000 meals and other supplies readily available in their support base to be mobilized to affected areas. Non-profit groups also volunteered during the Phase 1- preparedness stage for Matthew, focusing on safety efforts a day-ahead of Matthew's arrival (Stein, 2016). North Carolina, South Carolina, and Georgia declared, state of emergency days ahead of storm's approach as a step towards preparedness (Hersher, 2016). More than 1.5 million people were instructed to follow the issued mandatory evacuation orders (Domonoske, 2016). According to the source of the Associated Press, because of the short coastline of Georgia, more than 500,000 residents were asked to evacuate (Domonoske, 2016). Early predictions suggested that Hurricane Matthew would deviate from the east coast however, the hurricane stayed along the US coast longer than expected to make its final landfall in South Carolina (Brouillette, 2016).

7.3.2 Response within Haiti

In Jérémie, Haiti, it was reported that almost all the roofs were destroyed and in many locations that the level of damage and destruction was not clear during the first few days. In Port-au-Prince, a bridge in the National Route 2 collapse, which was the main way for the supplies, emergency responders and relief workers to transport and communicate (Hersher, 2016). The residents were alerted, but without the government support and were left to fend for themselves with minimal resources. Therefore, coordinating these residents in response stage became a difficult task. In addition, the lag-in-response by the Haitian government was also observed (Global Philanthropy Group, 2016).

The NGO's with their volunteers who were already grounded for the rehabilitation of the 2010 earthquake, paired together with the government authorities and initiated the response on 05 October 2016 soon after the landfall. The emergency responders faced extreme difficulty to reach the remote and hardest-hit areas.

Figure 7.3 Hurricane Matthew catastrophic damage in Haiti [Image source: Carlos Garcia Rawlins-Reuters]

The impact includes 80 % of the buildings and more than 30,000 homes destroyed in the City of Jérémie and its sub-provinces (Howe, 2016), as exhibited in Figure 7.3. By 08 October, it was reported that roughly 1,000 people were killed by Hurricane Matthew in

Haiti alone (Alexander, 2016; Hersher, 2016). However, the official reports of NHC state that the death statistics in Haiti was 546 (Stewart, 2017). The variation of the death toll by official and unofficial sources infers that a more rigorous measure should be involved to record accurate disaster data. As the hurricane continued its course in Cuba, major urban areas such as Guantanamo, Holguin and Las Tunas were also identified as the most impacted areas. (Virtual OSOCC, 2016). In Baracoa, a municipality within Guantanamo was reported with 90 % of the homes either having partial to major damage or destruction. Although no deaths were reported in Cuba, the country faced severe crop damage (FAO, 2016).

In St. Augustine, Jacksonville, Florida around 7,000 residents were identified as non-evacuees despite the early warning of 8 ft (2.4 m) storm surge communicated by the local emergency operations centre (Johnston et al., 2016). During Hurricane Matthew (2016) the U.S. coastal cities were observed to be overwhelmed with information which created ambiguity in certain places while Haiti had limited information available about the hurricane (CERC, 2014). The storm reached the south-eastern coastline of USA, the storm had weakened to a Category 2 hurricane still produced damage and created power outage affecting nearly 3 million people along the coast of Florida and Carolinas (Miller et al., 2018).

7.3.3 Recovery within Haiti

Due to the political instability in Haiti, the recovery and response were carried out in collaboration with various international organizations such as UNICEF, Office of the Coordination of Humanitarian Assistance (OCHA), WFP (World Food Program), PAHO, Food and Agriculture Organisation (FAO) and other volunteer NGO organizations (Global Philanthropy Group, 2016). Emergency relief and recovery actions took place immediately after Matthew's landfall. The US Navy shipped three vessels of emergency supplies as a relief and recovery to Haiti (Hersher, 2016).

Hurricane Matthew resulted in a humanitarian crisis in Haiti, leaving the country to struggle during the phase-3 recovery stage. According to the UN, almost half a million children needed humanitarian assistance and were still identified to be in extended recover phase (UN News, 2016). The UN Development Programme (UNDP) reported that 98% of the City of Jérémie and Grand' Anse had been destroyed (UN News, 2016; Jones & Holpuch, 2016) as shown in Figure 7.4.

Figure 7.4 Devastation in the cities of Les Cayes and Jérémie during Hurricane Matthew [Image: Xinhua/Barcroft/ Ruck (2016)]

Due to the resultant major roadways blockage, truncated bridges and critical infrastructures, such as the water systems being damaged or destroyed completely, prolonged the recovery in Haiti specifically in Grand' Anse Department, Sud Department, Jérémie. Figure 7.5(a) shows the before and after-image of the collapsed bridge in Grand' Anse, Haiti which truncated emergency responders and supplies and prolonged the recovery process.

Figure 7.5(a) Collapsed bridge in Petit-Goave, Haiti post-hurricane Matthew [Image source: Google/Reuters]

Efforts were undertaken on rebuilding access to the bridge in Grand' Anse department as this bridge was the only possible route for the emergency responders to access the impacted areas (CARE, 2018). The mountainous regions of Grand' Anse received little assistance and these were the hardest-hit areas, which took around five months to repair and rebuild the damaged houses (GRID, 2017). Haiti's vulnerability and poverty together played a critical role in delaying recovery and rehabilitation. Call for funds, donations, emergency supplies and assistance were pooled internationally to support and expedite the recovery process of the devasting situation in Haiti (CARE, 2018).

Around three hundred schools were heavily damaged out of which around 150 schools were set up as emergency shelters for the evacuees were also included in the damage (Global Philanthropy Group, 2016; United Nations Institute for Training And Research's UNOSAT, 2016). Nearly half a million people of Haiti's total population were children and under 18's and were in the south-western Haiti where the hurricane severely impacted the country. International organizations and NGO's were involved in various recovery areas of south-western Haiti. UNICEF initiated temporary learning spaces for the children to continue their learning and education (Global Philanthropy Group, 2016).

After three months since the landfall of Hurricane Matthew in Haiti, 85-93% of families were severely affected by food insecurities (FAO, 2016). Due to the severe and extended food insecurity, the World Food Program (WFP) supported with food assistance for nearly 925,000 people until April 2017, for six months since the landfall (USAID, 2017). During the recovery phase even after a year, extended shelter rehabilitation works took place in areas which were adversely impacted. The World Vision International provided humanitarian assistance for around 246,000 people in the communities that was severely impacted (World Vision International, 2017).

Whilst Haiti had previously received humanitarian assistance following the 2010 earthquake, Hurricane Matthew was the first 'cyclone' event to request and receive humanitarian assistance due to the extensively affected and displaced population. The weather event and its significant impact left the country with key lessons to be learnt to adapt for a future situation. Some of the key lesson were to increase the capacity building, improve training of national and international actors during emergencies, understanding the bottleneck issues in logistics. Logistics was one of the main key lessons learned within logistics during the crisis, e.g., the bridge collapse hampered the primary transport route (Logistics Cluster, 2018). The USAID/OFDA partnered with J/P Haitian Relief Organisation (J/P HRO), Mercy Corps in support of covering the sheltering needs. These partnerships worked in providing shelter kits and liaised in providing training in support of enhancing the livelihood and promote more robust and resilient neighbourhoods.

Figure 7.5 (b) Temporary shelter (right) (USAID, 2017) built post aftermath and durable shelter(left) built in Haiti, post-hurricane Matthew [Image source: Habitat for Humanity]

More than 6,000 households were furnished with shelter solutions (USAID, 2017). Figure 7.5 (b)-(left) is a sample of 300 houses built using Habitat's shelter materials (Habitat for Humanity, 2020) and Figure 7.5 (b)-(right) shows the temporary shelter solutions.

7.3.4 Mitigation within Haiti

Due to the extensive damage and the ongoing recovery, there have been very few (if any) mitigations measures applied within Haiti in preparation for any future storm. This may be compounded due to the lack of financial resources within Haiti for both public and industrial sectors. This contrasts with the very developed country such as the US (such as Florida, South Carolina) who have undertaken extensive reviews of the data and initiated mitigation or resilience measures.

The NHC initially predicted that Hurricane Matthew would make landfall at Florida as a category 4 hurricane with a minimum of at least 8 ft (2.4 m) storm surge. However, this the surge did not produce the predicted surge levels. The forecast did not aid in assessing the potential impacts as the hurricane took a deviation (Stewart, 2017). The deviation of the actual path in comparison with the predicted path highlight how the technical aspects of understanding the hurricane intensity and succeeding structural change of the hurricanes needs to be improved further. The National Weather Service (NWS) issued a prototype of storm surge watch-warning during Hurricane Matthew at 2100 UTC, 04 October 2016 the same day when the declaration of emergency was issued for 6 states including Florida, North and South Carolinas, Virginia, and Georgia. The watch-warning were however issued only for few selected areas and was remarked that residents should still heed to the advisories. The watch-warning are only to communicate the risk and not to be misunderstood as risk being mitigated (Stewart, 2017).

Considering the direct impact from storm surge in South Carolina, revised construction methods especially emphasizing the durability, efficiency and sustainability were considered. This was implemented for all the rehabilitated, reconstructed houses in addition to the new constructions ensuring mitigation measures to increase the resilience for future disasters (The Department of Housing and Urban Development , 2017). To mitigate the severe power outage faced by South Carolina the national and state-level power and utility organizations participated in training and exercises to strengthen their utility infrastructure for during future emergency responses (Florida Public Service Commission, 2018).

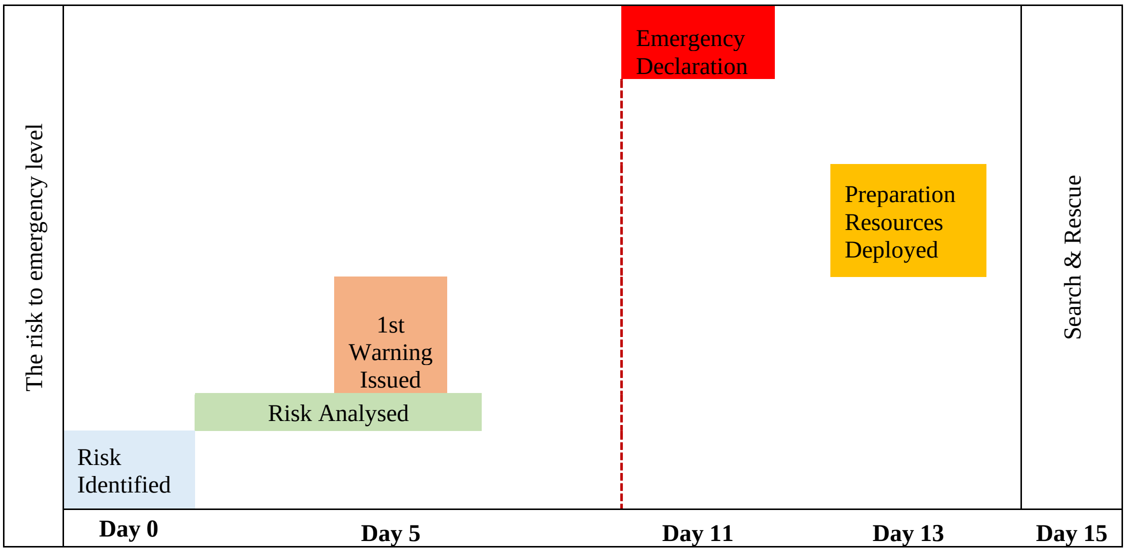
7.3.5 Summary of key activities and disaster phases during Hurricane Matthew

Table 7.2. Summary of the key activities and their achievements observed from Case Study Matthew

	Preparedness	***Response***	***Recovery***	***Mitigation***
Activities achieved	Declaration of emergency Public awareness and education Early warning Risk identification Hazard assessment	Evacuations NGO, INGO, and volunteers Humanitarian aid Incident stabilization	Search and rescue Damage assessment Health care Rehabilitation Recovery Debris removal	Lessons learned Community outreach Training and exercise
Activities unachieved /unidentified	Deployment of resources Emergency planning Capacity building Community outreach Technical prevention Risk analysis Scenario planning Training and exercise	Communication Telecommunication Community outreach Construction Coordination Emergency shelter Power and utility Transportation Vulnerable population Environment	Improving livelihoods Infrastructure Insurance Multi-agency approach Power and utility Reconstruction Stakeholder involvement Restoration	Vulnerable population Wetland mitigation Telecommunication Transportation Multi-agency approach Stakeholder involvement Strategic alternate approach Capacity building Public awareness and education Construction

Table 7.2 shows the list of key activities followed while executing the four main phases of the DRM cycle during the lifecycle of Matthew. The listed key activities were observed from the document sources using coding approach. The list of unachieved key activities identified was mainly due to the political instability in Haiti, weak economic capacity, limited and restricted resources which was prevailing since the 2010 Haiti earthquake.

Table 7.3 Overview of the timeline gap and risk emergency level observed during Hurricane Matthew



While observing the key activities the following timeline gap was also observed as shown in Table 7.3. Between the risk identification and issuance of the first official warning, only a four-day time gap was observed as an inactive period during which no preparedness activities were carried out. A country like Haiti, whose economic capacity is weak should focus more on phase-1 preparedness stage by increasing their organisational capacities through multi-agency approach. Even though the adaptive capacity is low, the country could have minimised the impact with the support of pre-established NGO's and their networks.

7.4 Physical damage and loss statistics

Hurricane Matthew with a sustained wind speed of 125.8 knots (145-mph) winds and with an 11-foot (3.4 m) storm surge together with the heavy downpours severely impacted the north-west, south-west and south of Haiti, particularly impacting Jérémie and Les Cayes (World Food Programme, 2016; PAHO/WHO, 2016). According to the Haitian Civil Protection Directorate (CPD) 15,623 people were displaced in Haiti and a total of

350,000 needed humanitarian assistance. An aerial view of the damage is shown in Figure 7.6.

Figure 7.6 Before and after-image of Jérémie, Haiti from the impact of Hurricane Matthew [Image source: Google/Reuters (BBC News, 2016)]

In the Dominican Republic, 21,951 were displaced (Virtual OSOCC, 2016)**.** As per the estimates of the International Federation of the Red Cross and Red Crescent Societies more than one million residents of Haiti were affected and required urgent humanitarian assistance (Jones & Holpuch, 2016). In Haiti, around 240,000 homes were severely damaged or destroyed. The economic damage in the Caribbean was estimated at US$ 5 billion. It was reported that transportation of emergency supplies was truncated in some of the hardest-hit areas such as Grand' Anse and Suds department (United Nations Institute for Training And Research's UNOSAT, 2016). Communication and coordination between emergency responders became difficult due to all the telecommunication hubs being disconnected and a key bridge connecting the route was cut-off (Jones & Holpuch, 2016; DHS & FCC, 2018).

Table 7.4 Estimated economic damage of Hurricane Matthew [source: Stewart (2017)]

State/Province	***Estimated Economic Loss (USD)***
Haiti	1.9 billion
Cuba	2.58 billion
Bahamas	600 million
The United States	10 billion

Table 7.4 displays the estimated economic damage in corresponding countries adapted from NHC's report (Stewart, 2017). In Cuba, Guantanamo faced significant damage from the storm surge and heavy winds of Hurricane Matthew. Around 9,000 homes were destroyed and around 30,000 homes suffered adverse damage with an estimated economic cost of US$ 2.58 billion. Overall, in Cuba, the estimated damage cost was reported to be more than US$ 5 billion (echoCuba & Outreach Aid to the Americas (OAA), 2016). In addition to public infrastructures, more than 29,000 houses were severely damaged, and 3,174 homes were destroyed completely. A further 35,019 people were also affected in the Dominican Republic (PAHO/WHO, 2016). As the storm's track was in parallel to the east coast of the US, and just before the landfall at South Carolina, Matthew was weakened to a Category 2 hurricane. So, the damage in the USA was not severe compared to Haiti. However, the USA suffered a substantial power outage.

Table 7.5 Power Outage caused by Hurricane Matthew in the USA [source: Florida Public Service Commission, 2018]

States (United Kingdom)	***Power Outage (No. of homes)***
Jacksonville	250,000
Georgia	300,000
South Carolina	800,000
North Carolina	900,000
Virginia	350,000

Table 7.5 displays the power outage experienced in the USA and the number of homes affected. Despite various measures taken against strengthening the utility infrastructure during emergencies yet the state suffered severe power outage from the storm event (Florida Public Service Commission, 2018).

7.5 Impact of storm surge

Storm surge inundation values along the coast of Haiti were not available clearly (Stewart, 2017), but the impact from the storm surge was described as destruction like the 2010 earthquake (Howe, 2016). The storm surge combined with the in-land flooding from the heavy downpours exceeded more than 15-inches (Miller et al., 2018). In the USA, hurricane Matthew's impact was observed to be severe only along the coasts of Georgia, North, and South Carolinas (Chappel, 2016). In South Carolina, power outages around 437,000 were reported (Chappel, 2016). In Florida Fernandina Beach, peak surge was observed as 9.88 feet measured by the NOS tide gauge. While the coastal communities near Flagler Beach Jacksonville Beach, Palm Coast, St. Augustine were impacted by 9 ft

(3.0 m) storm surge (Brouillette, 2016) as shown in Figure 7.7. In Georgia, the storm surge from the Hurricane Matthew coupled with high tide at Ft. Pulaski just below 8 feet. Some of the other damages associated with storm surge were the beach erosion, extensive escarpment of sand-dunes and damage of the pedestrian crossover along the coast of Florida, Georgia, and the Carolinas.

Figure 7.7 A1A in Flagler Beach eroded from the storm surge of Hurricane Matthew [Image source: Miami Herald]

Despite various circumstances, that the hurricane did not make a direct landfall and even when made landfall it was a weakened hurricane. However, the Kennedy Space Centre NASA's rocket launch facility, was adversely affected by the storm surge produced in Florida (Brouillette, 2016). The damage from Satellite Beach to Melbourne Beach which damaged the dunes, berms, beach foundations in Brevard County were estimated US$ 25 million. In Cuba, communication tower and bridge in Toa River was destroyed and the coastal highway along the Boca de Jauco Bridge was completely eroded (Brouillette, 2016).

7.6 Adaptive measures taken over post-Matthew

The post-landfall scenario in Haiti became difficult to regain 'back to normal' situation, due to the prolonged recovery and rehabilitation process. The 2016 presidential election in Haiti was postponed as some of its campaign centres were also severely damaged. A cholera outbreak was reported post-event occurrence. The USAID and Haiti worked on expanding community health services which includes creating awareness such as water, sanitation, and hygiene (WASH) initiatives in Haiti after the cholera outbreak. The UNICEF supported rehabilitation and restoration of 50 schools to support children's education and learning. Due to the ongoing requirement of humanitarian assistance since 2010 earthquake, followed by the landfall of Hurricane Sandy in 2012 and then by Matthew in 2016, the European Civil Protection and Humanitarian Aid Operations (ECHO) contributed additional US$ 37.4 million (The USAID, 2017). Reflecting on the current situation clearly shows that Haiti is still in the extended recovery phase of Hurricane Matthew. Despite the economic capacity, it is important that the country's coping ability to disasters, adaptive measures were essential to endure a future disaster is clear from this case study.

7.7 Hurricane Maria: origin and background

On the 12 September 2017, a tropical depression from the west coast of Africa was identified. The scattered wave was later organised to become a tropical depression by 1200 UTC 16 September 2017 about 580 n-mi east of Barbados and further strengthened to a tropical storm exactly six hours by 1800 UTC on the same day. Hurricane Maria was the thirteenth named storm of the 2017 Atlantic hurricane season. After gaining its official name, the Tropical Storm Maria underwent a rapid intensification and 24 hours later attained the hurricane status on 17 September 2017, by 1800 UTC (Pasch et al., 2017). The hurricane strengthened to a major Category 5 measuring in SSWHS with maximum winds of 145 knots (166.7 mph) and made its first landfall on 19 September 2017 by 0115 UTC in Dominica as shown in Figure 7.8 (Pasch et al., 2017).

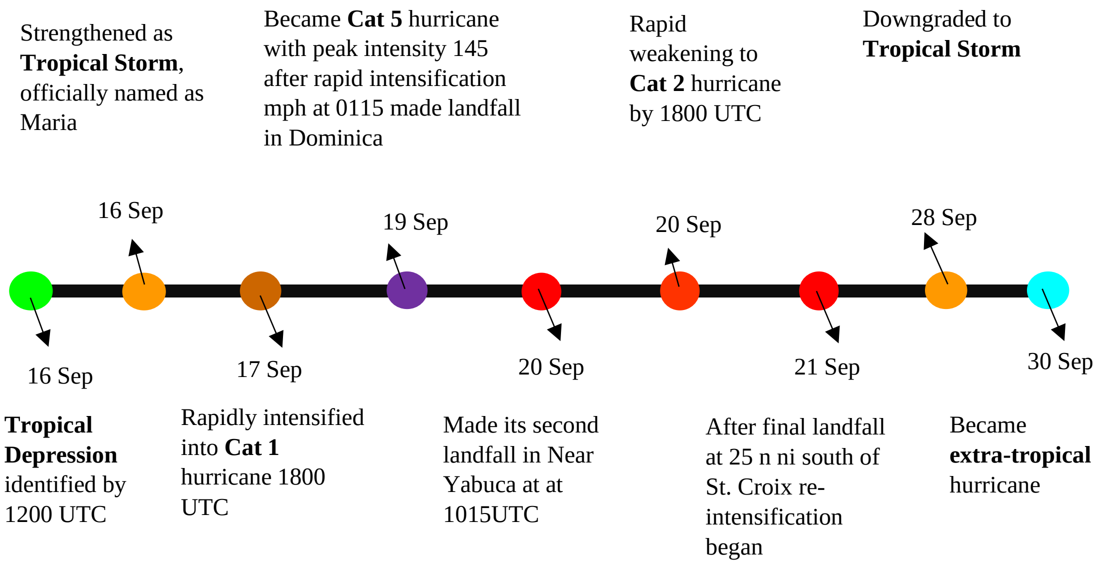


Figure 7.8 Timeline of Hurricane Maria (16 – 30 September 2017) [source: Pasch et al., (2017)]

Due to the mountainous islands of Dominica, the hurricane lost its interaction after its first landfall in Dominica. The loss of synergy created by the interruption of the mountainous islands of Dominica weakened the system downgrading it to a Category 4 hurricane. The storm made its second landfall near Yabucao Puerto Rico, on 20 September at 1015 UTC with 155 mph wind speed while continuing to grow in its size. Maria holds the record of being the strongest hurricane to make landfall in Puerto Rico since Hurricane Segundo, San Felipe in 1928 (Pasch et al., 2017). Table 7.6 shows the landfall history of Hurricane Maria.

Table 7.6. Landfall synopsis of Hurricane Maria (2017) [source: Pasch et al., (2017)]

Date	**Time (UTC)**	**Landfall Location**	**Country**	**Category During Landfall**	**Max. Wind (knots)**	**Max. Wind (mph)**	**Min Pressure (mb)**
19-Sep	0115	Dominica	Dominica	5	145	167	922
20-Sep	1015	Near Yabucoa	Puerto Rico	5	135	156	920
20-Sep	0300	25 n mi. south of St. Croix			150	173	908

The hurricane continued to gradually weaken and did not regain its peak intensity of 155 mph but maintained the major hurricane status until 0600 UTC 24 September 2017.

Figure 7.9 shows that neither the storm weakened nor shifted or deviated from its course until its three landfalls. Further, weakening to a Category 1 took place by 0600 UTC 27 September and lost its storm elements and became a tropical storm on 28 September. The storm became extra-tropical by 1800 UTC 30 September. A further detailed author's adapted version of structural change data, of Hurricane Maria, and the projected pathway, and the hurricane's watch-warnings issued by the NHC is included in Appendix B. This warning includes air pressure, wind field and strengthening or weakening of hurricane structure.

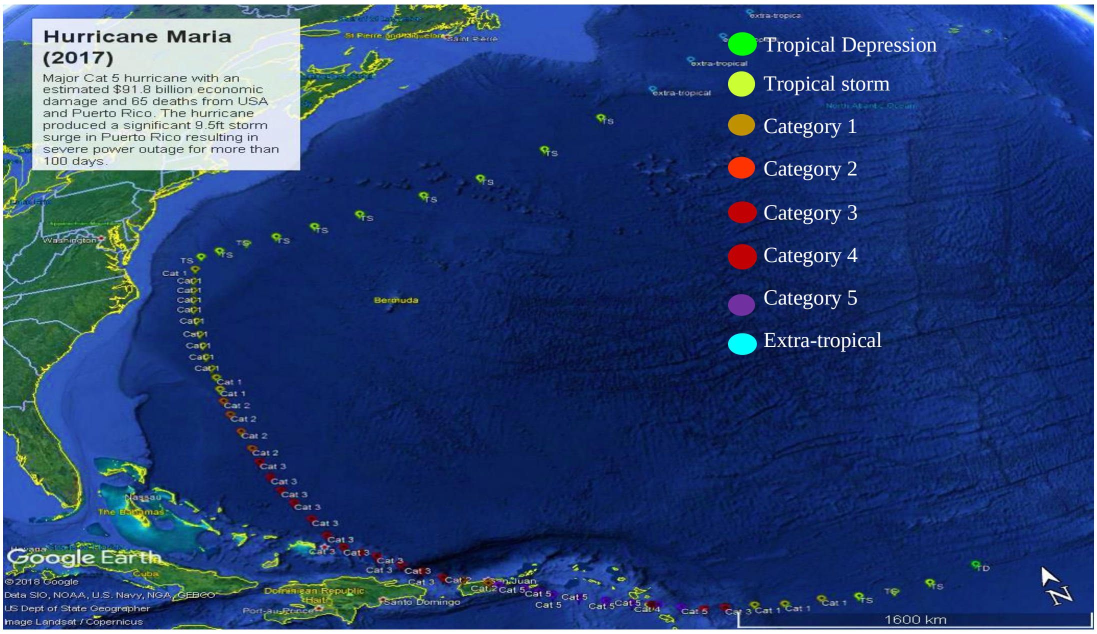


Figure 7.9 Hurricane Maria's projected path with colour coded themes for different hurricane categories (version adapted by the author using Google Map)

7.8 The disaster phases of Hurricane Maria

7.8.1 Preparedness within Puerto Rico

The National Hurricane Centre (NHC) provided warnings and forecasts to Puerto Rico, 54-hours ahead of Hurricane Maris's landfall (Folger, 2018). Around 6,200 personnel of the National Guard team were deployed during the preparedness phase of Maria to initiate various activities such as evacuation, shelter set-up, the supply of emergency kits, standby search and rescue teams (Inserra et al., 2018). As per the Caribbean Disaster Emergency Management Agency's (CDEMA) the first situation report issued on 20 September 2017, a structural change in the hurricane path was anticipated by the Caribbean Institute for Meteorology and Hydrology (CIMH). As per CIMH's anticipation, Hurricane Maria was expected to weaken to a Category 4 hurricane before Puerto Rico and US Virgin Islands (USVI) (CDEMA, 2017).

Prior to Hurricane Maria, another Hurricane Irma was forecasted to make landfall in the middle of the Puerto Rican island as a major hurricane. In contrast, Hurricane Irma maintained its course drifting away from the north of Puerto Rico and did not make a landfall, as predicted, and warned by the hurricane forecasters. The early warnings and the preparedness for Hurricane Irma which came about two weeks earlier than Hurricane Maria remained stationary. This further made the Puerto Rican residents underrate the approaching hazard from Hurricane Maria. Because the government was prepared and mobilized to respond for Hurricane Irma, the officials and the residents were at the verge of facing Hurricane Maria with the same preparations. However, Hurricane Maria largely varied from the structure and pattern that were of Hurricane Irma (Rivera, 2019). This clearly defines how a similar type of hazard can potentially vary and largely influence the storm surge characteristics. This further underlines the gap in hurricane prediction and resultant storm surge prediction.

According to NOAA the genesis of Hurricane Maria was not well-forecast, and this was attributed with the failure in hurricane monitoring and forecast. The cyclone formation occurred faster than the NHC's prediction which was critical for early warning and preparation for emergencies (Folger, 2018). The regional observation and early warning centre in St. Maarten and Puerto Rico were exposed to Hurricane Maria and the heavy winds of Maria damaged the observation centre as the storm approached near Puerto Rico. Due to the destruction of radars, the forecast was obstructed resulting in the unavailability of ground data impeding the issuance of early warnings to the coastal residents (World Meteorological Organization, 2018).

A recent study (Rivera, 2019) stated that the Puerto Rico Emergency Management Administration (AEMEAD) which manages the Catastrophic Hurricane Plan, and its protocol was not properly followed by Puerto Rican government during Hurricane Maria. The report further highlights that one of the sub-plans of AEMEAD's which is the 'Distribution Plan' was awaiting approval of execution. The unapproved distribution plan did not give a clear answer to the first responders whether to operate or not during Maria's response (Rivera, 2019).

7.8.2 Response within Puerto Rico

Hurricane Maria was recorded as the tenth most powerful Category 5 hurricane to hit the Puerto Rico region (Inserra et al., 2018). The Federal Emergency Management Agency (FEMA) and the Federal Communications Commission (FCC) together supported during the response phase of Hurricane Maria through its Emergency Support Function #2 (DHS & FCC, 2018). The National Guard team also extended their support during the response phase involving activities such as transportation of medical emergencies, debris removal and various related key activities (Inserra et al., 2018). As Spanish was the main communication language in Puerto Rico, the language became a barrier for the first responders from the US mainland to communicate and coordinate emergency assistance (CMTS & RIAT, 2018).

Puerto Rico's power grid was one of the critical infrastructures in the path of Maria and was adversely damaged by its effects (Department of Energy, 2017). According to the FCC during Hurricane Maria, there was no widespread reports or calls from the US Virgin Islands and Puerto Rico territories were recorded (DHS & FCC, 2018). This was because the emergency 911 call centres in both US Virgin Islands and Puerto Rico were impacted truncating the services completely from reaching the American mainland for back up and support. It is to be noted that only four emergency call centres were available in Virgin Islands and Puerto Rico serving two each for a total of 3.4 million population (DHS & FCC, 2018). An incident management team which includes the Department of Homeland Security-led emergency support function activated the Disaster Information Reporting System (DIRS) and supported during Maria's response phase (DHS & FCC, 2018).

Even before Hurricane Maria's landfall, around 60,000 houses were without power from the impact of Hurricane Irma which occurred two weeks earlier and this was an already existing situation in Puerto Rico (Inserra et al., 2018). With an existing critical condition of power infrastructure, Puerto Rico faced two hurricanes within a two-week time difference between them. The federal response both in-field and off-field observed by the US Senate was identified as inadequate. The Office of Management and Budget (OMB) communicated regarding disaster information and supported with funds from the Presidential team. The overall crisis management of OMB under certain key contacts was observed to be poor (Warren, 2018). However, the Department of Energy (DoE) together with FEMA, and Defence Logistics Agency (DLA) partnered with other federal departments during the response and facilitate the necessary resources (Department of Energy, 2017).

The Puerto Rico Electric Power Authority (PREPA) reported that 80% of the island's energy transmission and power distribution lines were either damaged or destroyed leaving most of the social infrastructure such as schools, hospitals, private homes inaccessible and caused severe business interruptions (Inserra et al., 2018). The devastation of the power grid left the territories with days of power-outage and the response towards the restoration of the power grid became critical (Marsters & Houser, 2017; Department of Energy, 2017). The devastation visibly highlights the vulnerability of power infrastructure and their significance during emergencies as a key lesson to be learnt.

In general, the shipping cost from the US to Puerto Rico was higher than shipping from the nearby islands (Inserra et al., 2018). This also impacted the shipping of emergency supplies post-Maria. The transportation and logistics were blocked resulting in the breakdown of supply chain operations and management leaving the first responders to arrange alternate solutions for transportation and means to access the victims and carry out the response and recovery operations (CDEMA, 2017).

The roadways were impacted with over 4 million cubic yards (approx. 3 million cubic metres) being damaged slowing the responder and the recovery process (CMTS & RIAT, 2018). Housing was the next major infrastructure that was adversely impacted by Hurricane Maria. As per the rough estimate provided by the Governor of Puerto Rico, around 87,094 houses were destroyed and 472,000 houses suffered serious damage, and another 385,703 sustained major damage (Oxfam, 2018). The impact of Hurricane Maria also affected an estimated 70% of potable water access (Oxfam, 2018).

The domestic shipping lines sustained the challenge of continuing the service to San Juan, Puerto Rico highlighting the significance of local stakeholders in disaster response and recovery (CMTS & RIAT, 2018). Although, the overall response was observed as beyond the capacity of the federal government on the plus sides Hurricane Maria's response shared the lessons learned from previous hurricane Harvey and Irma. The inter-agency collaboration was considered a significant achievement.

7.8.3 Recovery within Puerto Rico

A month after the landfall of Hurricane Maria, 75% of the island's which had 3.4 million residents were found with no electricity restored in St. Croix, St. Thomas, and St. John (Marsters & Houser, 2017). The government of Puerto Rico initially expected that 95% of the power restoration to be completed by the end of 2017. However, the restoration of power and potable water service was delayed longer than expected. By the end of 2017, only 65% of power was restored and by the end of April 2018, 97.31% of the residents were restored with power i.e., after seven months of restoration efforts (Centro, 2018).

After the catastrophic impact of Hurricane Maria in Puerto Rico, many displaced residents never returned and relocated to the mainland US especially to Florida, where many of the displaced and relocated population were reported to have welcomed (Inserra et al., 2018). Nearly 160,000 Puerto Ricans were reported as relocated to the US mainland (Centro, 2018).

Recovery process was prolonged and delayed by various factors. The territory's communication infrastructure almost froze to a static state for a few weeks after the landfall.

The combined effect of lack of power supply, shortage of supplies and resources, adversely damaged telecommunication poles and broadcasting antennas together contributed to the overall damage of the country's communication system (DHS & FCC, 2018). By mid-June 2018, 98% of the telecommunication was re-launched i.e., after nine months (Centro, 2018). More than 9,600 victims were provided temporary housing in Puerto Rico and 38 US states which were activated by FEMA through its Transitional Sheltering Program (TSA) for the displaced victims by 20 December 2017 (Centro, 2018; FEMA, 2017).

Figure 7.10 Road adversely damaged by Hurricane Maria [Image: Ricardo Arduengo /APF (BBC News, 2018)]

Figure 7.10 shows how the transportation infrastructure was severely impacted which further impeded the recovery. The Marine Transportation System Resilience Integrated Action Team (RIAT) activated by the US Committee on the Marine Transportation System (CMTS) claimed that Hurricane Maria left a major damage impact on the Marine Transportation System (MTS) (CMTS & RIAT, 2018).

During Phase-3 recovery stage, the assessment of the damage in Puerto Rico and the US Virgin Islands from both Hurricane Irma and Maria was underestimated thereby leading to inadequate funding requests. Although, the US House of Representatives who observed the magnitude of the damage and granted additional funding, this was stated by the Puerto Rican government as insufficient to recover from the catastrophic damage incurred by Hurricane Maria in both Puerto Rico and The US Virgin Islands (Warren, 2018).

By this time, the humanitarian crisis warning was flagged by the Governor of Puerto Rico and additional disaster aid was raised. This was also overlooked by the federal government and was provided with an aid in support of all three Hurricanes (Harvey, Irma, and Maria) as a conjoined disaster aid to be utilised for the recovery of Texas, Florida, and Puerto Rico. The federal government's response also exhibited delays in various situations from deploying the resources to providing disaster aid towards rebuilding (Oxfam, 2018). Due to these reasons, the recovery was prolonged more than ten months since Maria made a landfall (Warren, 2018).

The recovery phase was anticipated to extend for longer than expected. Therefore, additional humanitarian support was requested by all the stakeholders which include civil society, faith-based organizations, churches, and university students who supported the local responders post-Maria. The ad-hoc stakeholder team and their involvement aided in debris removal, restoration of potable water, and restart services (Oxfam, 2018). This highlights the importance of increasing the organisational capacities among stakeholder and suggests the consideration of enhanced stakeholder involvement.

7.8.4 Mitigation within Puerto Rico

The US Department of Housing and Urban Development (HUD) awarded US$ 1.5 billion through the Community Development Block Grant-Disaster Recovery (CBBG-DR) program towards the reconstruction of damaged house. The sanctioned grant was further utilised to cover business losses and interruptions in Puerto Rico. Hurricane Maria holds the record as one of the largest disaster housing missions in the US and its territories (Centro, 2018).

FEMA reviewed its activities of agencies who played a critical role during Hurricane Maria. The review highlighted various key issues such as agencies loss of track of resource movement, insufficiency in stacked resources, understaffing of emergency responders, lack of information during preparation and response phases (FEMA, 2017; Warren, 2018). The review not only identified key issues but also provided insights on areas to improve, adapt and mitigate for future disasters and response to be delivered by SIDS.

In March 2018, the FCC allotted US$ 954 million for the restoration and expansion of communication infrastructure, in both Puerto Rico and the US Virgin Islands and the US Army Corps of Engineers (USACE) stated that additional resources to be utilised to restore the power (DHS & FCC, 2018; CMTS & RIAT, 2018). As of 30 September 2018, the US Government of Accountability Office (GAO) and FEMA assigned around US$ 4 billion funding to Puerto Rico to mitigate the response for the 2017 Hurricanes Irma and Maria. A further US$ 3.63 billion was allocated for emergency measures like debris removal and US$ 151 million for the repair and maintenance of public infrastructure (US GAO, 2019). In August 2018, Puerto Rico developed a disaster recovery plan, which was aimed at increasing the government's capacity for building strengthening the infrastructure for future adaptation. As per the estimate total recovery cost would be US$ 139 billion with a recovery period from 2018-2028 (US GAO, 2019). The study has widely captured the extended recovery and restoration of power and water and highlights that mitigation and adaptive measures remain critical.

7.8.5 Summary of key activities and disaster phases during Hurricane Maria

Table 7.7 Summary of the key activities and their achievements observed from Case Study Maria

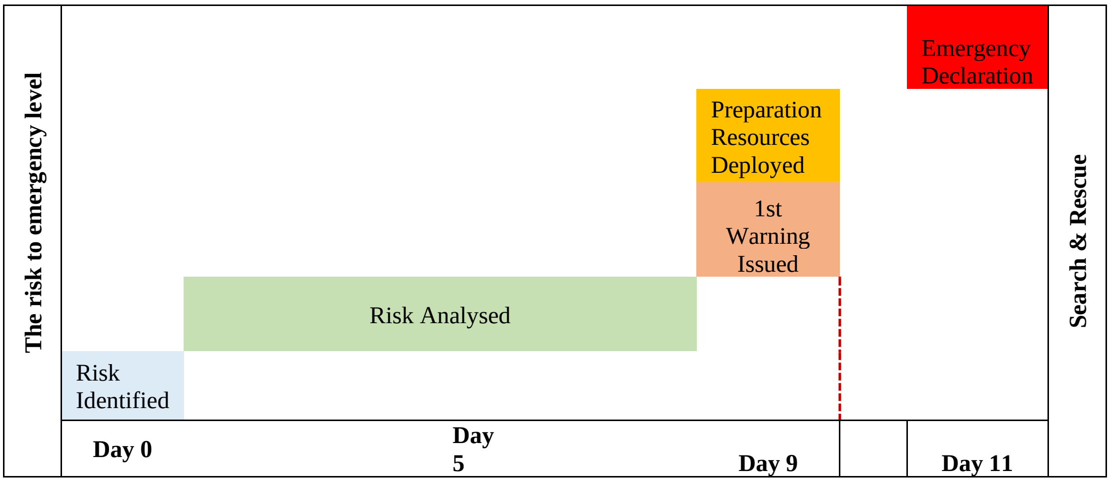
	Preparedness	***Response***	***Recovery***	***Mitigation***
Activities achieved	Declaration of emergency Deployment of resources Early warning Emergency planning Forecasting Risk analysis Risk identification Hazard assessment Monitoring	Transportation Emergency shelter Telecommunication Incident stabilization Construction	NGO and volunteers Search and rescue Humanitarian aid Debris removal Health care Insurance Organisational capacity Reconstruction Recovery Relocation Temporary shelter	Lessons learnt Multi-agency approach Relocation
Activities unachieved/ unidentified	Vulnerable population Scenario planning Technical prevention Capacity building	Power and utility Business interruptions Vulnerable population	Communication Coordination Damage assessment Power and utility Infrastructure Improving livelihoods	Public awareness and education Scenario planning Technical prevention Stakeholder involvement Strategic alternative approach Power and utility Wetland mitigation Training and exercise

The key activities observed during the four main phases of the DRM cycle is summarized in Table 7.7. The key activities were extracted through both coding and document sources. Failure to achieve the key activities were mainly due to Puerto Rico being a non-UN SIDS with limited resources and language barrier being a hurdle to communicate and request for additional support.

While observing the key activities the following timeline gap was also observed as shown in Table 7.8. The table shows the date of risk identification and issuance of the first official warning, between which eight days of an inactive period during which the preparation activities observed for Irma was continued for Maria.

However, the change in hazard and the vulnerability was not assessed in support of the DRM activities. This further remark that if the key activities and their corresponding phases were adapted according to Maria, the possibility of the current incurred death toll of 2,965 could have been possibly reduced.

Table 7.8 Overview of the timeline gap and risk emergency level observed during Hurricane Maria



7.9 Physical damage and loss statistics

Hurricane Maria, which made the first landfall in Dominica, killed 31 people, and resulted in significant structural damage (Folger, 2018). The official report from the NOAA states that in Puerto Rico the death toll was 64 (Pasch et al., 2017). However, this death count majorly differs with a study performed by George Washington University's Milken Institute of Public Health. Due to various reports on unsubstantiated death counts, the Governor of Puerto Rico raised an assessment of actual death toll attributed to Hurricane Maria (Milken Institute School of Public Health, 2018). This study was based on the actual death certificates, which confirms that 2,975 was the precise death count associated with Hurricane Maria (Milken Institute School of Public Health, 2018).

It remains debated as the indirect death need not necessarily attributed with the direct deaths from the hazard, which may be misunderstood (Folger, 2018) but the death toll in FEMA's reports the official death toll from Maria is 65 (updated 14 Feb 2019). Despite the storm surge being less than other hurricanes (i.e., > 6 ft), the recovery phases were particularly hampered due to the excessive wind-borne damage coupled with water damage (Select Bipartisan Committee, 2005) as shown in Figure 7.11.

Figure 7.11 Aerial view of damage inflicted by Hurricane Maria in Puerto Rico [Image source: FEMA/ Yuisa Rios]

As per of NOAA's estimation the storm resulted in estimated economic damage worth US$ 90 billion and became the official third costliest hurricanes in the US and its territories after Hurricane Katrina (2005) and Hurricane Harvey (2017) which replaced Hurricane Sandy (2012) (Folger, 2018).

Puerto Rico was one of the big pharmaceuticals and medicine manufacturing hubs for the US mainland. After the event, Puerto Rico’s sales dropped by 20.7 % versus its previous year’s sale. The force of Hurricane Maria resulted in the closure of factories and affected many production industries largely impacting the territory’s economy and exports, which were already enduring declining trend before the event (CMTS & RIAT, 2018).

7.10 Impact of storm surge

A maximum inundation level from 6-9 ft (1.8- 2.7) above the ground level was produced during Hurricane Maria as a combination of storm surge and storm tide (Pasch et al., 2017). These levels were observed near the coast of Humacao, Naguabo. Figure 7.12 shows the storm surge flooding in the San Juan, Puerto Rican communities.

Figure 7.12 Storm surge flooding in Puerto Rico [Image source: CBS News]

According to the US Geological Survey (USGS), high watermarks measured 4.9-5.1 ft (~1.5 m) above the ground level in Punta Santiago, Humacao. Other technical readings suggest that the near shoreline had surge levels as 9 ft (2.7 m) above the ground level. Along with south-eastern Puerto Rico, inundation levels were observed as 4-7 ft (1.2 -2.1 m) (Pasch et al., 2017).

7.11 Adaptive measures taken over post-Maria

In early September 2017, Hurricane Irma made its landfall in the US Virgin Islands (USVI), then in Puerto Rico, followed by Florida (DHS & FCC, 2018). Within two weeks times, Hurricane Maria made its landfall in the previously hit USVI and Puerto Rico. Therefore, the infrastructure damage and the death toll from Hurricane Maria is viewed as a combined effect of a previous Hurricane Irma which made landfall in two of the same locations. However, Hurricane Irma did not make a direct landfall and it barely brushed through the north of Puerto Rico. Hence, the magnitude of Maria's damage must be assessed individually and not to be foreseen as a combined effect (CMTS & RIAT, 2018).

Post-Hurricane Maria, the country suffered significant socioeconomic damage (Orengo-Aguayo et al., 2019; Centro, 2018). Puerto Rico's economy experienced a severe impact that the territory suffered financial bankruptcy after a year since Hurricane Maris's landfall (Centro, 2018). Societal impacts were also observed higher than usual especially those vulnerable age group including young adults.

Studies revealed that the residents were exposed to both direct and indirect impacts from Hurricane Maria by being exposed to numerous stress associated with the storm (Orengo-Aguayo et al., 2019). The Department of Education of Puerto Rico closed around 265 schools throughout the island (Centro, 2018). Considering the impacts from hurricane-led storm surge impacts of Maria, adaptive measures to mitigate a future scenario is vital. However, the US territory is currently in the extended recovery phase and various measures were taken to recover from the disaster, therefore, adaptive measures were observed to be critical.

7.12 Summary

The case study of Hurricane Matthew and Maria have provided understandings and aspects of DRM and DRR strategies currently practised in Haiti and Puerto Rico. One of the key differences observed between the two storm surge events that occurred in Haiti and Puerto Rico is the association with the United Nations. Haiti being a UN member of SIDS, received support both from the UN and its partnered agencies. But Puerto Rico is a non-UN member of SIDS had to manage within its capacities and bounded with limitations. Despite having experienced storm surge impacts in the past, no major adaptations or preparedness were practised, resulting in the significant damage to coastal communities, housing, and critical buildings in Haiti and Puerto Rico. If not for the UN's teams who were already based in Haiti for the recovery of the 2010 earthquake, it would have been a far more severe impact and longer-term recovery. Therefore, an action plan of enhancing the preparedness is vital for both these countries. Learning lessons from Haiti and Puerto Rico's responses, countries which have a multi-hazard profile and whose adaptive capacity is inadequate should consider a framework approach as a step of preparing for the worst possible scenarios ahead of time compared to developed countries. It is even more critical for island countries and communities, where there may be insufficient geographic territory to move to and deploy for safety. Some common activities exhibited from the case study observations were considered for further analysis leading further towards the development of the DAMSS framework.

CHAPTER 8

ANALYSIS, INTERPRETATION AND PROPOSAL OF THE FRAMEWORK

8.1 Introduction

This chapter discusses the cross-case analysis of individual cases, that were previously observed in Chapters 5, 6, and 7. This chapter further discusses the phases of disaster risk management that were previously examined via the case studies, providing the opportunity for analysis and interpretation of the collected data. The findings, analysis and detailed interpretation then supported in the development and proposal of the DAMSS framework, and the outline of the guidelines.

8.2 A cross-case analysis

The case studies discussed in Chapters 5, 6, and 7 are examined further using the cross-case synthesis. According to Yin (2014), there are no well-defined techniques in carrying out the analysis of case study evidence. In this study, the chain of case study evidence collected is displayed for further analysis and interpretations. The cross-case analysis allowed data comparison of individual cases, to identify patterns and then led to the analytic generalization of the observations. For that purpose, a combination of computer-assisted tools, such as Atlas.*ti*, from which the materials, evidence, coding (by activity), memos, quotations generated and the findings in previous chapters were considered together. By listing the approaches of the phases, limitations and the key lessons from various events, identification of linkages (if any) is carried out. This further supported in interpreting the common factors versus differences, which assisted in the final findings leading to the proposal of the DAMSS framework. Table 8.1 shows the four key themes of DRM and correspondingly grouped key activities observed across the six case studies. The key activities are marked with a tick (✓) symbol to show that these activities were achieved or identified during the execution of the different phases of the DRM. The key activities marked with the cross (×) symbol to show that these activities were unachieved or not identified during the execution of the different phases of the DRM. The difference between an activity being achieved or identified can be understood via a small example of case study Hurricane Katrina. In Case Katrina, key activity ‘forecasting’ (preparedness phase) is marked as (✓) means, activity is achieved whilst the key activity ‘damage to telecommunication’ (response phase) marked as (✓) means, activity is identified.

Table 8.1 Cross-case syntheses of the four main phases of Disaster Risk Management (data compiled from the six cases and their activities)

Phases of Disaster Management	Key activities/ areas	Katrina	Nargis	Sandy	Haiyan	Matthew	Maria
Preparedness	Forecasting	✓	✗	✓	✓	✓	✓
	Monitoring	✓	✓	✓	✓	✓	✓
	Early warnings	✗	✗	✓	✓	✗	✗
	Execution of the emergency plan	✗	✓	✓	✓	✓	✗
	Activation of the response plan	✓	✗	✓	✗	✗	✓
	Capacity building	✗	✗	✓	✓	✗	✗
	Risk identification	✓	✗	✓	✗	✓	✓
	Risk Communication	✗	✗	✓	✗	✗	✓
	Declaration of Emergency	✓	✓	✓	✗	✓	✓
	Storm surge hazard assessment	✗	✗	✗	✗	✗	✗
	Training & exercise	✗	✗	✗	✗	✗	✗
	Prior Community outreach for preparedness	✗	✗	✓	✗	✗	✗
	Prior deployment of resources	✓	✗	✓	✗	✗	✓
	Scenario planning from previous experience	✗	✗	✗	✗	✗	✗
Response	Evacuation	✓	✗	✓	✓	✗	✓
	Risk analysis	✓	✓	✓	✗	✗	✓
	Communication	✗	✗	✓	✗	✗	✗
	Coordination	✗	✗	✓	✗	✗	✗
	Resource deployment during response	✓	✗	✓	✗	✗	✗
	Emergency shelter	✓	✓	✓	✓	✗	✗
	Humanitarian assistance	✓	✓	✗	✓	✗	✗
	Humanitarian aid	✗	✓	✗	✓	✗	✗
	NGO, INGO's and volunteers	✓	✓	✓	✓	✓	✓
	Incident stabilization	✓	✓	✓	✓	✓	✓
	Mass care	✓	✗	✗	✓	✓	✓

Phases of Disaster Management	**Key activities/ areas**	**Katrina**	**Nargis**	**Sandy**	**Haiyan**	**Matthew**	**Maria**
	Damage to telecommunication network	✓	✓	✓	✓	✓	✓
	Transportation issues	✓	✓	✓	✓	✓	✓
	Power outage and utility damage	✓	×	✓	×	×	✓
Recovery	Damage assessment	✓	✓	✓	✓	✓	✓
	Search & rescue operation	✓	✓	✓	✓	×	×
	Rehabilitation	✓	✓	✓	✓	×	×
	Restoration	×	×	✓	✓	×	✓
	Reconstruction	×	×	✓	✓	×	×
	Debris removal	✓	✓	✓	✓	✓	✓
	Insurance	✓	×	×	×	×	✓
	Improving livelihood	✓	×	✓	✓	✓	✓
	Organisational capacities	✓	×	✓	×	×	×
	Temporary housing	×	✓	×	✓	✓	✓
	Health Care	✓	✓	✓	✓	✓	✓
Mitigation	Improved coastal protection	✓	×	✓	×	×	×
	Land use planning	✓	✓	✓	✓	×	×
	Technical prevention	✓	×	✓	×	×	×
	Public education & awareness	✓	✓	✓	×	✓	×
	Sustainable infrastructure	✓	×	✓	×	×	×
	Implementation of previous lessons learnt	×	×	✓	✓	×	×
	Strategic alternate approach	×	×	×	✓	×	×
	Environment	×	×	×	✓	×	✓
	Wetland mitigation	×	×	✓	×	×	✓
	Stakeholder involvement	✓	×	✓	×	×	×

The systematic execution of the ‘filter codes’ (e.g., keywords, actions, and processes) across various documents as key activities are compiled as shown Table 8.1 to display the array of activities grouped under the four main phases of DRM.

Table 8.1 also shows some key activities marked with the cross (×) symbol across the case study events. This is an interesting factor that, key activities such as the 'storm surge hazard assessment', 'training or exercise' are not identified across all the cases. Although these are crucial in storm surge understanding, yet, they are not carried out as part of the disaster management phases. This is a clear observation of how storm surge hazard is not assessed across different case study events which occurred between 2005- 2017. Key activities with a cross (×) symbol also underline that it is vital to adapt or mitigate these areas which is key to minimising the socioeconomic losses.

The identification of the list of key activities in individual cases resulted in deriving one or more uniform activities. This process of capturing the findings from all the six cases was selected as commonalities and differences, and a detailed reporting is discussed further in section 8.2.1- 8.2.4. Within these sections, the cross-case syntheses shown in Table 8.1 is further discussed using the relevant coding and data obtained from the coding and cases while trying to answer the three key questions as follows:

- What are the key activities that occurred during the event in each case?
- What are the factors responsible for the occurrence of these patterns of issues and their connection to the key themes?
- What is unique about these factors and their nature of repetition across more than one case study?

The discussion of the critical factors which hindered the execution of DRM strategies was identified as commonalities framing the Disaster Adaptation and Mitigation framework for Storm Surge (DAMSS) resilience and future adaptation.

8.2.1 Phase 1: Analysis of Preparedness stage

According to UNISDR (2009), the essential dimensions required to disseminate meaningful warning is to enable the vulnerable communities, organisations, and any individuals threatened by a hazard with sufficient time to prepare and act accordingly. Early warnings are considered as an essential step in reducing the direct loss of lives from the hazard. Geographic information and related technologies have improved within disaster management; however, inadequate early warnings can potentially weaken such advancements resulting in country's incapability to respond to such disaster. An effective early warning system with people-centred approach includes four key elements days (United Nations International Strategy for Disaster Reduction, 2009). An author adapted version of an early warning system comprising the four key elements as highlighted by the UNISDR is shown in Figure 8.1.

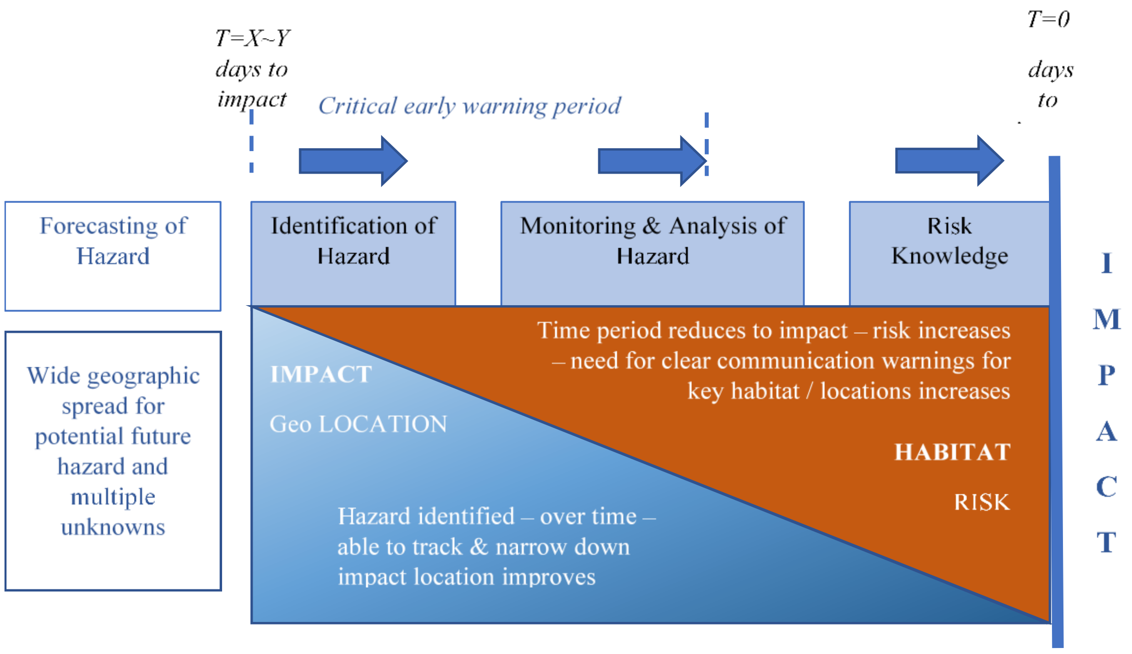


Figure 8.1 Author adapted version of four key elements of effective early warning suggested by UNISDR, highlighting the critical warning period before impact.

Figure 8.1 further shows the progression of different elements within the early warning system starting from T = X~Y days, to T=0 impact. The period of '*critical early warning'* emphasises the risk of communication to be disseminated to the coastal communities to reduce the loss of lives. Executing the observed action versus the proposed action by UNISDR, the following commonalities were observed across the series of multiple case studies and listed in Table 8.2.

Table 8.2 Identification of critical factors in the cross-case syntheses of the preparedness phase

Common key issues identified during preparedness	**Observation from coding**
Lack of early warning *No time to prepare*	- Hurr. Katrina: early warning issued 24-hrs before landfall, leaving the residents with insufficient time to prepare. Complicated evacuations leading to the non-evacuation situation, and a contributing factor towards 1,800 deaths. Certain population group did not receive any warning at all. - Cy. Nargis: lack of monitoring and forecasting issues, inactive or slow actions observed during

Common key issues identified during preparedness	**Observation from coding**
Lack of monitoring and forecasting *Lack of awareness* *Slow preparations*	the early stages. Officials alerted about the approaching hazard shortly before the landfall. Lack of early warnings directly resulted in non-evacuation, causing 140,000 deaths of the residents from the delta region. - Ty. Haiyan: due to lack of awareness especially storm surges, early warnings were issued on other hazards such as rainfall, landslides, and heavy winds. No warning issued regarding storm surges or their inundation levels. - Hurr. Matthew: Haiti was issued with early warnings mainly using radio, as their mode of communication of early warnings. Preparedness was generally slow and exhibited insufficient usage of the early warning system.
Lack of public awareness and education *Language barrier* *Lack of experience* *Lack of awareness*	- Hurr. Katrina: Non-evacuation of 25,000 residents, disabled, and vulnerable people were not advised about evacuation routes. Language barrier such as non-English speaking residents were not translated regarding storm warning or evacuations or storm-related instructions. - Cy. Nargis: The residents never experienced before a cyclone or storm surge in the Ayeyarwady delta region. Exposed to the hazard for the first time and residents were completely unaware of the hazard. Most of the resident in LECZs stayed back. - Ty. Haiyan: Residents have prior experience about typhoons and their heavy winds but unaware of 'storm surge'. Effects of storm surge were not interpreted in the local language

Common key issues identified during preparedness	Observation from coding
Unawareness of hazard	'Tagalog'. Emergency responders themselves were unaware of the hazard to communicate them to the residents. Fatalities of more than 6,300 lives after the landfall due to partial issuance of the early warning system and lack of public awareness of the hazard. The casualties list also included emergency responders who remained without evacuating and waiting for further order from officials. - Hurr. Matthew: Officials warned and provided early warnings 5 days in advance. Despite pleas and warning, residents stayed back ignoring evacuation. Due to the usage of radio as a warning system, residents in remote locations (no radio signals) were unaware of the hazard. Only coastal outlying residents were evacuated to the mainland.
Lack of risk communication *Poor dissemination of risk communication*	- Hurr. Katrina: The residents of the city of New Orleans, specifically the highly populated communities next to the Lake Pontchartrain was not communicated about the forecast or predictions. Officials were aware of the exposure of risk from Katrina entering the Gulf of Mexico continued to delay the process of communicating the leading to federal failures. Despite the deployment of resources in advance and readily available in standby condition, poor dissemination of risk communication led to a dormant situation with no effective action done during this period.

Common key issues identified during preparedness	Observation from coding
Singular-end communication	- Cy Nargis: Weak telecommunication infrastructure was identified in Myanmar. The only source of communication is by the official emergency teams, local authorities such as the Burmese Military Junta. Many residents did not have a mobile phone as mobiles were considered expensive and satellite phone was illegal and prohibited. Spreading of communication was very limited and restricted in a few areas.
Lack of clarity	- Ty. Haiyan: Residents were informed of partial risks using local radio to broadcast the disaster communication and verbatim was used during storm surge risk communications which lacked clarity. Many residents reported they did not understand the term ‘storm surge’ which was communicated by PAGASA.
Inadequate broadcasting of risk communication	- Hurr Matthew: Residents were aware of the early warning system in place. But the EWS depended mainly on radio broadcasting which was reported as not broadcasted in many areas. Especially those residents located remotely in mountainous regions, and tribal groups did not receive any communication.
Lack of interpreters, language barrier	- Hurr. Maria: Residents were warned and communicated about the risk. The magnitude of Maria was extensive and damaged most of measuring devices and instruments leading to loss of ground data. This made officials rely on neighbouring countries for the forecast. Language barrier was identified in

Common key issues identified during preparedness	Observation from coding
	communicating further risks due to the lack of interpreters.
Failure of hazard assessment and risk analysis *Weak hazard analysis* *Lack of risk analysis* *Hazard underestimation* *Underestimation of storm surge prediction levels*	- Hurr. Katrina: the risk was identified in advance by NHC, but the rapid intensification and the structural changes of Katrina were not estimated. The risk from the coastal flooding (storm surge) was predicted but the compounded effects of storm surge were not assessed. Being concerned of an already existing levee crack, associated risks such as the potential funnel-effect of storm surge in the creeks and bays of the Mississippi River leading to river over topping was not assessed suggesting weak hazard analysis. - Cy. Nargis: Lack of data on storm surge risk or related hazard analysis. Indian Meteorological Department (IMD) and Joint Typhoon Warning Center (JTWC) warned the hazard 48 hrs. in-advance. No further analysis was carried out by the authorities of Myanmar. - Hurr. Sandy: public and officials were prepared for the hurricane. But Sandy underwent a deviation in path, structural change and downgraded to a tropical storm and lost hurricane status. This made tropical warnings to be downgraded as a tropical storm watch. The hazard is underestimated as many residents stayed back stocking up on emergency supplies.

Common key issues identified during preparedness	Observation from coding
	- Ty. Haiyan partial analysis of hazard was identified. Due to oversight of above 7 ft storm surge levels, the accuracy in prediction was compromised leading to underestimation of storm surge levels. - Hurr. Maria storm surge warning was issued but their predicted levels were underestimated.
Declaration of emergency (DoE) *Delayed DoE* *No DoE* *DoE just before landfall*	- Hurr. Katrina: Delayed DoE. The then Mayor was waiting for Presidential declaration. DoE was ordered once the President requested to Mayor of New Orleans to issue orders. This was also associated with the issue of non-evacuation of coastal residents. - Cy. Nargis: Declaration of Calamity was declared 3 days after the landfall. - Hurr. Sandy: DoE 24 hrs. before landfall. - Ty. Haiyan: DoE 24 hrs. before landfall. - Hurr. Matthew: Instead of DoE, a red alert was issued 48 hrs. before landfall. - Hurr. Maria: DoE declared by the US president 24 hrs. before landfall.

In line with Neussner statement, “Messages have to be clear and unambiguous” (2014, p. 43). This emphasises how communication is an important factor within emergency management. This can be understood from the data from Table 8.2 highlighting the lack of an early warning system (EWS) directly resulting in loss of lives. Deciphering the early warning systems to coastal communities in a way they understand is an important factor within emergency management (Neussner, 2014).

Variations within early warnings include Katrina's delayed early warning; Nargis's no early warning; Haiyan's and Matthew's efforts of partial early warning; and Maria's lack of EWS from loss or interruption of instruments further resulting in the non-availability of ground data. These variations also highlight the significance of preparedness required for an effective early warning system. Regarding, 'risk monitoring and forecasting' only case Cyclone Nargis was identified where the country failed to monitor the risk.

Quotation 16: on Early warning

7:10 FINAL_REPORT_re_Effects_of_Typhoon_YOLANDA_(HAIYAN)_06-09NOV2013 (14:130:124-14:548:207) - D 7: FINAL_REPORT_re_Effects_of_Typhoon_YOLANDA_(HAIYAN)_06-09NOV2013

Content

The NDRRMC Operations Center is on **RED Alert Status** to continuously monitor and disseminate Weather Bulletins and 24-Hour Public Weather Forecasts to all RDRRMCs/OCDRCs through SMS, facsimile and websites for further dissemination to their respective Local Disaster Risk Reduction and Management Councils (LDRRMCs) from the provincial down to the municipal levels

9:3 Te Joint Research Centre (JRC) of the European Union warned of a stor...... (7:1439 [7:1742]) - D 9: Haiyan Case

Te Joint Research Centre (JRC) of the European Union warned of a storm surge on 06.11.13, while PAGASA did this one day later at 12:00h. While PAGASA overestimated the storm surge height in its forecast, the JRC and the Project NOAH storm surge estimates were closer to the actual height for Tacloban

Figure 8.2 A sample coding of the early warning system observed from case study Typhoon Haiyan through coding

From Figure 8.2 we can realise that the NDRRMC continuously engaged in monitoring the risk by issuing red alerts. While the second part of the coding highlights how evenafter, being warned for storm surge by the JRC, PAGASA delayed the risk analysis by 12 hours behind JRC's warning. This implies how a delayed risk communication resulted in socioeconomic loss, suggesting that an early warning system should primarily focus on communicating the risk to end-users and communities who are most vulnerable to storm surge hazard.

The difference between understanding the risk and lack of understanding can be comprehended in line with Fritz et al., (2009) findings. His report has identified that the coastal community of Mala, along Gwa coastline, Philippines which has faced frequent cyclones and storm surges, has employed mitigation measures such as safe shelters at high-ground and emergency and response plans. These adaptive measures were observed by the coastal residents of Mala, to have an impact on the community's progress in reducing the loss of lives. The cross-case analysis of the preparedness phase emphasised the theory of how effective step-by-step implementation of preparedness should be carried out as outlined by UNISDR. A detailed coding of the individual list of activities corresponding to the preparedness phase is produced in Appendix C.

A common key factor in the 'risk' assessments was the lack of clarity or risk regarding the habitat and housing of coastal residents. Apart from the lack of understanding, lack of early warnings made many people choose to stay in their homes and in some cases shelter in basements. Whilst occupants may have considered that there may still be a risk due to high wind speeds and lack of structural integrity of roofs, walls, and homes to withstand such forces, there appears to be little or no understanding of the lack of sufficient design of such buildings to address storm surge. This is not only about the low coastal elevation locations, but also that none of the homes, schools or hospitals or utilities were built in a raised-up position, nor had sufficient structural strength to withstand the waterborne forces.

Communities were not asked to move to higher grounds even after learning lessons from events like Hurricane Katrina. Infrastructure barriers within possible pre-deployment periods were also lacking in acute areas and communities which would be impacted most by storm surge. Despite, some case study locations having experienced previous storm surge, there had been either no changes to building regulations and planning for new housing; or any retrofit resilience measures applied to the existing housing or utilities. By looking the future storm surge resilience, likely, governments and regional authorities (within low elevated coastal communities) both in developed and developing countries required to undertake and deliver such changes to increase resilience preparedness levels for climate emergency factors.

8.2.2 Phase 2: Analysis of the response stage

The provision of emergency service and public assistance, executed immediately after the disaster, is termed as the '*response*' by the UNISDR (2009). Table 8.3 is the extraction of activities corresponding to Phase -2 response and these were commonly identified via the cross-case synthesis detailed in Table 8.1 across all the cases.

Table 8.3 Identification of critical factors from the cross-case syntheses of the response phase

Common key issues identified during response	Observations from coding
Failure of prior evacuation/ Delayed evacuation *Delay in evacuation* *No evacuation advisories* *Lack of people participation resulting in non-evacuation* *Lack of public awareness* *Partial evacuation advisories in the mainland*	- Hurr. Katrina: 25,000 residents identified as non-evacuees. Despite being aware of Katrina's potential over of the Gulf of Mexico, and the vulnerability of the Mississippi bays, residents were not evacuated. Concerns related to the delayed evacuation was linked with the delayed DoE. Re-evacuation was ordered after the Superdome which was acting as the emergency shelter was damaged. - Cy. Nargis: Failure of risk identification and early warnings further escalated to failure of evacuation. As no clear evacuation orders issued, most residents in the coastal delta region did not evacuate. - Hurr. Sandy: Mandatory evacuations were ordered twice as a precaution action to evacuate the last-minute non-evacuees. However, due to the downgraded hurricane status to a tropical storm, many residents did not evacuate despite the orders. - Ty. Haiyan: The residents of the Philippines experience 18-20 typhoons on an average. The experience of previous typhoons and super-typhoons encouraged the residents to stay back in their houses. Additionally, lack of public awareness and risk communication caused the failure of evacuation. - Hurr. Matthew: Evacuation was ordered, to the mainland and no warning or orders passed to remote locations.
Communication and coordination	- Hurr. Katrina: Lack of clarity in communication and coordination among the Federal-National-Local responders was observed. NGO's like Red Cross,

Lack of clarity *Inadequate communication and coordination* *Lack of coordination* *Communication and coordination issues* *Language barrier hampered communication and coordination*	Shelter, reported coordination issues with Federal agency (FEMA). Concerns related to communication and coordination led to delayed logistics of emergency supplies. - Cy. Nargis: Poor communication and coordination were identified when liaising with external international actors and NGO's. Unwanted restrictions to the United Nations and many established NGO's, INGO's and volunteers who were already in-field supporting the affected areas were restricted access, exhibiting poor communication and coordination issues. - Typhoon Haiyan: Language barrier in communication and coordination between local and international agencies identified. Further coordination issues were identified when NGO's forecasted the extension of recovery phase to near one year. - Hurr. Matthew: communication and coordination issues in organizing and channeling the international funding to the country's response and recovery support. - Hurr. Maria: communication issues identified in arranging Spanish interpreters and translators when the language barrier was impacting response phase.
Call for humanitarian assistance *Volunteers and stakeholder participation*	- Hurr. Katrina: No specific call for humanitarian assistance was made. However, volunteers and stakeholder's involvement were identified to support the emergency and recovery. - Cy. Nargis: Despite the request for humanitarian assistance being made by the Burmese government, a compounding factor in lack of activity was the delay in issuing visas for NGO's etc., to enter the country.

International level humanitarian assistance	- Hurr. Sandy: more than 17,000 volunteers were deployed to the affected areas. - Ty. Haiyan: The response exceeded the capacity of the Philippines government leading to the call for humanitarian assistance. National-level humanitarian agencies liaised with their partnering international agencies in coordinating the findings and relief supports.
Field- team support	- Hurr. Matthew: the humanitarian agencies already operating in the field since the 2010 earthquake and post-Ebola outbreak were coordinated for additional assistance and increased capacities.
Interruption to telecommunication led to call for humanitarian aid	- Hurr. Maria: Severe impact of the power grids and telecommunication infrastructure left the island with no cell phones, to communicate further. This led the Director of Telecommunication of Dominica to call for assistance from NGOs and volunteers in support of Puerto Rico's situation. Many hospitals were supplied with a generator from agencies operating in the neighbouring countries. ATM's (cash machines) were also non-operational due to the damage to telecommunication and power.
Lack of expertise in decision making *Lack of understanding of roles and responsibilities*	- Hurr. Katrina: Lack of understanding of roles and responsibilities and decision-making was exhibited in the earlier stages of preparedness. Many of the emergency response teams were awaiting official hierarchical orders underlining the lack of decision-making in executing the response plans.
Inflexibility and indecisive	- Cyclone Nargis: The Burmese Military Junta's stubborn stance in conducting the referendum post-landfall further exposed the country's indecisive approach of responding to a disaster. The inflexibility in negotiating with international governments hampering response was due to the

Lack of expertise	lack of expertise. Unnecessary complications (visa restrictions due to Referendum) and access restrictions to perform rapid damage assessment in the surge affected areas and exhibited poor choice of decision-making and delaying the response. - Hurr. Matthew: Haiti's economic and political conditions was a hindering factor during the execution of various activities. The poor choices of risk communications, residents left to self-respond to the disaster, and the overall slow response behaviour was identified. Lack of expertise and failure of pre-planning in key decision-making scenarios identified. However public participation with the UN's WFP, UNICEF, and other aid agencies was well-conceived.
Infrastructure *Poor building and housing infrastructure* *Lack of proper drainage system* *Inadequate communication infrastructure*	- Hurr. Katrina: Modern engineered infrastructures built to withstand 'Category 3 and above' hurricanes and their design failed to survive the hurricanes imapcts became a noticeable engineering failure. The US Army of Corps of Engineers 'levee system', The Louisiana Superdome, i-10 Twin Span Bridge, and the New Orleans pumping station were among such infrastructures. Houses were built using outdated building codes. The adverse impact on the electric grids, water treatment plants, sewage plants, pumping stations, ports, roads, bridges, telecommunication was clear evidence of non-resilient infrastructure. Except for a few structures, most of the buildings and structures were neither hurricane-proofed nor flood-proofed. - Cy. Nargis: The delta is mainly agricultural farmlands with most of the residents living in huts, mud houses and non-engineered wooden houses

	which were all completely levelled by the storm surge. The weak communication infrastructure, which had only a few communication poles and singular phone transmission lines were also uprooted or severely damaged entirely impeding the response and recovery. Power and utility suffered similar damage to that of telecommunication and no alternate back up of power generators were used.
Poor transportation, housing and power & utility infrastructure *Poor sewage and drainage*	- Hurr. Sandy: Despite Sandy's extra-tropical status, the extensive economic loss was due to cost inflicted by infrastructure damage. Seven subway tunnel inundations, Rockaway boardwalk damage, severe damage to power grids and utilities, and mass-transit facilities in low-lying lands, inundations of the waterfront communities demonstrated the city's weak infrastructure.
Poor housing, telecommunication	- Ty. Haiyan: Extreme damage to the infrastructure includes salination of freshwater, sewage system, power, utility telecommunication damage. 90% of the houses in the coastal communities of Tacloban, Leyte, Samar and Cebu regions were destroyed.
Inadequate transportation network	- Hurr. Matthew: 80% of the infrastructure such as roadways, water facilities, hospitals and schools, bridges were damaged. Over 29,000 houses and public buildings were destroyed or damaged.
Weak communication & power and utility Infrastructure	- Hurr. Maria: Power and utility infrastructure suffered extensive damage. Additionally, the communication infrastructure was also severely impacted with more than 1,600 telecommunication lines destroyed. The complete failure of power and utility systems resulted in the prolonged interruption of medical facilities indirectly contributing to the increased death post-Maria.

Power and utility *Submerged power and utility infrastructure* *Mechanical-Electrical-Plumping system* *Power Transmission line damage* *Weak power infrastructure*	- Hurr. Katrina: 80% of the city of New Orleans was inundated impacting the power and utility infrastructure. Around 2.5 million people were left without electricity. - Cy. Nargis: The country's power and utility infrastructure were the second most severely damaged infrastructure. - Hurr. Sandy: damage to the mechanical-electrical-plumbing system resulted in 8.4 million people being suffered from a severe power outage. - Ty. Haiyan: Around 1,959 transmission facilities that were connecting the entire coastal communities were damaged. - Hurr. Matthew: remote areas were hampered from accessing and suffered power outage for more than a month. - Hurr. Maria: The power and utility infrastructure faced severe impact leave 80% of the island being isolated from communications, health and further impeding the recovery process. 95% of the island's power was restored nearly after 7 months.
Lack of deployment of resources *Lack of coherence* *Restricted supply of resources* *Constricted resources*	- Hurr. Katrina: resources were deployed and were in standby. However, coordination issues impacted the flow and the availability of the resources. Though, resource deployment was within the capacity of the federal government, lack of coherence caused a resources paucity. - Cy. Nargis: Access for the restricted sites were granted only after 2-3 months from landfall limiting the supply of resources. Access restricted areas also faced poor distribution of the resource. - Typhoon Haiyan: Logistics was severely impacted, due to damaged road routes. There was no prior

	deployment of resources, and post-landfall access to resources was constricted.
Lack of resources	- Hurr. Matthew: The country's economic capacity led to shortage of resources. Resource deployment was carried out by NGO's already working in the field since the 2010 earthquake. Remotely located residents needed access to energy and other resources such as radios and even batteries which precluded them from access to EWS.
Transportation *Gridlock and traffic*	- Hurr. Katrina: Transportation blockage with gridlocks and traffic jams, railroads damages were identified.
No road routes	- Cy. Nargis: Remote region in the Ayeyarwady delta, could only be reached via boat, which even became inaccessible due to the debris piling up and blocking routes and hampering roadways.
Subway tunnel inundated	- Hurr. Sandy: Severe interruptions in the transportation network, subway tunnel inundations, blocked 80% of the city's transportation routes. The emergency vehicles which were assembled for standby were also inundated and remained unused.
Extensive blockage from debris	- Ty. Haiyan: With roadways severely being impacted, and delay in debris removal further blocked the airport access hindering the alternate logistics and supply of resources, and INGO's arrival impacting recovery.
Collapse of bridge	- Hurr. Matthew: roadways suffered severe damage and truncated transportation of emergency supplies. Breakdown of bridges hindered supply of emergency and relief supports.
Loss of telecommunication	- Hurr. Maria: The island was isolated by the interruption in the transportation network. Due to the loss of telecommunication the severe impact of roads, bridges could not be communicated.

Table 8.3 highlights the common key issues in communication, coordination, evacuation and negligence or poor execution of key aspects of contingency and response plans which were generally considered as 'inadequacy of response'. A sample coding using 'evacuation' taken from the case study Katrina is shown in Figure 8.3. Using the extraction of 'coding' approach across multiple documents and reports not only assists in

30:3 Despite the declaration of a mandatory evacuation on Sunday before la...... (1:1887 [1:2127]) - D 30: evacuation-katrina

Despite the declaration of a mandatory evacuation on Sunday before landfall, New Orleans offcials still did not completely evacuate the population.

Instead, they opened the Superdome as a "shelter of last resort" for these individuals.

Figure 8.3 A sample coding on evacuation from case study Hurricane Katrina through coding

understanding the response over key time-periods, pre-storm, during, and post-storm scenario but also assisted to summarize and understand the information produced in Table 8.3.

Figure 8.3 is an illustration of the ineffective evacuation plan, lack of public awareness and participation during emergencies. Apart from the commonalities of issues, certain differences were also identified underlining the impacts faced by developed countries like the USA.

2 Quotations:

26:1 Over 23,000 businesses and nonprofits employing 245,000 people were l...... (1:75 [1:179]) - D 26: Ch4.5_EconRecovery_FINAL_singles

Over 23,000 businesses and nonprofits employing 245,000 people were located in areas flooded by Sandy.

Figure 8.4 A sample coding on business interruption observed from case study Hurricane Sandy through coding

Figure 8.4 highlights the business interruptions experienced post-landfall of Hurricane Katrina and Sandy that contributed to the socioeconomic losses. The overall analysis highlights that there has been an identification of 'negligence of response' in some case study events. Whilst there could be a generic solution for mitigation the commonalities within *response* suggests a bespoke measurement should be adapted especially for developing and least-developed countries for future adaption to storm surge resilience.

8.2.3 Phase 3: Analysis of the recovery stage

Based on the United Nations International Strategy for Disaster Reduction (UNISDR 2009), a *response* is defined as the 'immediate focus or short-term needs' after any disaster, while *recovery* is the 'extended response'. Sometimes a response is also addressed as 'disaster relief'. According to the UNISDR, there is no clear-cut definition between response and recovery stage. Therefore, activities such as emergency sheltering are considered as response and temporary shelter, which is extended support, considered as recovery. The same situation of differentiating the key activities between response and recovery was recognised while reviewing case study data and analysing the search code outputs. Therefore, immediate action after the landfall was produced in Table 8.3 and those extended responses compiled in Table 8.4.

Table 8.4 Identification of critical factors from the cross-case syntheses of the recovery phase

Common key issues identified during recovery	Observation from coding
Search and rescue *Rescue from roof-tops* *Non-evacuees* *Aerial inspection*	- Hurr. Katrina: Initial days of search and rescue operation suffered various difficulties such as lack of information. Residents who were forced to move to rooftops had no access to mobile or communication devices resulting in search and rescue difficulties. But in general search and rescue were carried-out in many locations successfully rescuing thousands of people. DoD and army were involved in the operation. Complications in establishing the structure of incident command also confused the rescue operation. - Hurr. Sandy: The NYC emergency response team rescued the residents who were non-evacuees. Search and rescue were successful in most of the cases.

Rescue from remote areas	- Ty. Haiyan: The US DART team guided the search and rescue operation and the US military aircraft inspecting the affected areas aerially to support the operation and clearing the debris and the casualties. - Hurr. Maria: CDEMA's National guard together supported the search and rescue operations. - Cy. Nargis, Haiyan and Matthew exhibited similar difficulties in search and rescue. With the help of NGO's search and rescue were carried out in remote affected areas.
NGO, INGO, and volunteers *Relief support, search & rescues, temporary housing* *6-years of extended recovery support* *Reached remote locations with relief support* *Support during curfew times*	- Cy. Nargis: NGO's, INGO's supported search and rescue in reaching the restricted areas. Various level of influences and negotiation and liaison was carried out to regain access to restricted areas. After the negotiation of ASEAN with NGO's, INGO's access granted and the villages were provided with relief support, temporary housing. - Ty. Haiyan: The U.S. DoD, USAID, UNWFP, UNICEF, IRFC, CARE, ALNAP and various local and international agencies NGO's, INGO's and volunteers collaborated the search and rescue, humanitarian aid, relief support through partnerships and networks. NGO's continued to operate for 6 years post-event. - Hurr. Matthew: NGO and volunteers were able to reach the affected people in remote locations better than government responders. - Hurr. Maria: NGO's continued to support during the island's curfew times.

Lack of coastal prevention *Ignored levee cracks, design, and foundational failures* *Lack of prevention of underground systems* *No coastal protection in LECZs* *lack of investment in coastal protection*	- Hurr. Katrina: Evidence of design flaws and engineering failure were identified. A previous crack in levees was ignored causing a subsequent breach in the protection system underlining ignorance of proper coastal protection. Major drainage canals were identified with foundation failures. - Hurricane Sandy: Lack of coastal prevention (NY subway system and tunnels inundations) - Ty. Haiyan: the land use planning failed to instruct the communities as they lacked coastal protection. Most of the fishermen communities were close to the coast in low elevated coastal zones (LECZ's) completely exposed to hazard. - Cy. Nargis, Ty. Haiyan, Hurr Mathew and Maria were identified with little or no coastal protections invested to safeguard the coastal communities. Some communities were left to survive on their own.
Insurance *Ambiguity in flood insurance* *Extensive insurance claims*	- Hurr. Katrina: Some private insurance companies either abandoned or did not contract fully with policyholders and mortgage holders resulting in ambiguity within flood insurance. Furthermore, private insurance companies were able to provide payments only for the claims that suffered minor flooding. Housing which suffered serious damage was not funded by private insurance and residents were left to rely on federal funding. - Hurr. Sandy: Insurance-related issues and ambiguity in flood policies were identified. The recovery phase of Sandy was observed with the highest insurance claims relating to storm surge

Lack of insurance policies and reforms in developing & least-developed countries	flooding in the US hurricane history. The settlement of the raised claims was extended until late 2016. - Insurance was not commonly identified across cases such as Nargis, Haiyan, Matthew, and Maria. Rather, relief funds were channelled from various organisations and donations.
Housing *Significant damage to individual housing* *Coastal houses destroyed* *Multi-dwelling units, low-rise buildings were damaged* *Non-engineered houses were destroyed* *Housing adversely damaged or destroyed*	- Hurr. Katrina: An estimated range of 275,000-300,000 individual housing units were damaged in the overall Gulf region. - Cy. Nargis: 90% of the houses were destroyed by storm surge. Residents were provided with building materials and training kits and were further provided with training on the 'build back better' scheme. - Hurr. Sandy: 70% of the houses were multi-dwelling units and suffered severe damage or destruction. Coastline infrastructure and oceanfront buildings suffered adverse impacts including the fire damage in Breezy Point. Low-rise buildings suffered severe inundation and high-rise buildings and their MEP system was damaged. Houses built using outdated building codes were excluded from floodplain elevation and suffered adverse damage. - Ty. Haiyan: Most of the coastal communities, houses, non-engineered structures were destroyed or adversely damaged. Temporary shelter housing was provided 3 years after the landfall and permanent housing was provided in mid-2016. - Hurr. Matthew: Initial recovery phase was five months to rebuild the damaged and destroyed houses.

	- Hurr. Maria: Thousands of houses were destroyed or severely damaged. One of the largest disaster-housing missions in the USA occurred during Phase 3 recovery stage.
Rehabilitation *3-years of rehabilitation (severe inundation, debris, environmental contamination)* *6-years of rehabilitation (training and awareness, hygiene)* *Improved shoreline protection* *Unified rehabilitation measures*	- Hurr. Katrina: rehabilitation continued for more than three years since the landfall of Katrina due to the 27 ft storm surge inundation where debris removal alone was estimated to continue for several weeks. Environmental contamination, Flood insurance, claims, funding to repair or demolition, manpower, reconstruction grants faced delays at every step of the process obscuring the recovery phase. - Cy. Nargis: rehabilitation works continued 6 years since the landfall as various sub-phases. The initial phase involved the rehabilitation, temporary sheltering, healthcare ensuring basic hygiene. Phase two included desalination of community ponds, harvesting system to ensure access to communal ponds. Phase three included training, awareness and improving livelihoods programs. Overall, the GOP wanted to conclude the rehabilitation works in less than a year, however actual rehabilitation works carried out the NGO's was around 5 years. - Hurr. Sandy: Destruction of coastline infrastructure and oceanfront buildings were focused. During the rehabilitation, new improved shoreline protection systems and hardened dune system were implemented. - Ty. Haiyan: Presidential Assistant for Rehabilitation and Recovery (PARR) was implemented in the process to unify all the

Rehabilitation of public buildings	efforts of rehabilitation and recovery under this program. - Hurr. Matthew: Shelter rehabilitation was carried out US AID/OFDA. The first phase of rehabilitation involved in debris clearing, distribution of emergency materials and shelter kits. Rehabilitation of public building such as schools, educational facilities and support were provided to the residents and children.
Restoration *Prolonged restoration* *Improving livelihood was the primary focus* *Restoration of power was prioritised*	- Hurr. Katrina: Power infrastructure was severely affected, and pumping stations being incapacitated prolonging the restoration process. - Hurr. Sandy: restoration of power and utility infrastructures and subway system took longer than expected. - Ty. Haiyan: Power and utilities were restored in 56 villages out of 138 villages. Improving the livelihood was considered as the main section of restoration. This involves the restoration of 4 million workers who lost their jobs either temporarily or permanently. - Hurr. Maria: restoration of power and utilities was extended to more than 7 months. 70% of the potable water access was restricted. A bridge collapse in Port-au-Prince hampered the recovery, relief support delayed recovery.

Table 8.4 summarizes the list of common key activities identified across the cases. Key activities such as damage assessment, health care was excluded from the list of commonalities as they do not impact or change the adaptation and mitigation measures

taken. From the economic point of view, flood insurance was a critical factor identified during Hurricane Katrina and Sandy. The increased number of flood-related issues and insurance claims can also be interlinked with factors such as lack of land use planning in the coastal proximity; lack of appropriate coastal protection; failure of effective coastal zoning; recommending reassessment of flood policies and reforms. The Phase-3 recovery of Hurricanes Katrina and Sandy were viewed as reasonable efforts by the federal, national, and local response teams during this study. Relatively, the recovery efforts by Burmese government post-Nargis and the Philippines government post-Haiyan was not only inadequate but was also observed to be negligent. Nargis was an exception because of the blockade of the international aid agencies by the government.

The country's lack of adaptive capacities and voluntary in-action to respond and cooperate during the recovery phases demonstrated an abandonment of the SFDRR goals. This contributes to a key lesson to revise the DRR strategies for future weather events. Besides, Haiti's political instability also contributed to delaying the response and recovery. Thankfully, the NGO's and the UN's MINUTSHA, who were already operating in the field post-2010 earthquake, had previously established relationships with the communities and assisted cooperation during the recovery. A detailed coding of the individual list of activities corresponding to the recovery phase is produced in Appendix C.

8.2.4 Phase 4: Analysis of the mitigation stage

Several factors that were identified in the previous three phases that are crucial and were the areas which were required to be mitigated. Therefore, adapting to future weather events is one of the key theme areas to be suggested via the DAMSS framework.

Table 8.5 Identification of critical factors from the cross-case syntheses of the mitigation phase

Common key issues identified during mitigation	**Observation from coding**
Lessons learned *Failure of implementation of lessons learnt*	- Hurr Katrina: New Orleans residents were left vulnerable and failed to implement the lessons learned from previous hurricanes. The previous simulation of Hurricane Pam (2004) and the knowledge gained from the simulation was not incorporated into the

Lack of previous experience *Lack of authority*	report for Hurricane Katrina underlining the failure of lessons learnt. - Cy Nargis: The storm was first to make landfall in the Ayeyarwady delta region. Previous lessons learnt were not available for this case. But the general DRR strategies were not followed or implemented and is one of the most significant factors in this case study. - Hurr. Sandy: Lessons learned from Katrina were identified in many areas. Raised generators, fire cable deployment, standby pumps to drain water after landfall, however, the power and utility infrastructure suffered significant damage. The MEP system which remained grounded was also affected and became a key lesson learnt post-Sandy. One of the additional key lessons identified was 'lack of authority'. - Ty. Haiyan: The Philippines faces 23 typhoons annually on average. Yet, the country failed to address the lesson learnt incorporate previous experience across all the four phases of DRM.
Land use planning *Poor land-use planning*	- Hurr. Katrina: Communities developed between Lake Pontchartrain and Lake Borgne, which connects with the Gulf of Mexico, exhibited poor usage of land-use plans and lacked to foresight the impending risks. Also, flood risk maps suggested that houses that were at high-risk zones were incorrectly identified as moderate risk zones. - Cy Nargis: No identification of land use plan before Nargis. The residents of Ayeyarwady were predominantly farmers and were relying

No proper land-use plans *Lack of modelled coastal zones* *Lack of coastal barrier* *Poverty contributing to poor infrastructure*	on agriculture as a prime source of income. The residents occupied the lands next to coasts as there were no stipulated land use plans in practice. Post-Nargis, the blueprints of existing housing and land use plans were adopted from international aid agencies and were customized for use in the delta region. - Hurr. Sandy: Land use plans and coastal zones were not modelled appropriately to survive future storm risks. Also, the city of New York lacked critical reforms and constant upgrading of plans and flood risk zones. - Ty. Haiyan: No proper land-use plans were identified. Many coastal zones were not mapped, and no visionary efforts adhered for future storm risk. Due to the country's economic capacity, the residents occupied coastal lands for residential use without any coastal barriers in place. - Hurr. Matthew: Country's low adaptive capacity led to overall poor infrastructure.
Coastal prevention *Replacement of old levees* *Restoration of mangroves was focussed*	- Hurr. Katrina: failure of existing levees, dunes and dykes over topping was identified. The levees were breached at more than 70 locations. New embankments, changes to levels T-walls, raised pumping station were some of the mitigation for coastal prevention is carried out. - Cy. Nargis, Ty. Haiyan and Hurr Matthew: The inundation and the extensive loss of lives not only underline the absence of appropriate coastal protection in place but also emphasises on the future mitigations. Restoration of mangroves and forests were

Installation of flood gates and flood proofed construction *Hazard mapping was the primary focus*	done post-Nargis as an enhancer of future coastal prevention. - Hurr. Sandy: coastal protection systems were in place but due to the city's heavily populated MDU and closely packed infrastructure, the funnel-effect of storm surge over topped the River Hudson rapidly inundating all the 5 boroughs of New York and the city of New Jersey. Installation of flood gates, sea gates and flood proofed housing were carried out till 2016. - Ty. Haiyan: Technical remained critical such as spatial planning, coastal zoning, building codes, risk, and hazard mapping. There is a wider scope for improvement in these areas.
Infrastructure *Elevation of key infrastructure (pumping station, power stations)* *Limited protection and improvement within*	- Hurr. Katrina: The much-affected New Orleans pumping stations were elevated several feet above the sea level 10 years after Katrina's landfall. Over the years, New Orleans's population is seeing an increase however, housing and infrastructure were still being built in high-risk zones. Few key activities such as early warning systems, evacuation plans were planned with key lesson incorporated during Hurricanes Florence and Michael (2018) which made landfall in New Orleans. However, damage to coastal communities and assets yet coastal population and assets continued to be exposed in the same storm hit zones. - Cy. Nargis: The recovery and rehabilitation process took almost six years and some infrastructures were identified to continue the same before Nargis. The densely populated

infrastructure *Elevated of key infrastructure and coastal housing* *Build back better scheme to improve infrastructure* *Build back safer to improve housing* *Wetland restoration was the primary focus*	delta region is still vulnerable with limited protection. Emergency shelter, suitably re-enforced embankments are found inadequate to mitigate future hazards. Communication infrastructure saw some development compared to those restricted by the Burmese military control during Nargis's landfall time. - Hurr. Sandy: Post-Sandy's infrastructure improvement works included a focus on raising buildings several feet above the BFE levels. Partnered projects between NYC and US Army Corps of Engineers were carried out and future projects were at proposal stage. Insurance Institute of Business and Home Safety (IBHS) and Department of Building (DOB) reassessed building codes used in NY and NJ. DOB utilised colour coded tags 'Green'- less/no damage, 'yellow'- significant non-structural damage, 'Red'- destroyed/severe structural damage. - Ty Haiyan: 'Build Back Better' was used to restore the 90% of damage in the infrastructure. Actions and measures were taken to strengthen the Local Government Unit's (LGU) capacity. Risk-assessment at schools and learning life skills program was also introduced to be prepared better in the future. - Hurr. Matthew: Through the Build Back Safer (BBS) program, sustainable shelter and housing solutions were ensured for the residents. Under this program construction of housing and buildings, their vulnerabilities

	were assessed and evaluated for future storm and hurricanes. - Hurr. Maria: Projects on wetland restoration and further stabilization of dunes, beaches were considered for future mitigation.
Multi-agency approach *Extended support from a retail corporation (Walmart) & volunteers* *NGO and INGO developed partnered networks (cross-national and cross-sectoral)* *International agencies and partnerships (cross-national and cross-sectoral)* *NGO and international agencies (cross-country) liaison*	- Hurr. Katrina, Sandy, and Maria: similar pattern of extended capacity, multi-dimensional and multi-agency approaches were included in the process. Walmart supported during Katrina and IFRC during Sandy and Maria. In these cases, roles and responsibilities were shared between federal agencies and volunteers, NGO's. - Cy. Nargis and Ty. Haiyan experienced difficulties in establishing coherence in coordinating with the government. In both the cases, in-field NGO who had already established rapport and liaison with the local authorities continued to find it tricky to liaise post-landfall. - Hurr. Matthew: International agencies like WFP, CARE was co-leading as cash working groups. International Humanitarian Partnership (IHP), including 17 health and education sectors were involved in the response and recovery of Matthew. - Hurr. Maria: Ford, Open Society, and Rockefeller foundations were involved in multi-year commitment and investment strategies. In addition to these volunteer agencies such as French Civil Protection Agencies, European Civil Protection, and Humanitarian Aid Operations (ECHO), UN Development Program (UNDP) supported

		during the logistics management, internet connections and information sharing. This was greatly beneficial as the country's power, utility and communication infrastructure were severely damaged.

Table 8.5 summaries some common mitigation approaches which had been undertaken highlight the potential mitigation and adaptation approaches required for the future. Case study such as Haiyan not only highlight the limitations in current approaches insisting on various key lessons learnt, but also confirms the post-Haiyan efforts taken place at different levels. The PAGASA worked on issuing storm surge hazard maps by adapting FEMA's READY project and incorporated the lessons learnt from Haiyan. Another key factor was the lack of coastal prevention or protection, which amplifies the effects of the hazards leading to direct exposure. While Hurricane Katrina was an example of weak coastal protection, Cyclones Nargis, Haiyan and Matthew were cases with a significant lack of coastal protection. Therefore, adapting appropriate coastal protections could provide one of the viable and feasible solutions to directly mitigate the risks involved, although, this can be high in cost.

Countries with low levels of coastal investment for resilience may consider a combination and natural engineering and wetlands. This could include mangroves and salt marshes as a possible combination to mitigate the hazard. The review of the case studies shows how the actions, adaptations and the adaptive capacity post-disasters has largely varied for the different regions. Even, the adaptation of the US after Hurricanes Katrina and Sandy varied largely concerning the adaptive measures taken by Myanmar, the Philippines or Haiti. Countries exhibiting different adaptive strategy and approaches show their adaptive capacity, their differences between developed countries and small island developing states (SIDS) such as the USA and Puerto Rico. Based on this observation, a future guidance 'framework' approach is likely to be helpful for many countries. To mitigate this future gap regardless of the country's adaptive capacity, using a framework approach to filter the best-practices and simultaneously address potential 'bottleneck' resilience is important. Furthermore, given the current climate emergency scenario and their relative impacts in many countries especially for those low elevated coastal zones is crucial. This may also be a guideline even for countries who are yet to experience storm surge, and such guidance will not only be helpful but will be essential to be incorporated into existing and future planning and construction.

8.3 GAP analysis of the timeline within DRM

While analysing the individual cases, with a concept of interpreting the success and failure factors during the execution of the disaster phases, the 'timeline' was observed to play a vital role in Phase-1 of DRM. As stated by Yin (2014) and Bryman (2012), timeline is a critical and a vital factor which helps in visualising the gap between specific scales, duration, and events. To analyse if there are any substantial difference in the execution of certain key activities, the timeline between Phase-1 (preparedness) and Phase-2 (response) of every individual event is observed. In each case, the selection of two critical factors namely 'risk identification' and 'issuance of first warning' was chosen between Phase-1 (before-impact) & Phase-2 (during-impact). The reason behind choosing these two phases is that the following key activities taken place between these two phases were observed to be crucial first step as suggested by the UNISDR (2006), which could contribute to a considerable reduction of mortality rate.

- Early warning system
- Forecast and monitoring
- The readiness of the emergency plan
- The readiness of deployment of resources
- Preparations for evacuation if necessary
- Readiness to set-up emergency shelters

The above listed factors across all the six studies were collected and merged to understand how the timeline between the progression of the hurricane against the preparedness steps was taken. Figure 8.5 shows the timeline gap during each event that was observed between the two critical phases. Day '0' is the day when the hurricane or the potential risk is being identified by the hurricane monitors and forecasters. 'X' is the day when the first warning is issued by the authorities to the communities. It is from this period, that any of the processes such as evacuations, preparing for the hurricane begins. It is also important how early they assess and how early they issue that first warning alerting the communities in preparation for the hazard. During this period, the resources such as food, emergency shelters, etc., were also deployed. The dotted red line indicates the landfall of the tropical cyclone and any preparedness ends by now as the disaster has occurred and only a response to the disaster is possible from this phase. From Figure 8.5 Hurricane

Katrina was identified with an inactive period of 11 days between the risk identified (Day 0) and the issuance of first warning (x). It not only highlights the failure of preparedness but, in case if the authorities had prepared between these 11 days the loss of more than 1,800 lives could have been minimised. Consequently, Typhoon Haiyan was observed with a gap of 1-day between risk identification and issuance of first warnings of NHC.

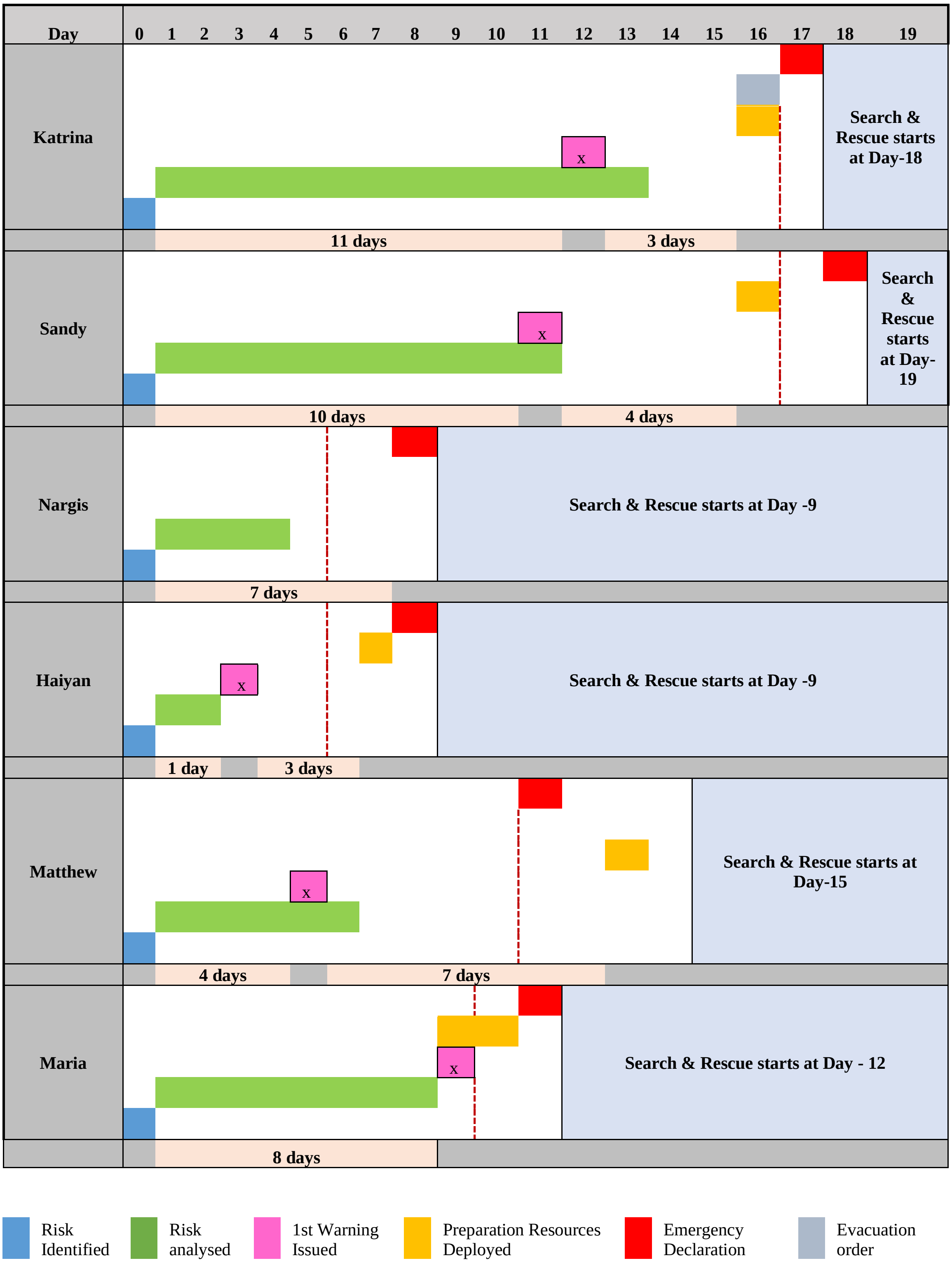


Figure 8.5 Timeline of the execution of key activities in Phase 1 and Phase 2

As highlighted in Figure 8.5 countries like the Philippines and Myanmar whose shallow coasts, bays, and estuaries are extremely vulnerable, should consider the fact that they may have lesser response period between risk identification and landfall. Therefore, it is recommended that their disaster governance and policies should include such crucial factors for future storm surge mitigation. Although this data does not produce the typical timeline of any event, this could be a guideline that if a hurricane of similar pattern and magnitude is forecasted in future in their corresponding ocean basin then these number of days denoted as ‘n’ days between pre-impact and during-impact phases will act as a ‘buffer’ to assist underlined the actions to be expedited.

8.4 Proposal of the DAMSS framework

The findings from the Chapters 5, 6, and 7 together with the cross-case analysis demonstrated there is no consistent approach to enhance the preparedness. Given the changes due to climate change, sea-level rise, and increasing hurricane and storm surge events more countries and communities will be affected in the future. A holistic approach to harness the preparedness investigating the storm surge impacts which can aid governments, planners, public departments, and the public is essential to reduce the socioeconomic losses.

As there is no prior framework for storm surge resilience identified in an academic environment, this framework was proposed after an investigation of storm surge impacts from previous responses and process of preparedness. It is also designed such that it is applicable regardless of the geographic regions. The framework this research put in forward is inclusive and might be applied to different countries with different economic capacities and geographic regions. It does not serve as a generic disaster approach which is identified as the current approach in the case study countries. The framework could harness previous learning outcomes which could also act as a feedback loop contributing to knowledge for countries and communities.

The Disaster Adaptation and Mitigation to Storm Surge (DAMSS) framework is proposed as Figure 8.6. The proposed framework is the culmination of the data presented via Table 8.1, followed by the specific analysis of the four phases listed in Table 8.2 - 8.5 where similarities of limitations have been drawn from the analysis.

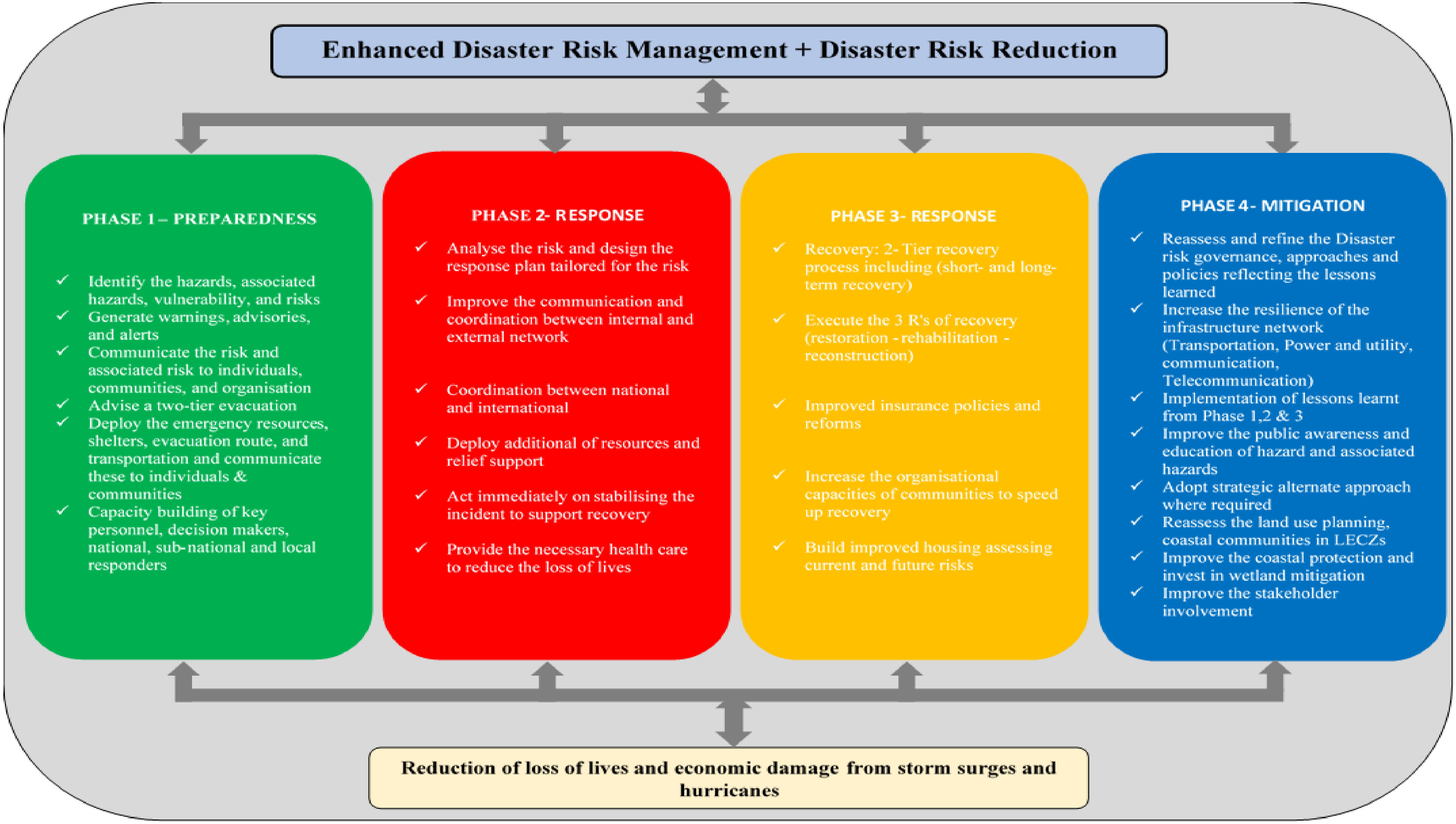


Figure 8.6 Proposal of the DAMSS framework

Phase 1: Preparedness

The first phase was designed to help focus on the pre-emptive to avoid the acceleration of an ordinary event into a disastrous event. From the analysis of cases, it is understood that the initial step before the occurrence of the event has the maximum scope in risk reduction and risk transfer in some cases. This is also equally critical as the possibilities and likelihoods of the tentative hazard are subject to change rapidly. The analysis of the cases and the aftermath of these events without a prevention mechanism suggests that a potential measure could contribute to reducing the mortality rate and economic losses. Therefore, planning the preparation of the equipment and relevant procedures must include at least the following key areas for increased prevention and lead further to effective response which is elaborated in phase 1 of the DAMSS framework.

- Pre-resilience measures (e.g., adapting future housing, utilities designed for storm surge floods, emergency shelter locations, community halls, medical centres)
- Risk identification (e.g., planning for storm surge floods, land-use restrictions, deployment of resilient infrastructure)
- Early warning system (e.g., timelines, risk area or zone, community identification)
- Risk communication (e.g., clarity, meaning, understanding and action to take)
- Evacuation (e.g., rendezvous locations, rebuilt higher evacuation zones, in-built roof access windows, ‘hold and rescue’ zones on roofs)

Phase 2: Response

The second phase of the DAMSS framework was designed based on the provision of immediate emergency services post-impact. This stage mainly focuses on reducing the loss of lives from disaster and ensuring safety measures to prevent the subsequent losses. The proposed list of key activities to address the disaster with an effective response must include increased capacity through effective communication and coordination.

- Emergency sheltering (e.g., rapid construction, weatherproof and flexible)
- Communication and coordination (e.g., across key public sector bodies, emergency services and utilities, hierarchy, roles, and responsibility, also utilising experienced responders i.e., NGO’s)
- Public health (e.g., classification of priority, operational response, the effectiveness of response inputs and outcomes).

Phase 3: Recovery

The third phase of the framework focuses on the extended response or recovery from the disaster. Commonly, most of the case study documents defined recovery as short-term and long-term recovery. The short-term recovery considers the quick restoration of affected communities which includes health and safety, restoring the assets and communities. The long-term recovery considers reconstruction, rehabilitation coupled with areas of improvement such as

- Rehabilitation, restoration, and reconstruction
- Health and safety
- Organisational capacities

This phase also involves public engagement, awareness, and training under rehabilitation processes.

Phase 4: Mitigation

The final phase of the framework focuses on the corrective measures of improved disaster risk management addressing the specific issues of the risk from previous learnt lessons. The action for this phase considers addressing the gap in the current practices:

- Lessons learnt of various activities of phases 1, 2 & 3.
- Reflecting on the critical factors and determining the measures
- Adapting the public knowledge for future through public awareness, training, and education

Phase 4 of the framework is considered to have the potential to improve the areas (where necessary) and contribute to reducing the mortality and economic losses in the future. The proposed DAMSS framework constituting the four phases with an additional focus of improving pre-emptive measures within Phase 1 (preparedness) and Phase 4 (mitigation). The proposed framework is considered not only to bridge the gap between the current practices and future adaption but also execute the following procedure thereby enhancing the resilience of coastal habitat to storm surge practices.

- Define DRM and DRR strategies outlined in DAMSS framework
- Execute the strategies
- Identify the gaps
- Learn from best practices
- Implement the lessons learnt

- Measure the gap again

8.5 General discussion of key activities of the DAMSS framework

8.5.1 Risk identification and early warning, monitoring and forecast

The United Nations's (2006) and UNISDR's (2009) statements on effective preparedness acknowledges a step-by-step execution of the early warning system. The UNISDR emphasises the importance of such an early warning system. Reflecting on the UN's statement, focus more should be on risk communication. A good risk communication also means focusing on the technical aspects of monitoring and forecasting and identifying the end-users who are most likely to be affected by the inaction of the early warning system.

The USA under its disaster governance wing, FEMA, adapts hurricane preparedness through a program called 'Ready'. The program instructs the first step towards preparing for such cyclones, and storm surges by initiating effective early warning systems (Department of Homeland Security, 2019). In addition to the existing hurricane watch-warning, predicted storm surge warnings were also issued within the early warnings. Strategic planning such as the 'Ready' program should be adopted by the developing countries toward enhancing their first step in DRM.

The Sendai Framework's Priorities for Action (PFA), also highlights the vitality of understanding the risk and enhancing disaster preparedness. In principle, these case study countries appeared to have risk assessments, protocols and emergency planning in place. Despite this, inadequacy in understanding the risk leading to an ineffective early-warning was observed. With existing conditions such as technical limitations in calculating the hurricane intensity, which greatly influences the storm surge levels, further extends the gap in risk analysis and hazard assessment. It is recommended that all coastal areas should run prediction models including the possible inundation from the 'funnel-effects' of storm surge.

Larger gaps in forecasting data and risk assessment are more likely to happen to countries where technical capabilities of hurricane monitoring and prediction systems are weak and have to depend on the neighbouring countries for weather prediction and forecast information. For instance, Myanmar who had to rely on the Indian Meteorological Department (IMD) and Japan Meteorological Agency (JMA) for its forecasts and monitoring has to enhance their communication and coordination when liaising with their neighbouring agencies. Flexibility and inter-dependency are vital for countries like Myanmar to reduce the future risk and enhance their disaster risk governance.

8.5.2 Communicate the risk and public awareness and education on storm surge

The gap in risk communications which was observed across the cases was witnessed to have occurred when authorities failed to understand their audiences. Typhoon Haiyan was an example when the PAGASA's experts communicated in technical language whilst the common people were looking for information in a simple language without technical jargons. Also, the public is not a homogenous entity; therefore, different groups of society require different methods of communication.

CERC (2014) quotes that effective risk communication should include the following basic steps:

- Risk knowledge
- Communicating the risk
- Monitoring the outcome of the communication

Reflecting on CERC's quote on the characteristics of effective risk communication, it is suggested that the future communications should focus not only in communicating the risk, but it should also focus on the outcome of such risk communication. This key step not only ensures the public's understanding of the hazard but also induces the public's participation once the received communication is understood by the end user.

8.5.3 Understanding the role and responsibilities and decision-making during emergencies

Decision-making is another important factor that was observed during the analysis of the research. The USA, as a developed country, even with its utmost adaptive capacity, faced severe criticism post-hurricane Katrina (2005) mainly for its poor choice of decision-making. Beginning with insufficient EWS; delayed declaration of emergency; delayed evacuation orders followed by re-evacuation after landfall; every step was criticised for its poor decision-making that resulted in the loss of 1,800 lives and with an estimated economic loss US $108 billion (2005) which is currently estimated as US$ 160 billion (currency corrected with 2018 inflation). This is even highlighted in the report of the Committee on Homeland Security and Governmental Affairs (2006). Therefore, making the right decision at the right time not only becomes part of effective preparedness but also becomes essential in saving the country from socioeconomic losses inflicted by these disasters.

8.5.4 Execution of effective evacuation

The execution of the evacuation plan connects with both Phase-1 preparedness and Phase-2 response. The primary mitigation action towards an approaching tropical cyclone is evacuation, followed by an escalation of deployed resources to the victims. Although this sounds a very straightforward action, execution and planning mass evacuation as observed in the cases is regarded to be a complex process.

In the case of Sandy, even after two mandatory evacuations have been ordered, there was still a certain percentage of people chose to stay back. The case studies have highlighted how planning and executing emergency evacuations is a major procedure that requires a coordinated response from officials and cooperative responses from people. The analysis also highlighted that it is not an identical approach that is adapted during every emergency and was often subject to change. This implies that an 'ongoing' understanding and assessment is required to achieve successful evacuation before every event. A more transparent and explanatory evacuation plan, provision of continuous drills and training at regular intervals, realistic communication of anticipated hazards, can enhance public participation during evacuations.

8.5.5 Implementation of response plan

The DRM approaches indicate that understanding the roles and responsibilities to execute the contingency plan appropriately is the key to implement the response plan and related strategies. Except for Hurricane Sandy, almost all the cases exhibited overall inadequate execution of the response plan. This was recognized because of the lack of understanding of roles and responsibilities of the emergency responders, and interaction between the national, sub-national, and local response. This seemingly weakened the process of making the strategic decisions required on time thereby offsetting the primary focus of responding to the emergency. Even though response plans were in place as a guiding principle, issues were underlined during the implementation of the response plan in a 'vertical approach' as shown in Figure 8.7 (right) where the sub-national and local team were awaiting orders from their hierarchical national teams. Kapucu (2016) discusses the advantages of horizontal escalation of roles and responsibilities during emergencies.

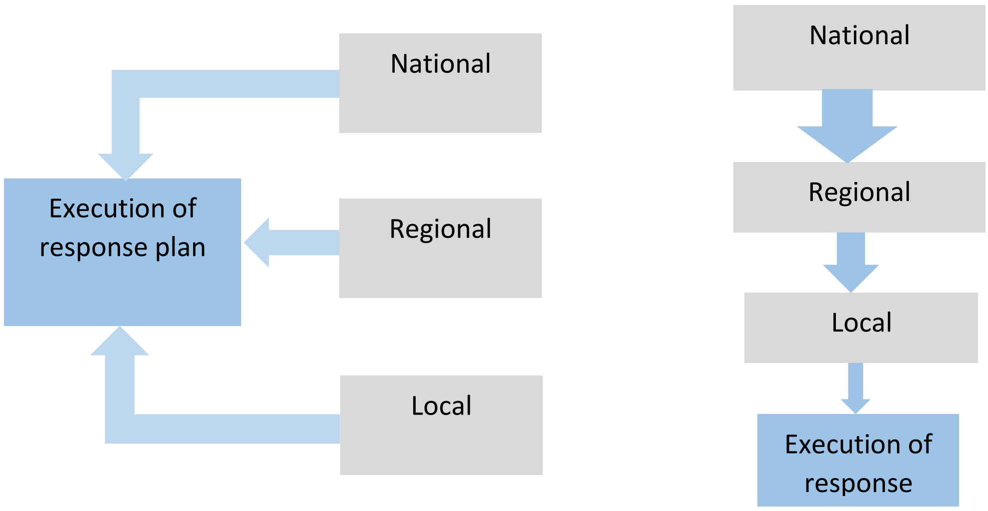


Figure 8.7 Recommendation on horizontal escalation (left) of responsibilities versus a vertical (right) approach

Adapting to Kapucu's statement, and applying the theory of positivism in achieving results, a 'horizontal approach' and its implementation within the response plan is suggested via Figure 8.7 (left) in comparison with the illustration of a vertical approach. The suggestion was given based on the disadvantages identified in a vertical escalation and with an assumption of possibly executing the key activities and sharing the responsibilities simultaneously.

8.5.6 Land use planning and coastal communities

According to the UNISDR's (2009) terminologies, the process of identifying, assessing, and deciding on the various options of land usage is called land-use planning. This process involves the analysis of long-term economy, social and environmental hazard data. As stated by the UNISDR, the key to successful study and mapping of the land use planning relies on the formulation of alternative land-use decisions.

The cases have highlighted how such land-use planning (or lack of) for the coastal communities have determined the vulnerability of the country through their exposure level to the hazard. The heavily populated communities in the New Orleans; or the coastal communities in the City of Tacloban; Ayeyarwady delta in Myanmar; or the MDU's in the five boroughs of New York City and New Jersey; were subjected to insufficient land-use planning relative to the risks. Developed countries are often financially capable of bearing the cost of damage as seen in the recovery phases in the USA, in comparison with the 4 years of extended recovery phases identified in cases such as Nargis and Haiyan.

From Katrina and Sandy, it is obvious that these developed countries have ‘coastal zoning’ systems under which coastal lands were classified as high, moderate, or low-risk zones. The breaches in coastal zoning system in Sandy and Katrina cases reveals the closely packed infrastructures and land-use intensity. Issues with coastal habitat zoning systems beyond their mapped areas highlight the possible gaps between mapping methods and actual observation. This could be mainly from issues such as the use of outdated maps, the decadal gap in the census records, and continuous change in coastal hydrography. But they specifically indicate the requirement for reassessed coastal zones and land-use plans to adapt for future surge events. Also, land use planning can also aid in mitigating the disasters risk specifically by reducing the risk of exposure to coastal extremities.

8.5.7 Linking NGO’s, INGO’s and volunteers for multi-level networking

The role of Non-government Organizations (NGO’s) and International NGO’s during and post-impact period was widely accepted and recognized. These NGO’s have a competitive advantage than the local government themselves in engaging with the regional residents. Their partnerships and collaborations with private and local governments were observed in the recovery and extended recovery phases during almost all the cases. The recovery phases of Haiyan demonstrated how the NGO’s and volunteer’s contribution have encouraged women participation during rebuilding, restoration, and reconstruction works. NGO’s were also observed to have the potential to support capacity building at greater levels by building community-level participation. This may be mainly due to their resources and flexibility to act locally and internationally. Although local NGO’s have limited access than the local governments, their knowledge from various previous disasters can be greatly beneficial to communities who have never experienced the impact from certain disasters, as observed during Cyclone Nargis. Across certain cases, their services (NGO’s) were observed to be more rapid than governments, especially in those less acessible, remote locations.

During the 2010 Haiti earthquake, although the aid from various countries was provided, only minor portions were channelled through the government. This is not because Haiti, is a low-income country, but various other reasons include political instability, non-localized evacuation plans, and poor infrastructure. The United Nation’s Stabilization Mission in Haiti (MINUSTAH) who were already operating in field since the 2010 earthquake were also involved during the post-Matthew recovery phase. Improvement by way of channelling the international emergency funding was observed since the 2010 earthquake, mainly due to the involvement of NGO's and the United Nations.

By adapting to a cross-sectoral partnership, the lack of risk knowledge could be reduced by working with trained volunteer or NGO teams operating in the field. NGO's participation could be one of the most resourceful communication media routes in the process of creating awareness in remote and rural coastal areas of developing and low-income countries. Through a well-coordinated multi-level network and organised relationships, knowledge transfer and learning from other global events concerning disaster risks and response needs into effective communication outreach could be achieved. While highlighting the support and assistance received from NGO's, and international agencies throughout critical emergencies, considerable emphasis should be placed on expanding the multi-level networking for its advantages.

8.5.8 Developing stakeholder involvement

By reviewing the multiple case studies, involving Phase-2 (response) and Phase-3 (recovery), it is noticeable that the required levels of response and recovery activities were beyond the national response team's capacity and capability in developing countries. During those circumstances, the involvement of the primary stakeholder highlighted in blue could provide the required additional support.

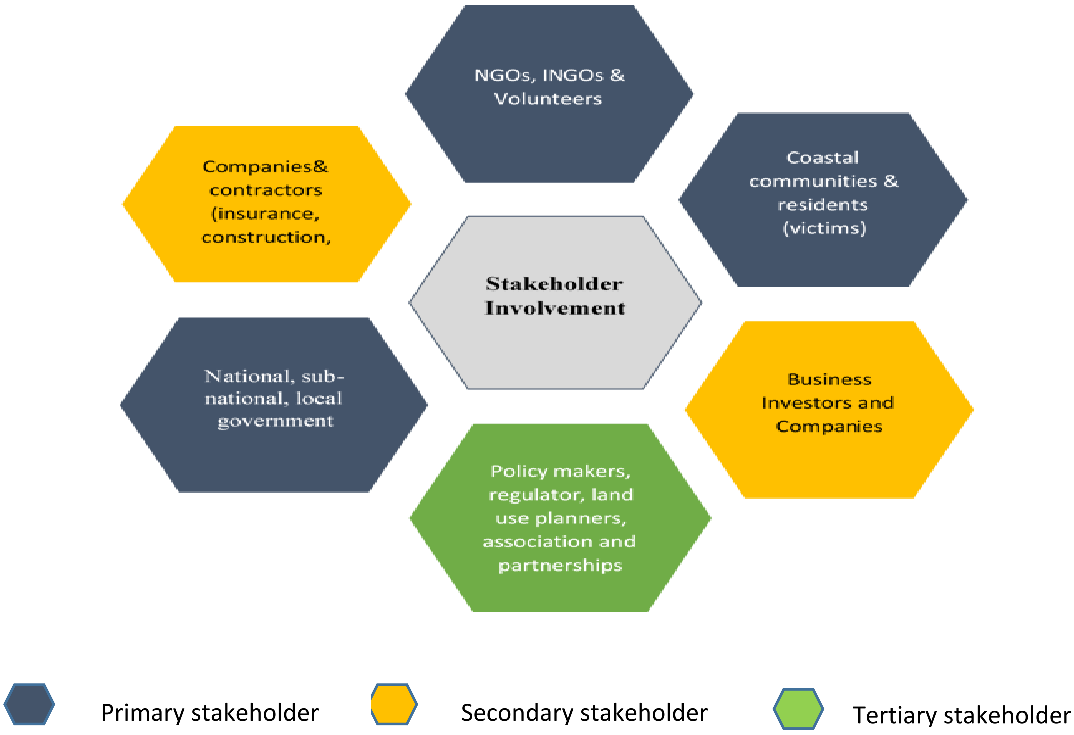


Figure 8.8 Overview of a stakeholder involvement enhanced within DRR

From the case studies, it is identified that stakeholder participation has supported in various instances during the recovery phase of the incident management. Additional support from the secondary stakeholder highlighted in yellow was observed during the Phase-3 recovery stages. Finally, the involvement of tertiary stakeholder highlighted in green was observed to have supported during the Phase-4 mitigation where policies and land-use planning post-cyclone events were carried out. The different stakeholders which have been identified during this analysis which has strategic input are shown in Figure 8.8.

As observed during the cases, the key role of all the stakeholders was to enhance the collaborative partnerships and multi-dimensional access to resources in support of the emergency. Although, these may look more of generic stakeholder involvement, for developing countries like Haiti, the Philippines, Myanmar, external stakeholders have played key roles as observed from the case studies. These cases were identified to have stakeholder involvement on ad-hoc basis only during the time of disasters occurrence. However, for a long-term improved network and to understand the coastal communities and the people's requirement during the emergency, a more structured approach is required. Such an approach should be formalised with an understanding of roles and responsibilities of primary, secondary and tertiary stakeholders is required. Previous established networks could minimise the communication and coordination issues which occur during the response and recovery phases and increase the coastal adaptation for a better future.

8.5.9 Increase coastal resilience with appropriate coastal protection

Low-income countries and few developing countries are not likely to invest and allocate resources on coastal defence (PreventionWeb, 2015). This was observed during the analysis of the cases. Case studies on tropical cyclones Nargis, Haiyan and Matthew, also confirmed that these countries have either little or very few coastal investments. Primarily this may be the reflection of the country's adaptive capacity, or socioeconomic inequalities, or poverty. However, it appears there was also an inclination by authorities to not to allocate resources on coastal defence or refine their coastal flood protection policies annually. As stated by Wallemacq & Below (2018), poverty and lack of economic capacity, directly connects the country's adaptive capacity in terms of disasters which further increases the gap within adaptation and mitigation measures which this author terms as 'protection-gap'.

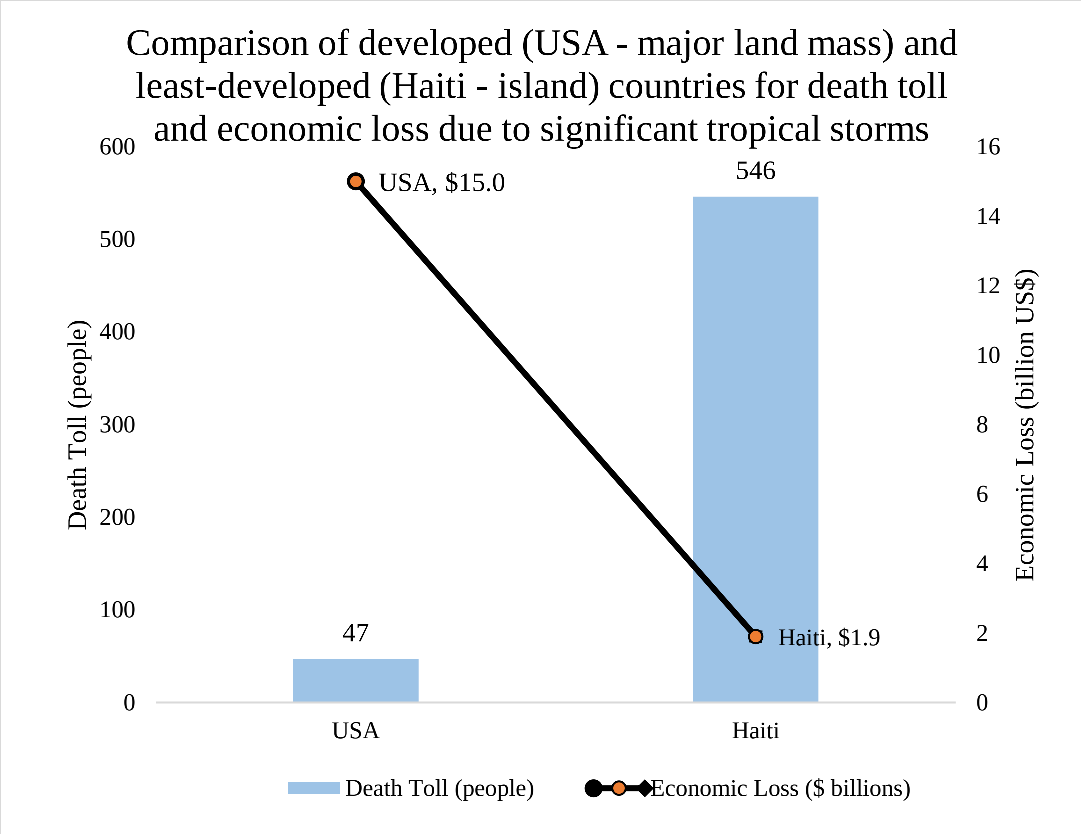


Figure 8.9 Comparison of developed (USA - major landmass) and least-developed (Haiti - island) countries for death toll and economic loss due to significant tropical storms

According to Lewis (2014), the societal loss of the developing countries is generally higher than those developed countries and consequently, the economic damage of the developed countries is generally observed to be higher than those faced by developing countries. In line with the statement of Lewis (2014), the case study data of Nargis, Haiyan, Matthew and Maria have been identified with little or no coastal protection in their corresponding countries. From another perspective, considering Hurricane Matthew's losses (financial and deaths) in the USA versus Haiti, reproduced in Figure 8.9 demonstrates the diversity of impact. Haiti which is a small island but less developed for coastal protection resilience than the USA had low economic losses but experienced a much higher death toll. The case studies of Hurricanes Katrina, Sandy, and Matthew identified that various coastal protections such as seawalls and levees were already in-place protecting the communities. The sea wall in front of the financial district in Lower Manhattan; the I-walls of the 350 km of engineered levees replaced by T-walls in New Orleans; restoration of embankments, dune and dykes in New Jersey; all highlight the importance of having coastal protection. Though these coastal protections were in-place the communities suffered substantial damage during significant events. This suggests that these coastal protection or over-engineered coastal infrastructures installed in other global locations as a solution for storm surge mitigation. It is to be noted that these engineered protection systems should be constantly maintained,

Consequently, building those engineered storm surge barriers incurs high construction and maintenance cost as discussed earlier in Chapter 3. Reflecting on projects such as the 'Ike-Dyke' proposed after the Hurricane Ike (2008); New York's-New Jersey Storm Surge Barrier proposed after Hurricane Sandy (2012); were still in the proposal stages.

The probability of constructing such barriers in a low-income country are practically not realistic. McIvor et al., (2015), emphasised the advantage of mangrove vegetation in attenuating the storm surge peak water levels to a certain degree. Mirroring his thoughts, the analysis further suggests that low-income countries should focus on the alternate strategic approach to mitigate these coastal hazards in the future. Although McIvor's studies highlight mangrove vegetation (which is a much lower cost), it is suggested that this should be used alongside other coastal risk reduction measures, such as robust seawalls, high strength levees and flood protection measures.

8.5.10 Improved coastal construction and flood-proofed housing

Construction is another major sector that was identified to have suffered severe damage across multiple cases. This remarks on the necessity of improved coastal construction when it comes to risk mitigation. Bhatta (2010) stated that coastal urbanization, blue economy, and industrialisation have not only triggered physical environmental impacts, but their expansion as coastal sprawl further complicates the task of adaptation. New York's MDU or the Ayeyarwady delta's non-engineered structure were samples of coastal occupants and settlements.

Post-Katrina and Sandy, FEMA's - MAT team assessed the building where many were house were identified with outdated building codes. The rejection of many of the insurance claims post-Sandy was also an example of how the houses not being adapted under building codes. In line with Bhatta's statement, and in support of adapting construction, the new coastal developments and buildings should consider updating building codes, for both wind and flood proofed housing. Such adaption should include new techniques and building regulations that are durable and incorporate sustainable designs to cope with the shifting weather-extremities. Figure 8.10(a) & (b) shows the post-Sandy mitigation in construction is elaborated through the following codes.

77:5 FEMA recently issued revised advisory base food-elevation maps. It is…… (3:821 [3:1038]) - D 77: Post-Sandy-Rebuilding_IBHS

FEMA recently issued revised advisory base food-elevation maps. It is important to note that FEMA recommendations are not the law. Towns still must incorporate the guidance into local zoning and building ordinances

Figure 8.10(a) A sample coding of mitigation in construction observed from Hurricane Sandy

76:6 Three critical elements of building construction infuence how a buil…… (2:1168 [2:1415]) - D 76: Post-Sandy-Building-Codes_IBHS

Three critical elements of building construction infuence how a building fares in storm surge and fooding: 1) elevation of habitable spaces and utilities; 2) type of foundations used, and 3) use of food-resistant materials in vulnerable areas.

Figure 8.10(b) A sample coding of mitigation in construction observed from Hurricane Sandy

Various ongoing improvements in the construction industry such as smart cities, green infrastructure, and blue-green infrastructure observed in Phase-4 (mitigation) of Katrina and Sandy. This is a positive approach towards climate change and sea-level rise adaptation and mitigation.

The research further suggests such adaptations should also be considered by the developing and low-income countries in agreement with their economic capacity. It is worth noting that the exciting sectoral developments, should not camouflage or divert the important critical basic aspects of improved design and building regulations, which are required in many countries to cope with future risks.

8.5.11 Mitigate the issues within the transportation network

Transportation plays a key role in society's mobility and this infrastructure was detected to have experienced adverse impact immediately after the landfall of many hurricanes and storms. Serious hampering of transportation network was observed in all these cases when the cyclones combined with storm surges. The data from the individual cases registered the impacts undergone by the transportation network from uprooted trees, knocked-down communication poles, roads and bridges cut-off and rail routes and airports hampered by debris. The dynamics of transportation are profoundly challenged in Phase-2 response and Phase-3 recovery stages when national response teams or NGO's try to reach the victims during emergencies. The lesson learnt from these cases highlight the vulnerability of transport infrastructure and its network to cyclones and surges. Regardless of the storm size or status they can still cause potential damage. Disruption in logistics of emergency resources (food, water, and medical supply) mainly caused by impeded transportation. Phase-1 transportation issues related to gridlocks, and blockade of evacuation routes temporarily creating bottleneck situation, further complicates the evacuation process.

Although such significant changes have increased the robustness of the transportation network, their efficiency is challenged during unpredictable conditions and have become inevitable in every single event. So, to mitigate this risk, planned evacuation and emergency transportation at safe standby locations, alternate evacuation routes should be included in the emergency plans for future execution. This is even more important for island communities with limited geographic dispersal availability for populations to move to safe havens. Expanded multi-level networks and increased stakeholder participation can also be considered. During Katrina's response, the support from Walmart by distributing the emergency supplies using its delivery vehicles. when the federal response team's standby emergency vehicles were submerged and became unusable, was a strong example of extended stakeholder involvement. It is recommended that when local authorities or region are planning emergency responses, they engage with other stakeholders, industry in the preparation and practice exercises for such response.

8.5.12 Sustainable power and utility infrastructure

The power outage is a crucial factor which remains critical during hurricanes and storm surges. Although, power grids are designed to sustain the hurricane's heavy winds, the case studies identified how power and utility infrastructure has suffered severe damaged or destroyed during storm surges. The period of seven months for the restoration of power and utilities in Puerto Rico post-Maria explains the critical attributes of this infrastructure. Hurricane Maria's death toll was also associated with the loss of power outage over a prolonged period cutting access to life-saving instruments. Few solutions which can be adapted more easily by developed countries include installation of food gates, prioritization of investment in utilities, energy station and pumping motors operated in sealed water-tight gates like those observed post-Katrina Phase 4 mitigation measures.

Raising power grid substations as witnessed in the Phase 4 mitigation stage of Hurricane Sandy, may serve as possible future solutions for many countries to reduce power outage period. Developing and low-income countries should focus on the usage of battery-operated emergency lights, alternate power-backed inverters for households through encouraged multi-level networking and support from neighbouring countries. Additional insights for future innovations such as real-time power outage and restoration time frames could support community engagement during the restoration period.

8.5.13 Improving the recovery phase from the insurance perspective

According to Tower Hill Insurance (2013), a private insurance company, 'storm surge' is a peril that creates ambiguity for the people to understand. The insurance policies currently differentiate the classification of damage into 'water damage' and 'wind damage'. As such storm surge is linked to both, primarily water-borne but originates from pressure wind source.

In line with the annual report of the Marsh Insurance (2015), the insurance industry has made changes to their policies and in the way of assessing risk based on the lessons learnt from significant storm surge events such as Hurricane Katrina and Sandy. In agreement with this report, Phase 4 mitigation observed changes in the way risk is being assessed and insured.

However, these events also underline how the simulated catastrophic models and their results have greatly deviated and have exaggerated or underestimated the risk compared to the actual loss in the past. While carrying out the analysis for case Sandy, additional data were identified on FEMA's- NFIP - Flood Insurance Risk Map (FIRM) do not appear to have incorporated the future forecasted sea-level rise 2100 scenario, which leaves a potential gap in policies (FEMA, 2017).

As far as observed in Myanmar, Philippines, Haiti or Puerto Rico, no standardized insurance programs or policies were being commonly put into practice, unlike the USA. These countries after having faced significant cyclone events have not mandated any such reforms within insurance, flood risk or property damage funding for those residing within the LECZ's. These countries generally rely on national disaster relief funds to rebuild their houses. Considering the difference in developed versus developing or low-income countries highlights the gap within the insurance, and further raises questions concerning to the role of private insurance companies and their stakeholder participation. If participation of insurance as a key stakeholder in developed countries are delicate regardless of utmost adaptive capacity, then the situation in developing and low-income countries remains even more critical.

8.6 Additional factors to consider for enhanced resilience

8.6.1 Sustainable drainage system

During Katrina, the most efficient pumping system of the New Orleans, which could drain 300 million gallons of water in a day, was fully inundated by storm surge making the system inoperable leaving the city flooded for more than two weeks. The similar situation was also observed post-Sandy in New York. Drainage system controls the surface water, especially during inundations from inland and coastal flooding, can become critical. This can also invoke outbreaks of infectious disease, health-issues and epidemics, post-disaster. The observation of the cholera outbreak in Haiti post-Matthew is a sample of the poor drainage system. The situation occurred in New Orleans clearly emphasises the necessity for increased drain holes, and efficient sustainable drainage system as an active protection measure. Economically efficient investments such as trench drainage systems, French drains, spoon drains, roof water drains, gully grate, open channels could be installed in developing and low-income countries.

8.6.2 Media involvement and social media

According to a study published by Five Thirty-Eight's Dhrumil Mehta (2017), it is observed that Hurricane Maria received less media attention relative to the previous hurricanes such as Harvey and Irma, which had its landfall in the US mainland (Centro, 2018). The general observation from the cases identified that media coverage of these disasters was subjective in some instances. While collecting the newspaper data, many events were identified to have not received sufficient media attention in comparison with the hurricane activities monitored in a few other countries. Because media one of the key stakeholders, their increased involvement is vital during emergencies. This could also increase the country's obligations to respond in a reasonable homogenous way.

Additional observation of Hurricane Sandy exhibited a new way of communicating risk via social media. Many residents used Twitter as a platform to network and communicate with FEMA, state, and local response teams. Although this trend is widely observed in developed countries, and the authorities of developing and low-income countries were yet to migrate to this technology entirely. The language barrier, illiteracy rates, ambiguity in understanding modern terminologies and communications were identified to take the lead for occasional or less use of social media. It is highlighted via this research that this could be a possible next-generation approach for effective risk communication.

8.6.3 Lack of record and data

This is one of the key limitations observed while collecting research data and caste study data. Some events were observed to have two set of data such as official and unofficial or direct and indirect death statistics. Cases such as Hurricane Matthew, where the official statistics in Haiti is 546 (Stewart, 2017), and the reported unofficial statistics of 1,332 deaths (Aon Benfield, 2017). Similarly, in 2017, during Hurricane Maria, 65 deaths are recorded as official death statistics but, new reports claim the death statistics are as high as 2,975 (Milken Institute School of Public Health, 2018). As disaster damage data are vital to analyse the underlying risk, lack of data or inaccurate data can result in the underestimation of actual storm surges risk. This research suggests the importance of constant and consistent maintenance of the disaster database for future risk analysis and assessment of the return period of these events.

8.7 Summary

This chapter considered the analysis of the research data collected via the six case studies. Each case study which was chosen as a typical representative of the total research population were not considered as a sample but as an opportunity to conceive and conduct empirical analysis. The analysis of individual case studies as cross-case syntheses led to the identification of commonalities and differences as key findings and provided the evidence of limitations and challenges within the current approaches of disaster risk management and risk reduction. The identification of the commonalities across the cases which was considered as both strengths and weaknesses from the cross-case synthesis were given as guidelines towards achieving the best practices in DRM and DRR. The analysis which produced the lessons learnt of the lessons learnt as research findings, the gap analysis of the timeline within the first two phases led to the development of the DAMSS framework. The final section includes the discussion of the various key activities which supported in the development of the framework.

CHAPTER 9

DISCUSSION OF THE DAMSS FRAMEWORK AND GUIDELINES

9.1 Introduction

The previous chapter provided the analysis, findings and interpretation of the results based on the case studies, which has supported the recommendations in the proposed DAMSS framework. This chapter discusses the issues of current generalised risk reduction frameworks, such as Sendai. This chapter discusses how the framework is aligned within and to the key priorities of United Nation's Sendai Framework for Disaster Risk Reduction (SFDRR). This may help synergize, align, and incorporate the recommendations in an existing framework structure, allowing the flexibility for earlier or 'ready' future adoption. In future if a specific framework for improving the resilience for storm surge was to be introduced, the DAMSS framework proposed in Chapter 8 and aligned against the Sendai could act as a guideline.

9.2 Alignment of SDG and the Sendai Framework for DRR

As discussed in Chapter 3, the Sendai Framework for Disaster Risk Reduction (SFDRR) is the successor of the previous Hyogo Framework for Action (HFA) with a goal period of 2015-2030 (United Nations, 2015). According to SFDRR, countries *should develop plans for existing and new disasters* through a strong commitment to achieving seven global targets through four priority phases (United Nations, 2015). The seven global targets (A-G) are spread over two distinct categories of reducing and increasing, as shown in Figure 9.1.

<table>
<tr><th colspan="2">Reduce</th><th colspan="2">Increase</th></tr>
<tr><td>A</td><td>Mortality</td><td>E</td><td>Countries (national and local) DRR Strategies</td></tr>
<tr><td>B</td><td>Affected people</td><td>F</td><td>International co-operation for developing countries</td></tr>
<tr><td>C</td><td>Economic loss</td><td rowspan="2">G</td><td rowspan="2">Availability & access to EWS, DRR information and assessments</td></tr>
<tr><td>D</td><td>Damage to critical infrastructure</td></tr>
</table>

Figure 9.1 Sendai Framework seven global target indicators [source: United Nations (2015)]

The UNDRR guidance and international knowledge platforms such as 'prevention web' for disaster risk reduction have alignment (as shown in Figures 9.2 and 9.3) with three primary UN Sustainable Development Goals 1, 11, and 13 involving: *No. 1 - No Poverty; No. 11 - Sustainable Cities and Communities and No. 13 - Climate Action.*

UN Sustainable Development Goal (SDG) Indicators		**Sendai Framework Indicators**
1 NO POVERTY	**Goal 1.** End poverty in all its forms everywhere	
11 SUSTAINABLE CITIES AND COMMUNITIES	**Goal 11**. Make cities and human settlements inclusive, safe, resilient and sustainable	
13 CLIMATE ACTION	**Goal 13**. Take urgent action to combat climate change and its impacts	
SDG Clauses	***Synergies between SDG and Sendai***	***Section***
1.5.1, 11.5.1, 3.1.1	***REDUCE*** *Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population*	*A1, B1*
1.5.2, 11.5.2	***REDUCE*** *Direct economic loss attributed to disasters in relation to global gross domestic product (GDP).* ***REDUCE*** *Damage to critical infrastructure and number of disruptions to basic services, attributed to disasters*	*C1, D1, D5*
1.5.3, 11.b.1, 13.1.2	***INCREASE*** *Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015-2030*	*E1*
1.5.4, 11.b.2, 13.1.3	***INCREASE*** *Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies*	*E2*

Figure 9.2 Alignment of the UN Sustainable Development Goal Indicators and Sendai Framework Indicators [source: United Nations (2015)]

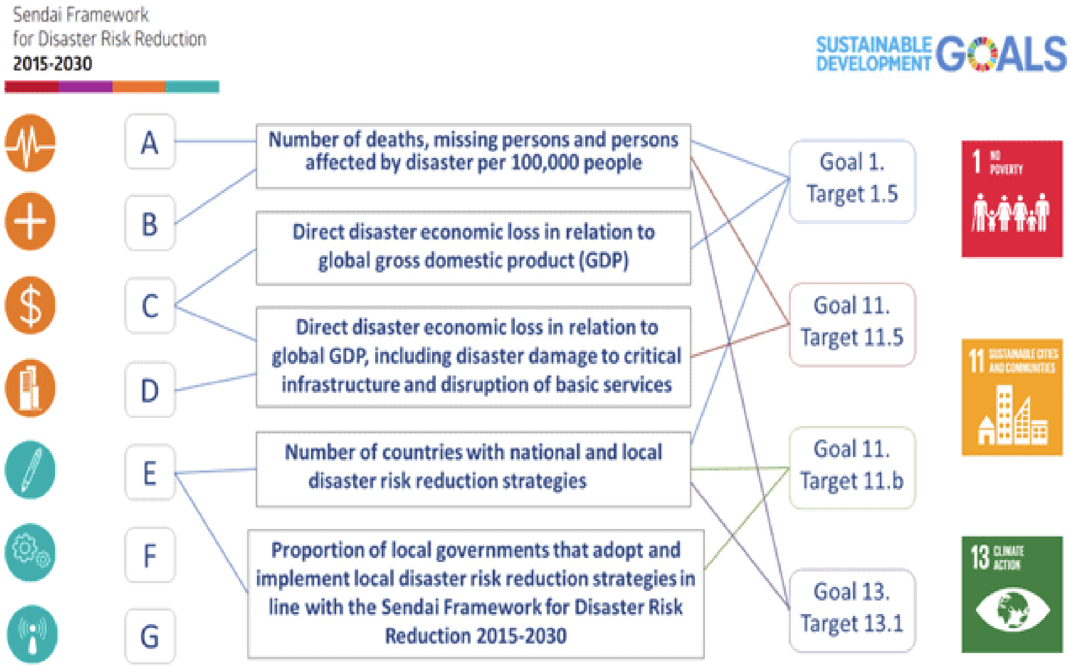


Figure 9.3 Diagram showing the alignment of the Sendai (SFDRR) seven global target indicators and UN SDG goals and target indicators [source: PreventionWeb, n.d.]

9.3 Global DRR frameworks and integration of the DAMSS framework

One of the major drawbacks of the current global frameworks (such as the SFDRR) found during this study is an imprecise or generalized approach to disasters. Whilst there are some primary aspects, processes and structures which have a commonality in existing global frameworks. The common characteristics however are not aligned nor do not give the sense to be custom-made to specific types (storm surge) and there are no sub-frameworks for this specific disaster response. This highlights how the DRM framework is not being implemented considering specific sub-disasters types.

Oxley (2015) claims that though the SFDRR framework is a successor of the HFA framework, it under utilises the lessons learned from HFA's and rather proposes a new set of targets and priorities. He further adds that SFDRR is weak at problem analysis and connecting the lessons learnt and implementing future actions. This research considers the proposal of SFDRR as a positive approach towards DRR while also recognising its weaknesses as stated by Oxley (2015).

Despite the availability of various international protocols, frameworks, and federated emergency management plans being utilised the significance of storm surge awareness is still underestimated. As discussed in Chapter 3 there has been an increasing trend in storm strength, economic cost, and societal impact due to storm surge. Reflecting on the critical importance of these current limitations within DRM and DRR and forecasting the future exposures to storm surge, it is understandable that a holistic focus through the framework approach is required. Such a focus of an operational framework should cover the individual phases of DRM overarching, to help mitigate storm surge risk. Hazards such as climate change and sea-level rise take their course over an extended period. Long-term planning and approaches do not align with near-term hazards such as storm surge.

The SFDRR's seven global targets as shown in Table 9.1 have a focus for improvements in the key indicators between the years 2015-2030. It is unlikely that such a generic framework could impact within the specifics of storm surge and within low elevated coastal zones. The period for SFDRR targets, changes and plans are much shorter than the global warming and climate change time actions of net-zero by 2035, 2045 and 2050. The risks from storm surge are in the 'near and present' and it is recommended that any storm surge resilience approach should be able to be rapidly adopted and utilised. The case study findings and the current gaps before and after the proposal and implementation of the SFDRR highlight the way that these PFA's could act as an abstract for disaster risk reduction. The underlined requirement of additional tangible key actions designed within the DAMSS framework aims to add value to the SFDRR which is considered as an 'abstract' version of DRR by the author.

Although there are few setbacks with the current SFDRR frameworks highlighted by Oxley (2015), this framework is adopted by the UN's participating countries for the period 2015-2030. Instead of proposing a new variable for the DRM and DRR approaches, the DAMSS framework is aligned against the SFDRR to underlines the fact the framework is adaptable and a possible integration within existing frameworks and indicators. This alignment assists in creating synergy and tracking of key indicators across such frameworks. This would also assist in the cross-referencing of the indicators, deployment, and actions to enhance the DRR approaches for storm surge. As the Sendai Framework is a global framework for Disaster Risk Reduction (DRR), a comparison of the key components of the Sendai Framework's PFA's, with the DAMSS framework is considered 'implicit validation' of the framework.

The Sendai Framework has four priorities for actions (PFA) are as follows:

- *PFA 1: Understanding the risk*
- *PFA 2: Investing in disaster risk reduction for resilience*
- *PFA 3: Strengthening disaster risk governance to manage disaster risk*

- *PFA4: Enhancing disaster preparedness for effective response, and to 'build back better in recovery, rehab and reconstruction*

If coastal countries adopted the DAMSS framework approach within their national or local plans, this may provide a positive contribution to increasing the resilience, specifically for those vulnerable low elevated coastal communities. Figure 9.4 shows the Sendai (SFDRR) priorities for action (PFA) and the alignment of proposed DAMSS priorities for actions (PFA's).

SENDAI (SFDRR) Priorities for Actions	**Disaster and Adaptation to Mitigate Storm Surge (DAMSS) Priorities for Actions**
PFA 1: *Understanding the risk*	***DAMSS Phase 1:*** *Better modelling of the risk. Better design preparedness in planning, construction and retrofitting.*
PFA 2: *Investing in disaster risk reduction for resilience*	***DAMSS Phase 2:*** *Investing in Phase 1 measures to protect critical infrastructure, utilities and habitat. 1) Raised utilities, 2) housing [habitat] levels above minimum surge height levels, 3) Safe roof zones, 4) Effective communications - Early Warning Systems (EWS)*
PFA 3: *Strengthening disaster risk governance to manage disaster risk*	***DAMSS Phase 3:*** *Governance structures for storm surge disasters for management, co-ordination and communications. Multi-stakeholder both national and local to prep, respond and recover.*
PFA 4: *Enhancing disaster preparedness for effective response, and to 'build back better in recovery, rehab and reconstruction*	***DAMSS Phase 4:*** *Enhancing education of communities to EWS and storm surge risks, continuation and protection of key transport recovery routes, building back better in damaged areas post storm surge aligned to DAMSS 1 & 2.*

Figure 9.4 SFDRR priorities for actions (PFA) and the integration of a DAMSS framework (PFA)

Therefore, by aligning and validating the DAMSS framework, the recommendation is to increase the storm surge awareness in all the countries adapting the SFDRR as a step towards enhancing their DRM and DRR approaches. The DAMSS is designed to act in harmony with the SFDRR, which may further lead to policy refinement and best practices and minimise the inadequacy particularly in the field of storm surge.

Various issues identified within the subject area are (i) formulation of DRR related policies (ii) lack of awareness of the hazard (storm surge) (iii) inadequate pre-emptive measures and (iv) technical knowledge. The DAMSS framework and its findings as potential guidelines resonate the claim of Hansom (2015) who suggested that having a framework is important to alleviate the impacts. The framework further resonates on Wilson & Fischetti (2010) who emphasised on developing innovative approaches to address the changing risks. This framework provides an opportunity to act as 'step-change' required to fill the potential gap in understanding storm surge as highlighted by Ellis (2015). By reflecting on Nguyen's (2012) statement on enhancing storm surge awareness, this framework also creates a contribution to storm surge knowledge for coastal communities. This research extends further into a wider data collection and analysis of storm surge and its preparedness issues. As highlighted previously in Chapter 3, this research contrasts with Bouwer & Jonkman (2018), which claimed that the mortality rate from storm surge is decreasing. The reason for contradicting is based on various points such as the study exempted South East Asian Cyclones and the study period ended in 2015. This research reinstates that since 2015 there are changing patterns, increasing sea-levels which sets the new base for storm surge and further highlighted in Chapter 2 and 3, how the increase in frequency and intensity of hurricanes is capable to trigger more storm surges in the future. In general, this study contrasts with previous studies and further reinstates that since 2015 there are changing patterns, and storm surge should not be deviated and considered non-perilous. In general, this study contrasts with any previous studies which deviate or underestimate storm surge as non-perilous. Adapting to augment the emphasis and activities by *improving preparedness* through a DAMSS framework approach, aligned with a timeline-based approach for early warning processes, would allow the countries to be prepared ahead for better response. This may be influential for the future declarations of emergency soon after the risk and its associated hazard and their potentials are analysed.

9.4 Guidelines and recommendations intended for best practices

The following recommendations and guidelines were provided based on the in-depth analysis of the common key issues identified in Chapter 8. Some of these recommendations and guidelines may have already partly been practised in some developed countries. It is the recommendation of this research to embed such approaches across developed countries and to enhance the current practice in developing and low-income countries. Because developing and low-income countries are less likely to invest and allocate resources on coastal defence mainly due to their socioeconomic inequalities (PreventionWeb, 2015), these suggestions and recommendation could guide in assuring a concerted baseline approach is practised.

9.4.1 DAMSS PFA1: Understanding the Risk

Land-use planning*:* Critical coastal lands like the case study location such as the Gulf of Mexico, North Atlantic basin, 7,600 islands in the Philippine, and various bays, creeks, estuaries, and rivers connected to the ocean often combat with elevated storm surge activity from cyclones. Coastal environment, evaluation of exposed assets, communities and segmentation of coastal zones should be reassessed. Whilst the developed countries were recommended by the DAMSS framework and the guidelines, to reassess their existing zoning system, initiating 'coastal zoning system' becomes paramount in developing countries, island countries and low-income countries.

Modelling of low elevated coastal zones*:* for various storm surge heights would enable a better understanding of the risk. This coupled with the understanding of the types of construction habitat, locations and heights of key infrastructure such as major roads, rail, airports, and utilities (e.g., electricity substations) would assist in prioritising future the DAMSS resilience and risk reduction investment.

Realization from the previous experiences*:* Analysis of multiple case studies also highlighted the scale of damage to private and public buildings such as schools and hospitals post-events. Taking this into account as vital lessons learnt from the immediate past events should be transferred into future strategies, approaches or plans. Further integration in the subsequent risk assessment and disaster plans will project a cohesive approach of best practices.

9.4.2 DAMSS PFA2: Investment in Risk Reduction

The following section outlines some key aspects to be considered in the future DAMSS framework PFA2, regarding investment within the built environment to reduce future risks, which include:

- elevated infrastructure,
- housing adaptation to existing roofs,
- raised housing habitat constructions, and

- construction or adaptation for ‘safe community zones’ above the potential surge levels.

One of the critical factors of storm surge is their strength of inundation when there is a shallow continental shelf which is considerably higher than their strength over a steep coast. This characteristic when combined with the increasing sea-levels in future will observe new elevated surge levels.

NOAA provides an example of the difference in surge height which can occur. A Category 4 storm hitting the Louisiana coastline, which has a very wide and shallow continental shelf, may produce a 20 ft storm surge. While the same hurricane in a place like Miami Beach, Florida, where the continental shelf drops off very quickly, might see an 8 or 9ft surge. As such the planning, design and construction of future elevated building structures and building codes for coastal locations should specifically consider the coastline features. The construction sector already designs for wind loading based on regional and local variations of wind speeds resulting in changes to the structural facade wind loading designs. So, in effect, incorporating future geographic regional or local variations to building codes or design standards does have precedent.

Table 9.1 shows the maximum storm surge level observed during each case study event and a resultant proposed future elevation of construction of coastal buildings. Although the proposed elevation is provisional, nevertheless it could provide a base level guidance of surge elevation levels and the recommended construction elevation above these levels as a starting point. This aligns with this study’s findings that it may be necessary to re-evaluate the baseline assessments (BFE) for constructions thereby improving resilience for future events.

Table 9.1 Maximum storm surge levels and proposed elevation for shoreline housing and constructions

Event	***Year***	***Ocean basin***	***Maximum storm surge levels observed ft (m)***	***Proposed elevation of construction ft (m)***
H. Katrina	2005	Atlantic	27.8 (8.5)	>30 (9)
Cy. Nargis	2008	Indian	16 (4.87)	>16.5 (5)
H. Sandy	2012	Atlantic	12 (3.7)	>13 (4)
Ty. Haiyan	2013	Indian	23 (7)	>26 (8)
H. Matthew	2016	Atlantic	9.88 (3.0)	>13 (4)
H. Maria	2017	Atlantic	6 (1.9)	>13 (4)

Elevated infrastructure: Findings from the analysis have identified housing with insufficient base flood elevation (BFE) levels (Katrina & Sandy) and building codes to cope with the storm surge flooding. By elevating the key infrastructures established in the shoreline such as power and utilities, water pumping stations, chemical plants, communication systems and housing, to higher grounds to avoid the direct impact from the storm surge flooding is also recommended. Recommendation of elevating the infrastructure above the BFE levels could be one of the possible solutions in addition to developing robust building codes. The existing constructions and public buildings should also be evaluated against the maximum surge levels and elevated accordingly.

This is one of the important recommendations to the developed countries whose assets are endangered from the substantial storm surge damage. Coastal infrastructure in the developing, small island developing states (SIDS) and low-income countries (LCD) could consider installation of appropriate embankments, revetments rock armours (tripods and tetra pod), sand-dunes where possible.

In addition to the elevation of infrastructure alternate strategic design innovations such as increased structural strength to withstand the magnitude of storm surge, exit roofs, flood-proofed or elevated mechanical-electrical-plumbing units, should also be considered for future 'worst-case scenario'. Water treatment plants should also be included within elevated infrastructure, specially to avoid the saltwater intrusion, damage to treatment plants during storm surge flooding. Furthermore, the drainage system and underground sewage system should also consider their corresponding resilience measures to mitigate future flooding and contamination scenarios.

Housing: New or retrofitted housing should further focus on emergency exits from roof spaces (within attics) such as roof windows (also termed roof-lights) to allow people to escape during inaccessible (jammed) main doors conditions, and in case of sudden flash flooding and rapid storm surges. Such retrofitted and newly fitted roof-lights should also consider design innovation leading to a 'safe-haven' platform for occupants to await before the arrival of rescue teams. Buildings, including existing housing, which are low elevated high-risk areas for storm surge, should be retrofitted and amendments made to approved building codes. New developments should also readily incorporate these changes to increase resilience and safety for occupants. Household-level measures such as the installation of sewage water backstop, elevated boilers, walls coated with sealants (to stop walls from being discoloured and peeled post-flooding) could be considered. Moreover, checked inlet and outlet pipes and non-return valves, sump/pump to drain floodwater, raised electric sockets could also increase the resilience of housing to storm surge and coastal flooding. These additional efforts would also minimise the flood damage potentially reducing future flood insurance premiums and further claims post-events.

Construction use of housing habitat zones above surge levels: from this study it is evident that given the typical surge levels which can take place; therefore, the study suggests a review of the current practice of habitable spaces within buildings at first floor in low elevated coastal zones. Future housing design which can provide habitable space above 3m from finished ground level would lead to fewer impacts and reduced recovery costs. Whilst this would be a major global change to the design of new housing (and where possible adaptation of existing housing) given the forecast rise in sea levels, there will likely be an increase in the natural environmental factors which will dictate or guide future building codes. This has already happened in the energy performance of buildings and to target reductions of GHG emissions. For existing housing of two storeys or more communities may decide in future to alter the use of their buildings to utilise ground floor and basements for storage and move habitable spaces, utilities and 'white goods' to the first floor or higher, where practicable.

An area of future research is the study of the future types of construction systems for buildings in storm surge locations. There is evidence from the case studies that most of the housing damage occurred to lightweight structures, such as timber frame and lightweight gauge steel systems. One of the most comprehensive studies on storm surge damage to buildings was undertaken by Marshall (2014), which reviewed a series of storms and building damage from survey evidence from the US Army Corps of Engineers. This paper highlighted the impacts of both hydrostatic and hydrodynamic forces from the water on buildings, as shown in Figure 9.5.

Most of the damage (not unexpected) was on lightweight buildings and specifically ground floor levels (images A-H). In some cases, the hydrostatic and hydrodynamic forces of the storm surges were so strong resulting in complete building collapse (images A, B, C, E).

Figure 9.5 Examples of previous US storm surge damage to buildings [source: Marshall (2014)]

Whilst many concrete-based structures survived (image G) there were in some (few) cases of major collapse (image H). This was primarily due to some thinner load bearing walls being so badly damaged, leading to a disproportionate structural collapse. So, it is recommended for future research in this area that an assessment of existing thin concrete structures (walls/columns) requiring to be strengthened and for new building codes to be designed to avoid such disproportionate collapse.

Currently designing to avoid disproportionate collapse is included in many building regulations and codes globally for five storeys or more. But these are not currently designed for storm surge induced forces. This is a potential area of future research. It is also notable within some low-level housing images that there are no roof-lights or exit points from attic to roof zones in these homes. Here the term low-level housing refers to single main floor build above the street-level which may have basement and attics.

Construction or adaptation for 'safe community zones' above surge levels: in low elevated coastal zones with high population densities and insufficient funding to adapt existing buildings, one option may be to develop and construct safe-havens. As such the existing low-level housing is not altered and alternative resilience and safety are considered. This could be in the form of new community halls, schools and other public building assets which are constructed on an elevated site or artificially raised site, for communities to retreat to as safe havens during a storm surge. In some towns and cities in China, this has already been undertaken where community halls, schools and medical buildings are built on raised platforms.

9.4.3 DAMSS PFA3: Governance, Co-ordination & Communications

Disaster Governance: A sophisticated disaster governance considering the complexity and magnitude of the hazard in-terms of vulnerability (human safety and economic assets) should be planned and implemented. Multiple cases identified, inactive-key-period between risk identification and risk impact underlining the delay in various key activities such as response and evacuations. The future disaster plans, procedures and protocols should be tailored and integrated with the technical aspects such as early warning system. Continuous implementation and reassessment against the bench marked list of key activities are recommended. This would help minimise the lag in key-time periods (inactive periods) and achieve effective risk action lists, outputs and communication involving national and sub-national actors.

Public awareness and participation should be encouraged, through continuous drills on accessing: the evacuation routes; user-friendly risk maps to key locations; transportation modes and routes. Training workshops on kick-starting disaster readiness stage and exercises related to emergency kits and supplies checklist should be practised among the communities.

Education and training: In extension to the public awareness of the risk, schools and colleges should initiate disaster preparedness education. Under this initiation, students should be informed regarding their country's regional hazards. This measure could be significant to countries with low-literacy rate. Educating about disaster preparedness activities and evacuation drills in schools and colleges is recommended, involving students and their families. This approach will make the process of evacuation more straightforward to the public avoiding evacuation complications during unforeseen situations.

Stakeholder participation is pivotal in disaster management and future prevention. It is recommended to define a clear structure of formal vs informal activities, temporary vs permanent roles, synchronisation between primary, secondary, and tertiary stakeholder, during emergencies should be planned within the DRM strategies. Stakeholder involvement can lead to identifying risk reduction opportunities and innovative developments.

Multi-level stakeholders*:* Disaster management and risk prevention involve various actors from national to international. Cross-border (regional and national) coordination of stakeholders may also result in combining resources and extending the scope of knowledge and input. Cross-operational partnerships between corporate businesses, NGO's, volunteers, regional bodies, and academia can also enhance the multi-level stakeholder approach. This is an approach which many developed countries have adopted such as UK, The USA, Japan, Italy, and France. In less developed or developing countries such an approach or structure would assist DAMSS PFA3.

9.4.4 DAMSS PFA4: Enhancing disaster preparedness and response

Early warning system: Low-income countries whose technical facilities are limited should increase their institutional capacities to strengthen their technical facets such as early warning system, forecasting and monitoring. A standard EWS agenda with a systematic distribution of warnings and alerts should be discussed among the local authorities, key experts, and governments. As mentioned earlier, by minimising the inactive period between the risk identification and risk impact period, and by improving the current practices of the early warning system, potentially could reduce the loss of lives from these major events.

Risk communication should be prioritised to minimise the existing imbalance between the emergency responders and the population/residents. Case studies analysis identified 'lack of clarity' in communication resulting in non-evacuees to take shelter within their basements followed by loss of lives from storm surge flooding. Certain case study events of developing and least-developed countries identified many victims as 'passive recipients' of information, resources or assistance. The inversion from passive to 'active recipients' is proposed as a future recommendation. The communication and coordination between the responders and the residents should be complemented with public awareness and public participation. Also, designated volunteer or community-based wardens could eliminate the inconsistency in communication between officials and residents. The designated volunteers should be trained to act as a primary focal point in disseminating the warnings as received from authorities and comprehending the same to the residents.

Use of diverse communication: *such as social media platforms* should be enhanced for countries whose land-based telecommunication infrastructure is limited. Many developed and developing countries are considering social media as an emerging substitute for risk communication. The current COVID-19 coronavirus pandemic in many countries is an example of how social media and diverse media communications have reached wide populations and specific groups.

Image/video sharing, threaded communications under a common hashtag has generated new dimension in risk communication over the traditional practices such as the use of radios and telephones. New channels broadcasting disasters and live field situations have sustained in gaining public attention worldwide. Stakeholder participation from trusted news channels and other media source should be enhanced to support the increased focus of attention by the public.

Temporary emergency sheltering: During emergencies, public buildings such as schools, colleges, libraries, and other communal spaces such as churches assessed in advance could act as a temporary emergency shelter. This measure is recommended to ensure that evacuated population were moved to safety and no further re-evacuations were needed.

Maintenance of storm surge database is recommended especially in low-income and developing countries. Currently, most databases are maintained only for cyclones with storm surges as an underlying risk. Maintaining this database supports during the analysis risk assessment and analysis with history of data and creates an awareness about the risk. This is a low-cost effort which helps in future analysis and storm surge return-period calculations.

Growth of mangrove vegetation and its primary effort of acting as a natural buffer should be made emphatic within coastal communities. Discussion with coastal ecology expert Professor. Mark Huxham at Edinburgh Napier University who had spent two decades on local Kenyan communities provided various insights on mangrove coastal defences.

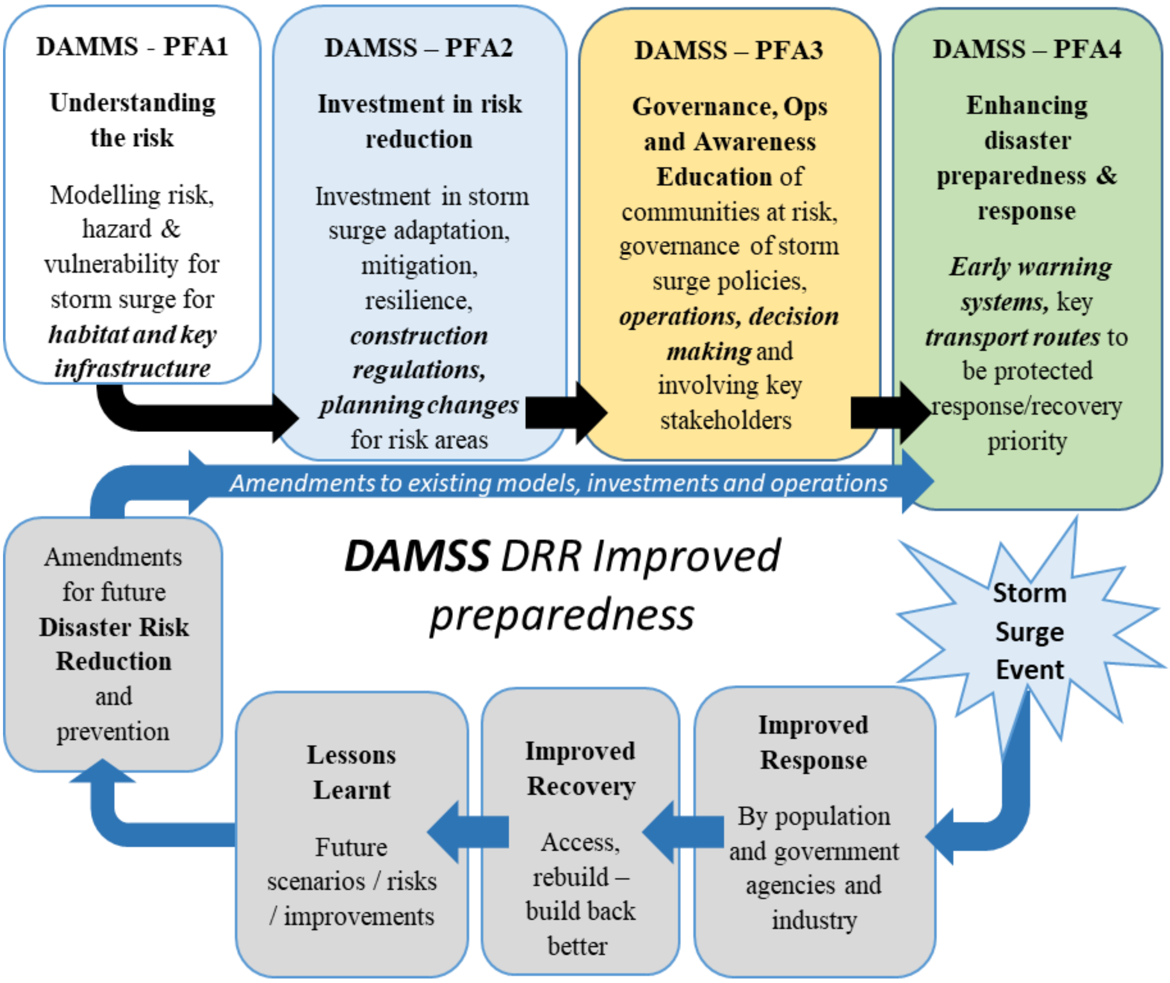


Figure 9.6 Proposed DAMSS framework PFA's and interlink with 'continuous improvement or knowledge approaches' to enhance resilience from storm surge events

His inputs (Huxham et al., 2017), on how mangroves can grow according to the increasing sea levels and continue to act as a barrier in attenuating storm surges are significant. This research also recommends the investment in natural vegetation in coastal lands to attenuate the direct impacts of storm surge and coastal flooding. This lower cost intervention may be attractive for low-income countries. However, it is to be noted that, mangroves could attenuate storm surge to a certain extent, while it is unable to completely reduce impacts of tsunamis. Although storm surge and tsunamis share similarities in bringing harbour waves to its coasts, these two phenomena differ significantly. Figure 9.6 summarises the proposed DAMSS framework PFA's and interlink with 'continuous improvement/knowledge approaches' to enhance resilience. The DAMSS framework and recommendations, when integrated within the four main priority phases of disaster risk management (DRM), with continuous reviews of the process and impacts would possibly enhance the formulation and implementation of livelihood strategies and risk reduction (DRR) activities.

9.5 Storm surge risk countries and DAMSS framework

Table 9.2 List of continents and countries exposed to storm surge hazard

Continent	Country / States / Provinces / Cities exposed to storm surge risk
North America	***The United States of America*** Alabama, Delaware, Florida, Georgia, Louisiana, Maine, Maryland, Mississippi, New Jersey, New York, North Carolina, Rhode Island, South Carolina, Texas, Virginia
	US Territories Puerto Rico, Guam, US Virgin Islands
	Caribbean Islands Antigua and Barbuda, Barbados, Cuba, Dominica, The Dominican Republic, Guadeloupe, Haiti, Martinique, The Bahamas, Grenada, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, British Virgin Islands
	Canada Nova Scotia
	Mexico Gulf of Mexico, Tamaulipas (Yucatan), Campeche, Veracruz, San Blas, Honduras, Guatemala, Belize, San Miguel de Cozumel, San Blas
	British Overseas Territories Anguilla, Turks and Caicos Islands, British Virgin Islands, Cayman Islands
Asia	***India*** Odisha, Bombay, Chennai, West Bengal
	China Fujian, Guangdong, Jiangsu, Shandong, Shanghai, Tianjin
	Bangladesh Khulna, Barisal, Chittagong
	Japan Regions: Kyushu, Shikoku, Okinawa, Kansai, Kanto
	The Philippines Cebu, Dinagat, Las Pinas, Leyte, Manila, Palawan, Paranaque, Samar
	Myanmar Ayeyarwady (Irrawaddy) delta region, Yangon
South America	***Venezuela, Coastal Columbia***
Europe	***Netherlands, Venice, United Kingdom,***
Africa	***Madagascar, Mozambique, Zimbabwe***
Australia	***Cairns, Mackay, Port Douglas, Burke town, Anguru, Townsville***

As mentioned previously in Chapter 3, Section 3.2 highlights the requirement to consider storm surge as a global priority. Table 9.2 is compiled by drawing from the literature review and considering global storm surge using various sources of SURGEDAT, EM-DAT, NHC, Caribbean Disaster Emergency Management Agency (CDEMA), SwissRe, Australian Bureau of Meteorology (BoM). Table 9.2 shows the list of continents, countries and their corresponding cities, states, and regions vulnerable to storm surge.

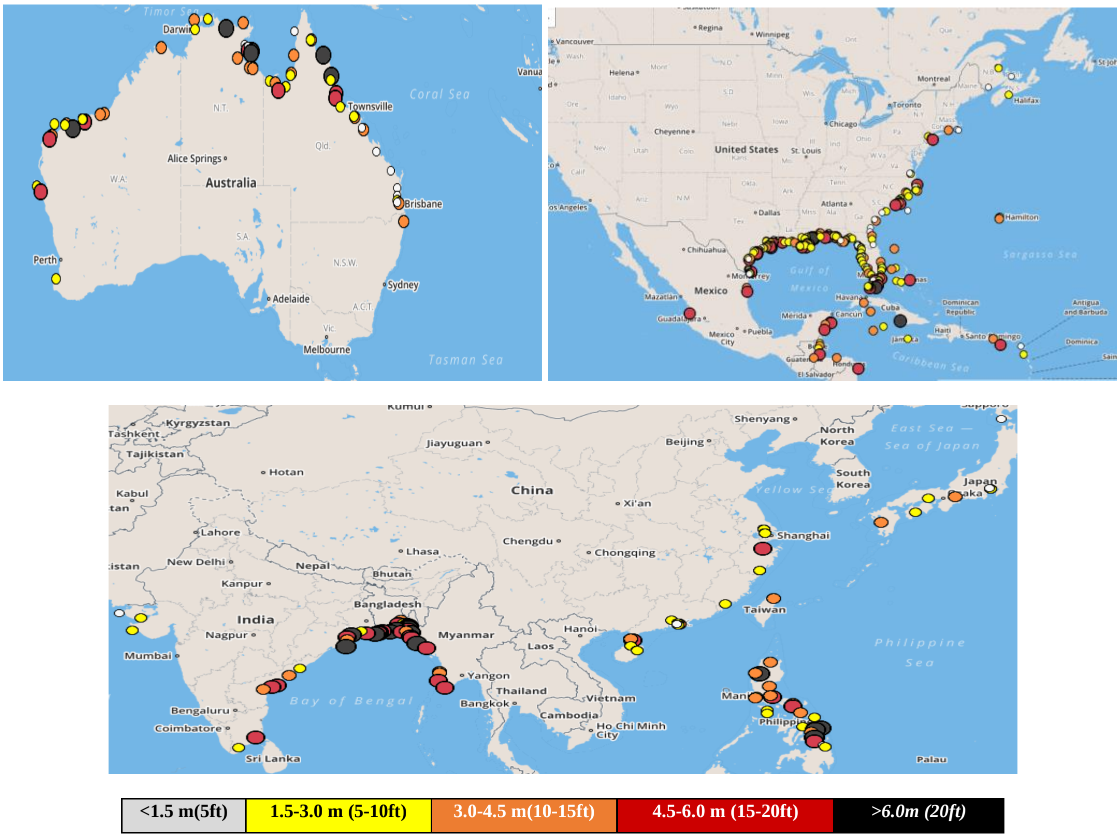


Figure 9.7 Global peak surge levels observed in different continents [source: SURGEDAT, n.d.]

Figure 9.7 shows the global storm surge vulnerability across different continents (SURGEDAT, n.d.; Needham & Keim, 2012). Understanding the storm surge risk zones coupled with DAMSS approaches supports enabling and future planning and impact scenarios. The development of the DAMSS framework along with the guidelines can be utilised to integrate, systematize, assess, design, or regulate the country's vulnerability, risk, and adaptation strategies. The framework could also be utilised as a tool to think and comprehend their current DRM and DRR strategies for developed countries. Those countries who do not have a standard DRM and DRR strategies could utilise the framework to develop heuristic approaches, policies for future adaptation.

9.6 Overview of execution of the framework and guidelines

The challenges and the limitations identified in all the stages of this research has assisted in guiding the development of the proposed DAMSS framework. As the framework aims to potentially enhance the performance of DRR and DRM, it is important to understand the benefits of executing the framework. The effectiveness and the benefits of executing the framework can be answered using the following questions.

(i) How the model is expected to fill the current gaps?

Drawing on the proposal of the DAMSS framework discussed in Chapter 8 and Chapter 9, the implementation of the framework is expected to fill the following gaps:

- By addressing a systematic evaluation of the performance of current DRM and DRR practices at regular intervals.
- By enhancing the efforts of all four phases of DRM underlining preparedness and mitigation as core phases.
- Minimise the execution errors in risk planning and risk communication.
- Increasing the capacity building for awareness-raising.
- Enhance multi-level organisational and institutional participation by closing the gaps in stakeholder involvement.
- Minimise the miscalculations in technical specifics such as hazard mapping, risk modelling, micro, and macro coastal zoning etc.

(ii) What are the benefits of the DAMSS framework?

By encouraging the beneficial factors and by continuous practising it is further anticipated to increase the effectiveness and efficiency of DRM and DRR overcoming the current limitations.

Figure 9.8 depicts the preview of the execution of the DAMSS framework. While all the four phases are important, two phases namely *preparedness* and *mitigation* are significantly important to prevent the scale of future damage in cost-effective manner. The below factors are stated as anticipated implementation benefits in support of the DAMSS framework and practice guidelines.

1. To offer valuable guidance, for future adaptation intended for local environments, particularly in developing and low-income countries that demand special attention beyond a standard approach.

2. Implementing of explicit and implicit demands of risk, associated risk assessment in concurrence with the changing risk patterns and the increasing densities of coastal lands through a cost-effective solution.
3. Strengthen the integrated disaster risk governance by involving multi-level stakeholders.
4. Translating best practices to required minimum standards and progress towards disaster prevention.
5. Improving the micro and macro-level factors influencing the adaptation and mitigation strategies.
6. Adaptation and utilisation of the DAMSS framework, guidance, and recommendation for best practices in conjunction with the country's existing national and local frameworks without altering the country's inputs.
7. Partnership with industries as key stakeholders to reduce future economic and societal impacts and operational capabilities.
8. Commitment to translate learning into the planning and implementation of DRM strategies.
9. Contributing practical recommendations to policymakers through frameworks and highlighting where existing procedures were obsolete.

Although the DAMSS framework has listed key activities for each phase, the guidelines, and suggestions, when executed in line with the lessons learnt, would support the disaster risk reduction and future disaster risk prevention.

Figure 9.8 illustrates the beneficiaries of executing the DAMSS framework, from a horizontal perspective of interlinked stakeholders. As mentioned earlier stakeholder involvement is pivotal and ensuring the ongoing participation of these contributors when adapting the DAMSS framework in-conjunction with the guidelines, recommendations will be one of the key benefits. The sub-themes within the dotted lines are the key focus areas for the developing and low-income countries to prioritize their actions for future storm surge mitigation. The emphasis on the sub-themes further enables the identification of potential gaps in various sectors involved in an emergency management.

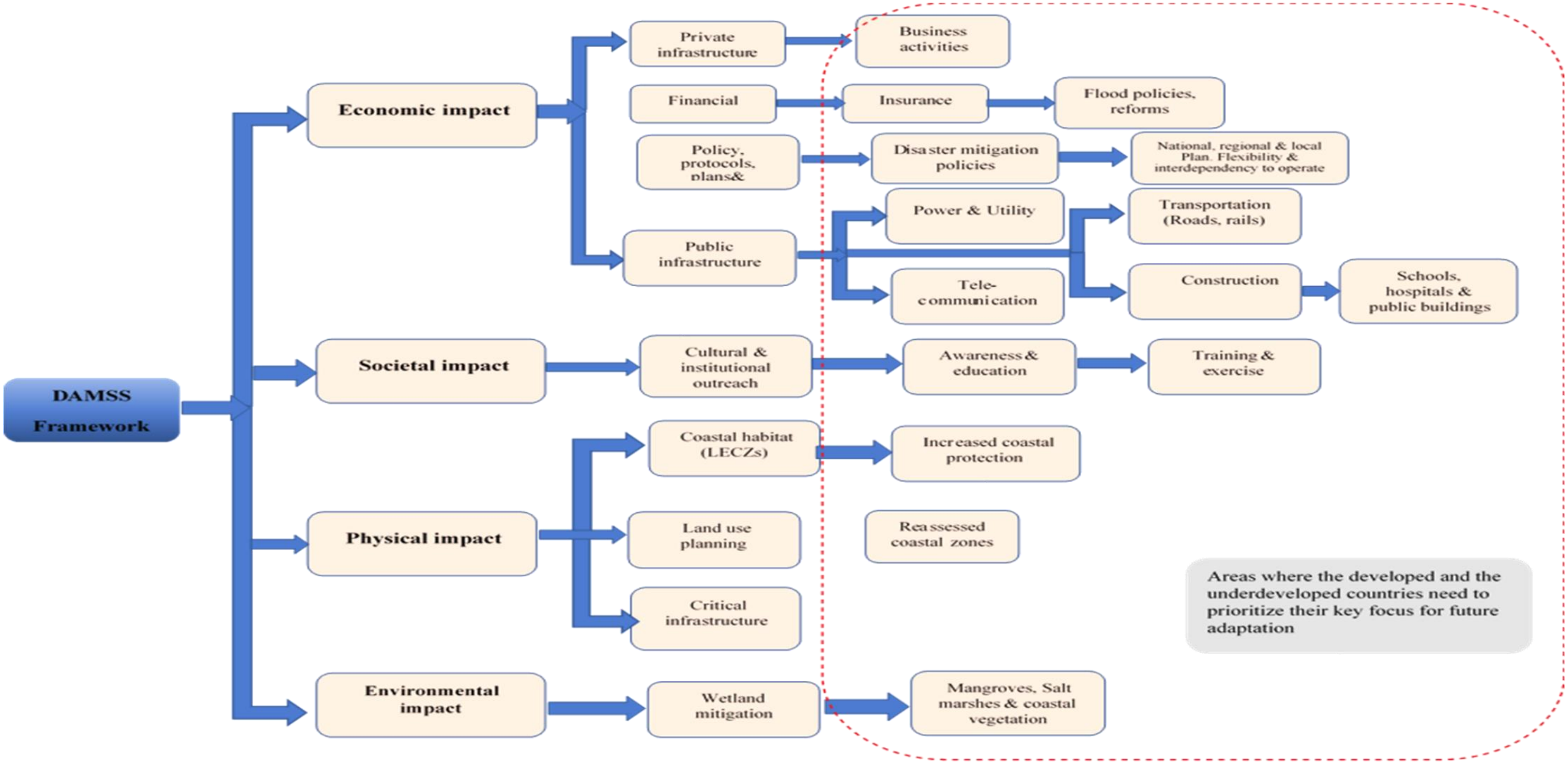


Figure 9.8 Beneficiaries of execution of the DAMSS framework and guidelines

9.7 Summary

Many people globally are yet to experience a storm surges and their direct impacts. The global frameworks play a vital role in disaster risk reduction; however, they lack in emphasizing the practical actions for individually identified hazards. Without achieving this major component, transforming from disaster management to disaster prevention becomes unrealistic. To overpass this gap, the research studied various root causes that impeded the execution of DRM. With an effort to address the 'risk blind spots' the DAMSS framework was proposed not only to support the findings but also recommend its contributions to all its major participants including governments, victims, organisations, institutions, industries and sectors. The DAMSS framework is proposed with an aspiration to support an integrated approach in reassessing risks, hazard, and vulnerability of current and future storm surge scenario in an economically efficient and effective way. The alignment and operation of the DAMSS framework proposed within this research provides a continuous chain-link structure from the UN Sustainable Development Goals, the Sendai Framework and aligns with the Priorities for Future Actions (PFA's), as outlined below as Figure 9.9.

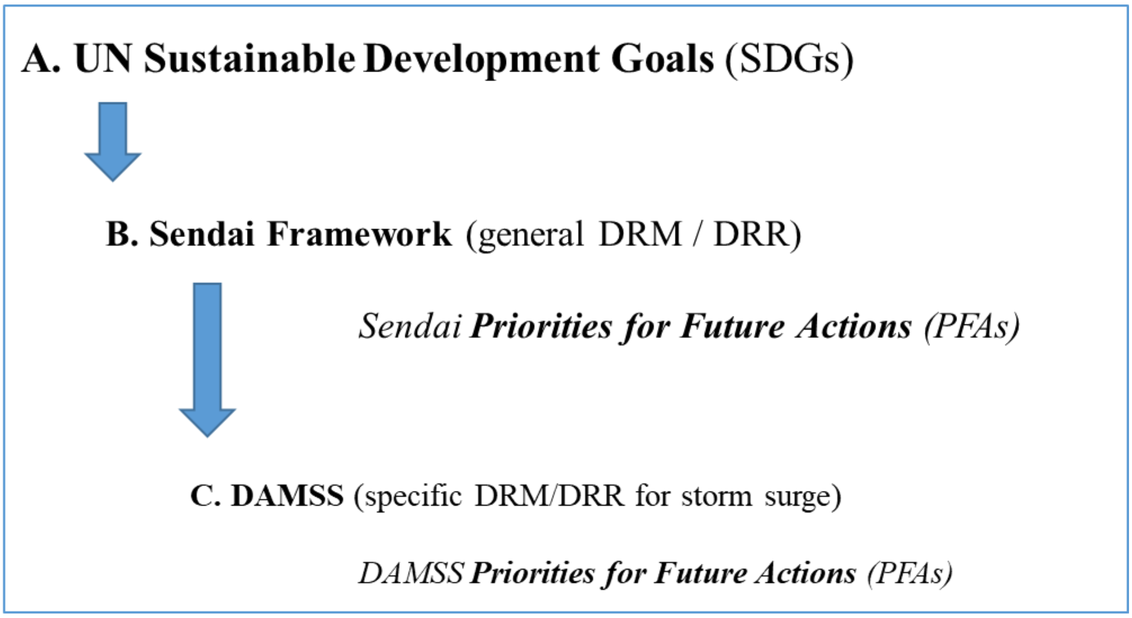


Figure 9.9 Summary of DAMSS's alignment with UN SDF and Sendai framework

CHAPTER 10
CONCLUSION AND RECOMMENDATIONS

10.1 Introduction

Based on the key findings from the case studies and analysis, this thesis proposes a framework to enhance storm surge resilience. This concluding chapter addresses the research questions and themes outlined in Chapter 1. By reflecting on the overall research outcome, an understanding of how the aim is examined at a broader level, connecting across the different chapters, highlighting the preliminary findings from the literature review and the key findings from the analysis can be understood. This chapter also discusses the achievement of the aim and objectives that were designed for the research. The critical reflection of the Disaster Adaptation to Mitigate Storm Surge (DAMSS) framework and any limitations are also highlighted with suggestions and recommendations for future research.

10.2 Summary of the research process

This research has studied the various aspects of disaster management implemented in the context of the six chosen case study events. The case studies examined the process of disaster management involving planning, preparing, organising, communicating, coordinating, and executing the actions required. Chapters 5, 6, and 7 presented the individual case studies regarding the underlying conditions of the disaster management protocols practised by a region or their community. The individual cases gathered information on activities in the operations corresponding to the preparedness, response, recovery and mitigation phases, and their effectiveness in managing the incident. All the collected data within the case studies were analysed and compared against the same primary list of activities. The usage of the Atlas.*ti* software facilitated the investigation across the case studies involving a wide range of reports, documents, articles, and media extracting information relating to activities that took place. This was also termed as coding (activity) within the study.

The observations from pre-impact conditions included preparedness, early warning, monitoring, forecast, and risk communication which identified scenarios such as the usage or non-usage of advanced early warning system (EWS) in some countries. The relationship between national and sub-national was explored. Then the response phase which is list of the activities carried out during the impact was studied. The observation of the during-impact conditions included evacuation, shelters, incident management, communication, coordination, NGO, and volunteer participation. This phase also identified the impacts of delayed evacuation, failure of evacuation leading to fatalities. From all the case studies, Cyclone Nargis (Myanmar) was considered to have the most significant failure of response. Hampering the efforts after requesting the humanitarian assistance by the Burmese government was a unique situation which was observed during this cyclone. None of the other cases was identified with such a response. The imposition of such restrictions was condemned by countries such as the USA, UK, Canada and by the UN. This particular observation summarised the difference in the approach of evacuation in developed versus developing countries. Furthermore, differences were observed in terms of searching and rescuing the victims, providing safe shelters, the adaptive capacity in addressing the vulnerable population was also observed under this phase.

The recovery phase which is an extension of the response phase was studied and collated case studies of this phase provided information on the long-term recovery, rehabilitation and reconstruction works that took place in the case study countries. This study further attempted to understand the improvements, measures, and time taken to recover from the incident. The overall findings of this phase supplied the information on how and to what extent even developed countries suffered the impact from storm surge. The case study of Hurricane Katrina is considered as an important observation of recovery being extended for more than five years considering America's economic capacity. The lack of learning and applying outcomes from Katrina such as the need to flood-proof or elevate the electrical substations was not implemented until during Hurricane Sandy in New York, some seven years later.

Mitigation phase or the post-impact phase was also examined. In this phase, the actions, adaptations taken towards the reduction or moderation of challenges and limitation faced in the past event were studied. The observation also highlighted the substantial change within the capacities that have been developed or proposed to be developed in future for the recurrence of a similar situation.

Many such observations supported by evidence, before and after images, maps and by document search using software (Atlas.*ti*), supported the research investigations and the subsequent analysis and recommendations. The cross-case syntheses of all the six case study events and the analysis of the pre-impact, during-impact and post-impact conditions encompassed within the four phases of DRM was complemented with the identification of commonalities and variations. The analysis broadened the understanding of the relationship between the federal-state-local or the national and sub-national level and the village-communities level practised in the developed and developing countries. The commonalities identified during the findings were grouped to complement the development of the DAMSS framework.

The DAMSS framework was supplemented with guidelines and recommendations. The key recommendations for developing and low-income countries include a focus in the early warning system, evacuation, adaptation of infrastructure, risk communication and coordination, public awareness and stakeholder participation.

Throughout the progression of this research one of the significant reflections that were observed was the recent increase in the intensity of the tropical cyclones in the Atlantic Ocean since 2015-2018, which resulted in triggering increased storm surge events. Because the cases chosen for study were a representation of a typical case, the framework can be implemented to 'similar-case' which replicates the original case. The subsequent recommendations and the guidelines may also have the benefit of being adopted by any country those experience threats from tropical-cyclone and storm surge.

10.2.1 Reflection on the theory of this study

The research began with a very generic question which is *what are the current practices and strategies of disaster management for storm surge hazard triggered by tropical cyclones?* The very first stage of the study began by understanding the choice of approach. The qualitative research approach was preferred over quantitative to retain the degree of freedom in exploring the research. Because the research is exploratory, a further 'inductive theory' approach was adopted. The research progressed with the notion of looking at various storm surge incidents and considered 'all the data' approach. This strategy allowed the research, to not to ignore or preclude any data. Each incident then became the indicator of the concepts within the data and supported in an unbiased understanding of the main concern of the subject of study and not the researcher's main concern of the study.

The qualitative research allowed the researcher (oneself) to be an instrument in data collection. From a quantitative perspective, this may be overlooked as a 'subjective' and 'impressionistic'. To avoid this, a careful choice was made to eliminate the subjectivism affecting the view of the researcher. Positively the choice of exploratory research with open-ended approach resulted in a much wider literature review. This advancement allowed the research to continue investigating the preliminary data and identify potential gaps in the subject field of study. The follow-on process of data and information convergence assisted narrowing-down the context leading to a more focused process.

The converged data was then transformed as coding for further analysis and development of the framework. As mentioned earlier in Chapter 3 regarding the Pfeffer and Sutton's (1999) theory of "the knowing-doing gap" the proposed framework fulfils the gap by improving the storm surge understanding between 'what was done' (current approach) and 'what should be done' (future needs) to minimise the losses incurred from the incident in future as shown in Figure 10.1

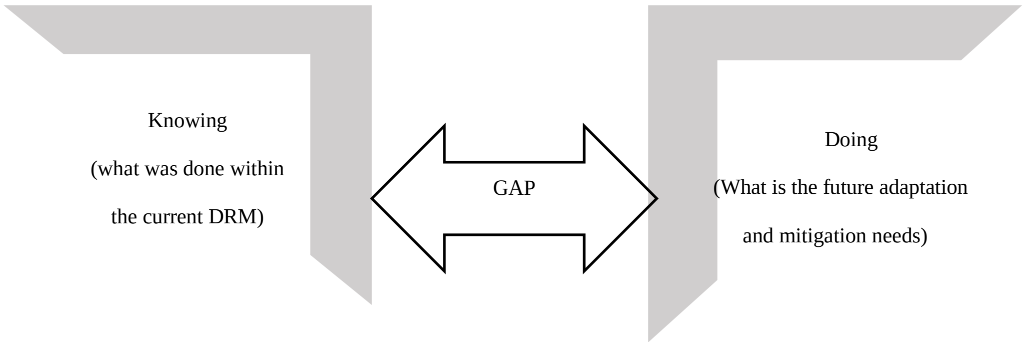


Figure 10.1 The knowing-doing gap [source: Pfeffer & Sutton (1999)]

10.3 Achievement of the research aim

The impact of storm surge on coastal habitat and communities was the underpinning drive for conducting this research. These impacts and the apparent lack of resilience or preparedness motivated the investigation further towards a non-structural solution to storm surge resilience. This led to the concept of developing a framework as a sustainable solution for this long-term battled hazard. The study aimed to develop a framework for storm surge resilience adapting to the current and future increasing coastal hazards and weather extremities. The proposal of the framework with supplementary recommendations outlined in Chapter 8 reinforces the achievement of the aim of this research.

Following a presentation of the research by the author at an international conference on disaster resilience, a very positive feedback from senior public health and international resilience experts was that a '*framework had never been suggested before for storm surge and there was a need to develop and start such a process*'.

10.4 Achievement of research objectives

The research objectives outlined in Chapter 1 were fulfilled and integrated at various stages within the research process.

10.4.1 Background study

The characteristics of the storm surge and their uniqueness in impacting the coastal communities and critical infrastructures were reviewed. The interconnection between climate change, global warming, sea-level rise, tropical cyclones, and storm surges were also investigated. It is with the help of the research objectives; it was determined how the risk incurred from storm surge were predominantly higher than the risk incurred from tropical cyclones. The reassessment of the various cyclones, typhoons, or hurricane events, when assessed in terms of storm surge, revealed that the estimated damage from the water was more than the estimated damage from the wind. The background study exposed how a particular 'funnel effect' of the storm surge has the potential to inundate villages, towns, and cities deep inland. The study further revealed how the complexity of the surge was influenced by these six characteristics such as the cyclone forward speed, the angle of approach, the pressure and the intensity of the storm, the continental shelf, and the coastal bathymetry. In addition to this complexity, the review of the existing storm surge measuring systems, current mitigation measures and the limitations of the coastal protection mechanisms underpinned the need for framework approach.

10.4.2 Literature review findings

Literature in this field was principally connected with hurricanes and their impacts under which storm surge was partially considered. The literature also highlighted how areas such as dynamics of storm surge characteristics, hurricane intensities remain critical with limited studies. Drawing from the results of a regional study, some research tends to deviate from the actual understanding of the underlying risk from storm surges. From the literature, one of the preliminary findings that were identified was the ambiguity in the classification of storm surge as a convective storm which underrates the genuine threat from this hazard. The critical review of the existing research and journal papers provided insights on the vulnerability of some coastal communities who have never experienced the impact of storm surge in the past and how they would be impacted in the future. The review also showed how some global frameworks developed are generic and not customised to individual hazard. Furthermore, the review underlines how such generic addressing of the hazard could be trivial and inconsiderate regarding the changing hazards. The regional disaster frameworks are tailored according to the regional factors limiting the extended usage. The comparative review of the global and regional framework was identified to establish the gaps and limitation both in addressing the key activities within DRM and in addressing future DRR.

10.4.3 Case study data

Each case study provided an event synopsis, followed by the review of the four phases which are the preparedness, response, recovery, and mitigation continued with the physical damage and impact from storm surge. A breakdown of key activities and their corresponding key phases executed during the events were examined. The achievement of the objectives was fulfilled not only by investigating the events and their disaster strategies executed but also by finding the gaps within the current approaches identified under their corresponding key themes. This facilitated the investigation and assessment of DRM practices.

10.4.4 Case study analysis

The investigation of the key activities is carried out through the cross-case analysis. In each phase, the common issues within the key activities were grouped under their corresponding key theme. In addition to the common issues, the difference in issues between the cases was also addressed. While observing the commonalities and differences, the lag in the timeline of execution of the key activities was also identified. The timeline analysis depicted the gap in the execution of the activities in developed and developing countries. The exploration of the analysis and the findings from the commonalities became fundamental for the development of the DAMSS framework.

10.4.5 Framework development

The aim was to propose a framework by determining the list of key actions categorised under their corresponding themes. The proposed list of actions was designed with anticipation to enhance the current practices and minimise the existing limitations within the disaster management. The framework was further supplemented with recommendation and guidelines as a holistic approach towards enhancing the storm surge resilience for the coastal communities and critical infrastructures. By proposing the framework, the aim and objective of the research is accomplished. The DAMSS framework was compared and aligned with the United Nation’s Sustainable development goals (SDG) and the Sendai Framework for Disaster Risk Reduction (SFDRR) as shown in Chapter 9 which is considered as an implicit validation. This comparison allows the end-user of the DAMSS framework to realise how the framework specifically focuses on storm surge as a priority among the other disasters and could be adopted within existing overarching guidance and frameworks for disasters. However, a detailed validation is required to pilot the framework further which is listed as a future recommendation.

10.5 Overall knowledge

The major contribution of this study to overall knowledge is the proposal of a new framework for storm surge protection as there is currently no evidence-based framework available specifically designed for this purpose. This research gained insight into the understanding of the performance of the disaster risk management, strategies, and protocols followed in countries chosen for the study. The integration of the DRM and DRR elements within the DAMSS framework, along with the guidelines and recommendations, contributes to knowledge by creating awareness of storm surge hazard. Creating such awareness could be beneficial to the communities, particularly to those developing countries with limited capacities. This research further contributes to knowledge by initiating a 'call for action' towards improved and structured disaster governance in terms of storm surge. The critical importance of learning from previous events and revising the resilience measures was recommended to be an integral part of any future resilience measures. This was embedded within the DAMSS framework approach. This knowledge if piloted and trialled could contribute further by advancing the overall disaster risk reduction and anticipated to enhance community resilience and human security. These contributions can create both short-term and long-term beneficial factors and further act as a knowledge loop if fed continuously together with the lessons learned in creating a better understanding of the storm surge hazard from a third dimension.

10.6 Critical reflection and limitations of the framework

Despite adding value to the theory and the practice, the study was identified with some limitation. Critically reflecting on the research is considered significant and therefore, aimed at raising as many questions as possible to answer.

The limitations of this research were identified as follows: -

(i) choice of method.

The case study methodology was the choice of the method used to collect the data. This research embraced desk-based data collection of information. However, an additional approach such as focus group discussion among the affected people and emergency responders, observatory tours and participatory experiments might have possibly added or provided additional insights to this research.

Another common limitation in the subject field of study is the ‘lack of accurate data’ and ‘abundant unwanted data’ concerning a disaster event, especially with storm surge events. The sources such as government reports varied from the organisation’s field reports. Therefore, an impression of the researcher’s subjectivism may have possibly had an unconscious bias which is not visibly identified.

(ii) choice of case studies

The choice of cases was identified as both an opportunity and a challenge for this research. The research population was extensive. As previously mentioned in Chapter 3, more than 700 hundred cyclone events were observed over a decade. However, when sampling the research population, many events did not have storm surge inundation data. This was observed either there was no such practice or loss of instruments, which measures such data, leaving little or no ground data in the subject of study. This was considered as one of the limitations.

The study is desk-based research, so data collection was carried out using documents as the primary source of information. After applying the initial screening of events and during the process of collecting information as documents about storm surge, another limitation was observed. A broad range of data was connected only with hurricanes, the development of their path, monitoring methods and their landfall data. But storm surge related information was sparsely observed despite being a major contributor in creating damage to the safety and well-being of inhabitants. Following the selection of optimal case studies as typical representatives of the wider sample, the thought of other exemplary or unique cases which might have drawn a different solution and might have given a different perspective to addressing a strategic disaster risk management is considered as a limitation.

Finally, some key activities of the case studies despite their crucial factor only reflected a regional approach, which is not typically followed by another region. Because of this unique difference they had to be extracted and excluded from the framework including only the commonalities identified among the cases. Although this was not included within the framework component, they were added within the supplementary guidelines as recommendations. Even though this does not limit the research and its findings significantly still was considered as an indirect element of limitations.

10.7 Recommendations for further studies

During the progression of the research, various recommendations surfaced in the process of data collection, observation of case studies, analysis of the observation and interpretation. Though limitations were identified in the research, recommendations of additional approach could only have led to additional insights rather would not have altered the overall results. Based on these limitations, and for the future education and learning, the following research suggestions and recommendations are proposed:

- The importance of this research relies in providing an understanding of disaster risk management and risk reduction for storm surge, an area that has not been studied previously. This study highlighted the key activities previously ignored or faced implications during execution. The obtained framework is expected to enhance the performance of the DRM and DRR. Therefore, 'validation of the framework' with expert opinion or focus groups articulating their perceptions with the suggested areas of improvements is recommended to increase the credibility of the framework.
- The second recommendation is 'piloting of the framework'. The piloting process will act as a 'trial and error' method to understand the progressive development of the framework. This will also provide constructive feedback on the effectiveness and feasibility of the framework. By monitoring and measuring the outcome, additional key activities or sub-stages may lead to other new outcomes or adaptations.
- The list of activities encompassed within the framework and their related stakeholder participating industries such as insurance, construction companies, transportation, land-use planning authorities could develop their strategies and new advancements measuring their performances concerning the four key themes. This could lead to industrial growth and innovative advancements for future disaster risk reduction. Research which analyses the effects and potential impacts of factors which alters the planning in built environment approaches in different countries to increase resilience (utilising previous storm surge data), would be useful.
- The framework is currently developed for storm surges triggered by cyclones. The utilisation of the framework could be extended to certain coastal hazards such as flooding. However, the applicability of the framework between cross-hazards and the multi-hazard situation is recommended for further studies.

- The future needs to adapt existing housing for roof escape and safe zones and the construction technology and architectural technology designs would also be useful.
- Finally, developing a future dynamic model which could be utilised by local authorities and governments to assess and map the risk for various coastal geographies. This could facilitate an earlier preparedness and resilience approach, particularly for less developed or developing countries where financial limitations exists. This will allow resilience investment to be focused on the most critical areas affecting population health and well-being.

Because the hazards and exposures are subject to variations with respect to future changes in coastal and marine hazards, this outcome of the research may become conditional in the future. Nevertheless, this research could be a fundamental and a prelude to many prospective studies and research. The change in risks and hazards tend to change the assessment and analysis of disaster risk management and disaster risk reduction strategies thereby concluding that the progression of the DAMSS framework will be an 'ongoing' process with continuous evolution paving way for future innovations.

If the outcomes of this research and DAMSS proposal are taken to a further stage of the trial, utilisation, and assessment by a public body, whether local or national, the author hopes that this will be potentially a 'keystone' to advancing awareness and preparedness for future coastal communities and provide a positive contribution to our global society's resilience.

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Appendices

APPENDIX A

Research Population and country profiling

Hazard means "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (PreventionWeb, 2017) . A country may even be subject to multi-hazard situations i.e. cascaded or cumulative events hazardous events may occur simultaneously or sequentially (PreventionWeb, 2017) According to the UNISDR disaster profile and ranking, the hazards contribution from Cyclones are 37.58% and storm surge are 16.67% towards the Average Annual Losses (AAL) (PreventionWeb, n.d.) . Some of the significant events which took place before the research's study period 2000-2017 are listed in Table A1.

Table A1 List of significant storm surge events before the study period

Event	***Year***	***Country***	***Death toll***	***Storm surge (m)***
	1737	India	300,000	12.0
	1864	India	50,000	12.0
	1876	Bangladesh	N/A	13.7
Cy. Mahina	1899	Australia		
Galveston, Texas	1900	TX, USA	8,000	
New Orleans	1915	Lou, USA		5.18
Cy. Mackay	1918	Australia		
Cy. Innisfail	1918	Australia		
Labour Day	1935	FL, USA		6.10
North Sea Flood	1953	Bristol, UK	2,551	
Oct 30-31	1960	Bangladesh	5,149	9.1
May 6-9	1961	Bangladesh	11,466	8.8
Carla	1961	Texas, USA		5.64
May	1963	Bangladesh	11,520	9.1
Sep-Oct 1	1966	Bangladesh	850	9.6
Beulah	1967	Tx, USA		5.49
Camille	1969	Mi, USA		7.50
Cy. Bhola	1970	Bangladesh	300,000	9.1
Cy. Ada	1970	Australia		
Eloise	1975	FL, USA		5.55
North Sea SS	1978	England		
April 19	1991	Bangladesh	140,000	8.2

Table A2(a): List of tropical Cyclone from 2000 – 2017

Event	Year	Country	Death toll	Economic damage cost (billion US$)	Storm surge ft(m)	Filtering criteria
H. Keith	2000	USA	24	0.2	4 (1.2)	Low surge low death toll
TS Allison	2001	USA	41	5	2.5 (0.75)	Low surge levels
H. Iris	2001	USA	31	0.25	15 (4.6)	High surge and low death toll
H. Isabel	2003	USA	17	3	8 (2.4)	Low death toll
H. Charley	2004	USA	15	15	>7 (2.1)	Low death toll
H. Frances	2004	USA	7	8.9	6 (1.8)	Low death toll
H. Ivan	2004	USA	92	14.2	10-15 (3-4.5)	High surge and low death toll
H. Dennis	2005	USA	42	2.23	9 (2.7)	High surge levels
H. Katrina	2005	USA	1,800	160	28 (8.5)	Costliest hurricane in US history, death toll and highest surge
H. Rita	2005	USA	120	10	10-15 (3-4.5)	Highest surge relatively low death toll
H. Wilma	2005	USA	22	16.8	-	Deaths associated with rainfall
Cy. Ingrid	2005	Australia	5+	0.014	1.08 (0.33)	Low storm surge
Ty. Saomai	2006	China	458	2.5	33 (10)	High surge range and significant death toll
Cy. Larry	2006	Australia	1	1.1	7.55 (2.30)	Moderate surge but low death toll
TC. George	2007	Australia	5	0.0158	7.2 (24)	High surge, but lowest death toll
Cy. Sidr	2007	India	10,000	1.7	16.4(5)	High surge, high death toll significant economic damage

Tc. Nargis	2008	Myanmar	140,000	12.9	16 (4.9)	Highest death toll First to hit the location Highest surge. Costliest Indian Ocean cyclone.
Tc. Nisha	2008	India	204	0.8	-	No surge data
H. Ike	2008	USA	214	24.9	16.9 (5.15)	High surge range and significant death toll
Ty Ketsana (Ondoy)	2009	Philippines, China, Vietnam	747	1.09	20(6.1)	High surge levels
TS. Agatha	2010	SW Mexico. Central America	204	1.1	6.6-13.1 (2-4)	High surge and death
Cy. Yasi	2011	Australia	1	3.6	23 (7.0)	High surge, but lowest death toll
Cy. Thane	2011	India	48	0.24	5 (1-1.5)	Moderate surge levels
Cy. Lua	2012	Australia	None	0.230	-	No surge levels
H. Sandy	2012	USA	147	72	14 (4.3)	Third costliest US hurricanes Largest NY/NJ damage
Cy. Rusty	2013	Australia	None	0.51	-	No surge levels identified
H. Manuel	2013	Mexico	169	4.2	2(0.61)	Low surge levels
Ty. Haiyan	2013	The Philippines	6,900	2.98	17 (5.2)	Highest death toll and economic damage
Cy. Ita	2014	Australia	40	1	-	A minor surge was recorded and merged with low tide. Limited damage.
H. Odile	2014	USA	18	1.25		Minor flooding
Ty. Soudelor	2015	Ph, Taiwan, China, Japan	59	4.09	1.97 (0.6)	Low surge
Ty. Meranti	2016	Philippines, China	47	4.8	7-10 (2-3)	Moderate surge and the low death toll
Ty Nepartak	2016	Philippines, East China	111	1.89	48 (15)	High surge levels

H. Matthew	2016	Haiti, USA	>800	15	7.5 (2.3)	Moderate surge and high death toll
Tc. Vardah	2016	India	47	3.4	-	No surge data
H. Harvey	2017	USA	68	125	6 (1.8)	Loss is not associated with storm surge. The death toll caused by rainfall
H. Irma	2017	USA	52(direct), 82(indirect)	77	<5 (1.5)	Moderate surge levels
H. Maria	2017	Puerto Rico, USA	2,967	90	>6 (1.8)	Highest death toll but moderate surge level
TC. Ockhi	2017	India	318 (actual) >800(predicted)	0.92	1-2 (0.3-0.6)	Poor early warning system Not associated with storm surge

The total research population is compiled from EM-DAT, CRED, NCAR list of tropical cyclones, Dube et al (1997), De (2005), Garriott (1900), Cline (1915), McDonald (1935), Dunn et al (1962), Sugg and Pelissier (1968), Simpson et al (1970), Hebert (1976), NWS (2003), Knabb et al., (2006), Keim and Muller (2009), Landsea et al., (2009) and Berg (2009). From the global research population Table A2(a), Table A2(b) is adapted.

Table A2(b): List of tropical Cyclone from 2000 – 2017

Event	Country	Hurricane Category in SSWHS	Death toll	Economic damage cost (billion US$)	Storm surge ft(m)	Reason for chosen as a case study
H. Katrina	USA	Cat 5	1,800	160	28 (8.5)	Highest surge, levee breach, costliest US (developed country) hurricane
Cy. Sidr	India	Cat 5	10,000	1.7	16.4 (5)	High surge, high death toll, low economic damage

Tc. Nargis	Myanmar	Cat 4	140,000	12.9	16 (4.9)	Highest death toll, costliest Asian typhoon, highest surge, high Typhoon category
Ty. Ketsana (Ondoy)	2009	Philippines, China, Vietnam	747	1.09	20 (6.1)	High surge levels
TS. Agatha	2010	SW Mexico. Central America	204	1.1	6.6-13.1 (2-4)	High surge and death
H. Sandy	USA	Cat 1	147	72	14 (4.3)	Contradicting low hurricane category but a high surge
Ty. Haiyan	The Philippines	Cat 5	6,900	2.98	17 (5.2)	High death toll, high typhoon category, high surge levels
Ty Nepartak	Philippines, East China	Cat 5	111	1.89	48 (15)	High surge levels
H. Matthew	Haiti, USA	Cat 5	>800	15	7.5 (2.3)	Moderate surge and relatively high death toll
H. Maria	Puerto Rico, USA	Cat 5	2,967	90	>6 (1.8)	Low surge and contradicting high death toll
TC. Ockhi	India	Cat 3	318 (actual) >800(predicted)	0.92	1-2 (0.3-0.6)	Very low surge and significant death toll

Country Profiling:

The United States of America:

With a population of 316 million, the United States of America ranks number one generating a $20, 494,100 million US (World Bank Group, 2018). The Atlantic Basin includes the Atlantic Ocean, Gulf of Mexico, and the Caribbean Sea. The United States and the Small islands developing states (SIDS), were potentially vulnerable and significantly at high risk along the East and Gulf coasts as most of the coastal megacities were in Low coastal elevation zone (LECZ's). Therefore, every year when the Atlantic hurricane season which runs from June 1st to November 30th the coastal cities could face a 'landscape inundation' threat by a hurricane triggered storm surges (RMS, 2015; National Hurricane Center, n.d.).

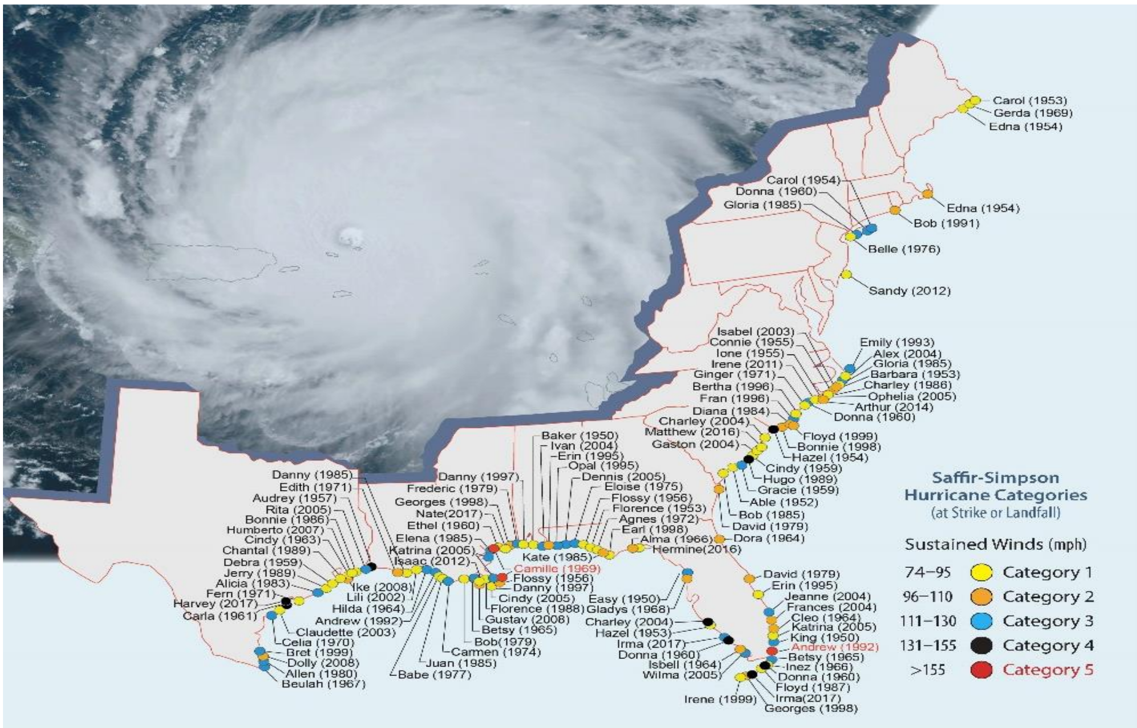


Figure A1 Continental U.S hurricane strikes from 1950-2017* (source NOAA) CONUS (Courtesy NCEI) (National Hurricane Center, n.d.)

The United States and the Small islands developing states (SIDS), were potentially vulnerable and significantly at high risk along the East and Gulf coasts as most of the coastal megacities were in Low coastal elevation zone (LECZs) as shown in Figure A1.

The Atlantic Basin includes the Atlantic Ocean, Gulf of Mexico and the Caribbean Sea, and the coastal cities along these basins were at potential risk of suffering a 'landscape inundation' threat from these storm surges (RMS, 2015); (National Hurricane Center, n.d.) in any given year when the Atlantic hurricane season which runs from 1st June – 30th November.

Table A3 Costliest mainland United States hurricanes from 1900 to 2013, by total economic damage (in 2013 billion U.S. dollars)

Year	*Storm*	*Damage in billion U.S. dollars*
2005	Katrina (SE FL/LA)	128.3
2012	Sandy (NJ/NY/CN)	72.1
1992	Andrew (SE FL/SE LA)	43.8
2008	Ike (TX/LA)	31.8
2005	Wilma (S FL)	24.44
2004	Charley (SW FL)	18.38
2004	Ivan (AL/NW FL)	17.42
2011	Irene (NC)	16.06
1989	Hugo (SC)	13.09
2005	Rita (N TX/W LA)	11.87
1972	Agnes (FL/NE U.S.)	11.6
2004	Frances (FL)	10.9
1965	Betsy (SE FL/SE LA)	10.43
1969	Camille (MS/SE LA/VA)	8.88
2004	Jeanne (FL)	8.48
1979	Frederic (AL/MS)	7.37
2001	Allison (N TX)	6.56
1999	Floyd (Mid-Atlantic & NE U.S.)	6.26
1996	Fran (NC)	4.75
1983	Alicia (N TX)	4.65
2008	Gustav (LA)	4.65
1995	Opal (NW FL/AL)	4.54
2003	Isabel (Mid-Atlantic)	4.24
1985	Juan (LA)	3.23
1985	Elena (MS/AL/NW FL)	2.73
2005	Dennis (NW FL)	2.63
1991	Bob (NC, NE U.S)	2.52
1985	Gloria (Eastern U.S.)	1.92
2005	Ophelia (NC)	1.9
1998	Georges (FL Keys, MS, AL)	1.64
2008	Dolly (TX)	1.13

Table A3 is compiled from the data published by (NOAA (Hurricane Research Division), 2017). Until 2013, Hurricane Katrina and Sandy were the costliest hurricanes and the most significant storm surge events. Therefore, these two events were chosen as the most significant events for study.

Table A4 Top 5 hurricanes in US history with the highest cost of damage

Name	***Year***	***The estimated cost of Damage (Billion US$)***	***Associated with storm surge (ft)***
Katrina	2005	161	27.8
Harvey	2017	125	Not associated
Maria	2017	90	6
Sandy	2012	71	14
Irma	2017	50	3-5

The Top 5 US Atlantic hurricane which also includes events from the year 2013 – 2017 were listed in Table A4.

Myanmar (Burma)

Myanmar is the largest country in the Southeast Asian which covers the land area of 676,578 sq. km ranked seventy-one in the World Bank Group's GDP 2018 ranking list with the yearly GDP of US$ 71,215 million (World Bank Group, n.d.). Roughly 30% of the population in the Ayeyarwady delta division was living below poverty. It is the same delta that is considered as the 'rice granary' of Myanmar depending primarily on agriculture for their income and living. Figure A2 shows the physical map of Myanmar.

Figure A2 Physical map of Myanmar (source: freeworldmaps.net)

The residents in this community were also considerably living without lands and in poverty mainly depending on wage labour (Dash, 2008) Myanmar is identified as one of the countries whose highest mortality rate is caused by the storm (PreventionWeb, 2015). Myanmar state controls the national media and restrictions were eased only since 2011, after the end of the Military Junta rule. The country currently experiences political instability and UN addresses the country genocide due to the Rohingya attacks (BBC News, 2018).

The Philippines

With a GDP of US$330,910 million, as of 2018, the Philippines ranks number thirty-eight as per the World Bank Group (World Bank Group, n.d.). The Philippines is made up of 7,000 islands with much of its populations living is eleven islands (BBC, 2018), shown in Figure A3.

Figure A3 Physical map of the Philippines (source: freeworldmaps.net)

The Philippines is extremely prone to meteorological and seismic disaster and holds a multi-hazard profile ranking as the third most prone country in the world according to the World Risk Report 2012 (UNU). With a total population of 105 million (Lum & Margesson, 2014), an average of 3 million people is affected by typhoons every year and suffers estimated economic damage of USD 200 million per year. The country has a previous typhoon history. Typhoon Bopha (Pablo) made landfall in 2012 on the southern island of Mindanao. The typhoon killed nearly 2,000 people (Lum & Margesson, 2014).

In 2013 the country was struck with a powerful 7.1 magnitude earthquake which displaced around 350,000 people. Before Typhoon Haiyan, the country was struck with Tropical Storm Thelma (uring) in 1991 which killed around 5,000 people (Lum & Margesson, 2014).

Republic of Haiti:

Haiti is classified as the low-income countries in the Americas and cascades under the Small island developing States (SIDS). It is further identified as a heavily indebted poor country by the United Nations (United Nations, n.d.) with a GDP of $9,658 generated per year (World Bank Group, n.d.). Haiti, with 10.2 million (BBC News, 2019) population is exposed to hazards such as earthquakes, cyclones, wildfire, landslide, and river, coastal and urban floods. The Physical map of Haiti is shown in Figure A4

Figure A4 Physical map of Haiti (source: freeworldmaps.net)

According to the Climate Risk Index 2016 rating, Haiti ranked the third among the countries affected by extreme weather events (World Food Programme, 2016). It also holds 163rd position out of 188 countries on the 2015 Human Development Index. The country suffers chronic poverty, and more than 50 percent of the population were undernourished (World Food Programme, 2016). Haiti was hit by a Category 4 hurricane Felix in 2007, then by 2010 earthquake, 2012 Hurricane Sandy in 2016 by Hurricane Matthew. Table A5 shows the top hurricanes made landfall in Haiti. The 2010 earthquake, together with the chronic political instability made the country to sustain as the poorest nation in the Americas (BBC News, 2019).

Table A5 List of hurricanes in Haiti: SIDS with the highest cost of damage

Name	***Year***	***The estimated cost of Damage (Billion US$)***	***Associated with storm surge (ft)***
Gustav	2005	161	27.8
Harvey	2017	125	Not associated
Maria	2017	90	6
Sandy	2012	71	14
Irma	2017	50	3-5

Table A5 shows some of the significant hurricane events which made landfall in Haiti resulting in severe socioeconomic damage. It is to be noted radio is the most popular news medium and hundreds of local and privately-owned media stations are there (BBC News, 2019).

Puerto Rico

Puerto Rico is one of the US territories, bordered by the Atlantic Ocean in the north and Caribbean Ocean in the South is one of the islands of Greater Antilles. Figure A5 shows the physical map of Puerto Rico.

Figure A5 Physical Map of Puerto Rico (Source: Freeworldmaps.net)

The self-governing unincorporated overseas US territory has a population of 3.7 million (BBC News, 2019). According to the World Bank's 2018 GDP, Puerto Rico was given sixty-three with a GDP of US$ 101,131 million (World Bank Group, n.d.). The territory's media is controlled by the US Federal Communications Commission (FCC) (BBC News, 2019).

Average Annual Hazard (AAL) by storm surge

Table A6 Average Annual Hazard (AAL) by storm surge (PreventionWeb, n.d.)

Country	*Population (in millions)*	*Gross Domestic Product 2018 (million US$)*	*Absolute Loss from storm surge (Million US$)*
The USA	316	2,726,323	8,774.38
Haiti	10.2	9,658	10.51
Puerto Rico	3.7	101,131	320.03
The Philippines	104	330,910	2,541.62
Myanmar	53.2	71,215	40.61

Table A6 complied from (PreventionWeb, n.d.); (Global Assessment Report on Disaster Risk Reduction (GAR), 2015); (PreventionWeb, n.d.); (PreventionWeb, n.d.). Table A6 shows the population of the target case study countries and their corresponding GDP in the year 2018 and their average losses incurred by storm surge for the year 2018. This table provides an overall idea of the total population and their exposure to storm surge followed by the economic damage caused by the storm surges. The full disaster Risk Profile (Global Assessment Report on Disaster Risk Reduction (GAR), 2015) of the target countries is attached at the end of Appendix A.

Vulnerability, hazard, and lack of coping capacity

The definition of vulnerability is according to UNISDR terminology is “The characteristics determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to impacts of hazards” (PreventionWeb, 2017). Table A7 shows the hazard, vulnerability and risk index categorised by INFORM.

Table A7 INFORM Risk index for the profiled countries (PreventionWeb, n.d.)

Country	***Hazard & Exposure***	***Vulnerability index***	***Lack of coping capacity***
The USA	6.7	2.9	2.1
Haiti	6.2	6.3	7.3
The Philippines	7.8	4.7	4.1
Myanmar	8.6	5.3	6.3
Puerto Rico	No data	No data	No data

Although there is no data on the risk vulnerability of Puerto Rico the Figure A6 shows the vulnerability of Puerto Rico particularly to hurricanes and storm surges.

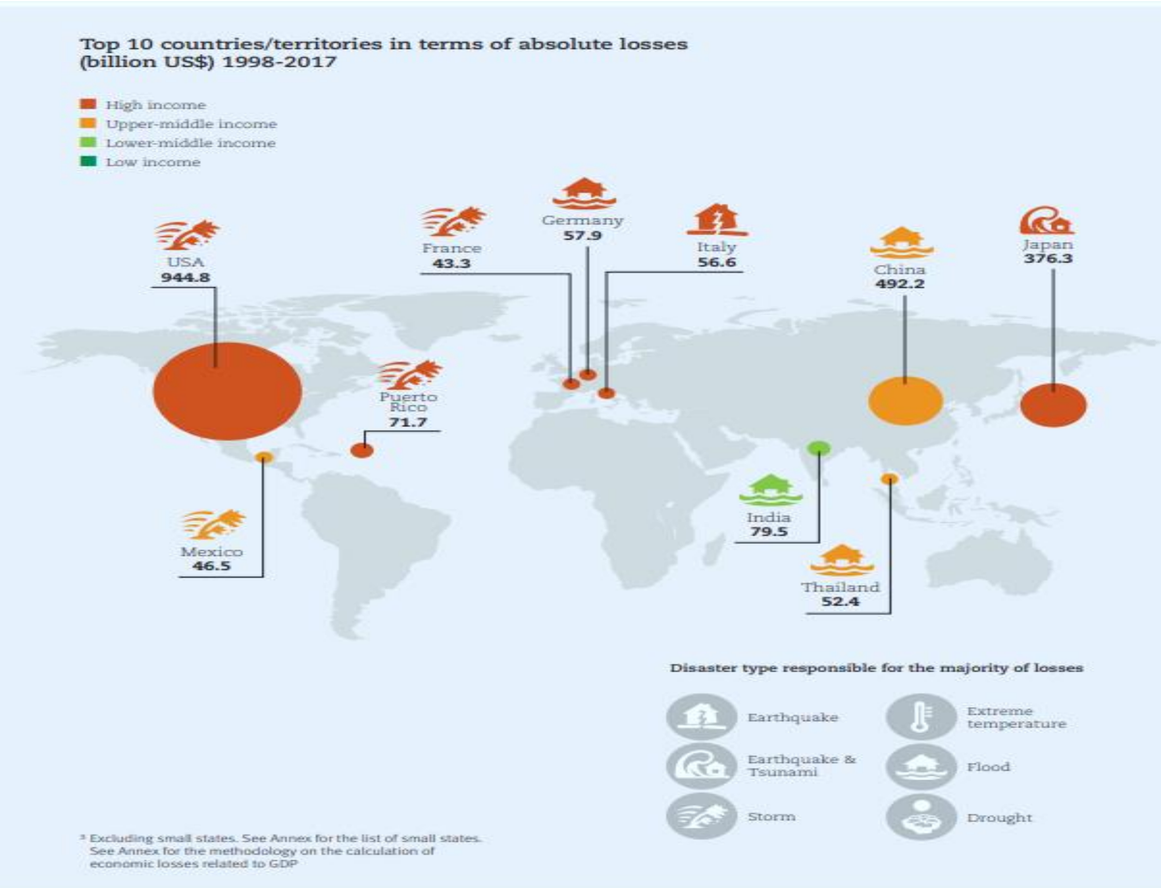


Figure A6 Top 10 countries/ territories in terms of absolute losses (billion US$) 1998-2017 (EM-DAT, 2019) highlighting Puerto Rico's vulnerability to storms

APPENDIX B

Hurricane Timelines, watch-warning and extended data

Case Study 1: Hurricane Katrina (2005)

(I) Predicted path of Hurricane Katrina

Table B1 Hurricane Katrina's track/path predicted by NHC/NOAA. (Data extracted from NHC/NOAA)

Date	Time (UTC)	Wind speed (knots)	wind speed (mph)	Stage	Location	distance (in nautical mi)	Structure Change
23-Aug	1800	30	34.56	tropical depression	Southeast of Nassau	175	
24-Aug	0000	30	34.56				
24-Aug	0600	30	34.56				
24-Aug	1200	35	40.32	tropical storm	east-southeast of Nassau	65	
24-Aug	1800	40	46.08				
25-Aug	0000	45	51.84				
25-Aug	0600	50	57.6				
25-Aug	1200	55	63.36				
25-Aug	1800	60	69.12				
25-Aug	2100			Category 1 hurricane			
25-Aug	2230	70	80.64	**First landfall as Category 1**	Border of Miami-Dade County and Broward County		
26-Aug	0000	70	80.64	**Category 1 hurricane**			
26-Aug	0500	60	69.12	tropical storm	North of Cape Sable		
26-Aug	0600	65	74.88	Category 1 hurricane			Rapid Intensification in 24hrs
26-Aug	1200	75	86.4				
26-Aug	1800	85	97.92	Category 2 hurricane			
27-Aug	0000	90	103.68				
27-Aug	0600	95	109.44				
27-Aug	1200	100	115.2	Category 3 hurricane	Southeast of the mouth of Mississippi River	365	eyewall evident in Infrared Satellite Imagery

27-Aug	1800	100	115.2				During this remaining day, inner eyewall deteriorated while outer eyewall formed. Katrina doubled in size
28-Aug	0000	100	115.2				
28-Aug	0600	125	144	Category 4 hurricane			New eyewall contracted into a defined ring. Second rapid re-intensification in less than 12 hrs
28-Aug	1200	145	167.04	Category 5 hurricane			
28-Aug	**1800**	**150**	**172.8**		Southeast of the mouth of Mississippi River	170	Peak Intensity
29-Aug	0000	140	161.28				A rapid weakening in 24 hr period. This created further structural change in hurricane characteristics
29-Aug	0600	125	144	Category 4 hurricane			
29-Aug	0900	115	132.48				
29-Aug	1110	110	126.72	**Second landfall as Category 2 hurricane**			
29-Aug	1200	110	126.72	Category 3 hurricane			
29-Aug	1445	105	120.96	**Third landfall as category 2 hurricane**			
29-Aug	1800	80	92.16	Category 1 hurricane			
30-Aug	0000	50	57.6	tropical storm			
30-Aug	0600	40	46.08				
30-Aug	1200	30	34.56	tropical depression			
30-Aug	1800	30	34.56				
31-Aug	0000	30	34.56	extratropical			
31-Aug	0600	25	28.8				
31-Aug	1200		0	**dissipated**			

(II) Watch-warning details of Hurricane Katrina

Table B2 Watch warnings issued by National Hurricane Centre for Hurricane Katrina

Date	Time (UTC)	Location	Action
23-Aug	2100	Central Bahamas to NW Bahamas	TS Warning Issued
24-Aug	0300	Seven Mile Bridge to Vero Beach	TS Watch Issued
24-Aug	1500	Seven Mile Bridge to Florida City	TS Watch modified to
24-Aug	1500	Florida City to Vero Beach	TS warning and Hurricane Watch issued
24-Aug	2100	Vero Beach to Titusville	TS Watch Issued
24-Aug	2100	Lake Okeechobee	TS warning and Hurricane Watch issued
25-Aug	0300	Florida City to Vero Beach and Lake Okeechobee	TS Warning / Hurricane watch modified to Warning
25-Aug	0900	Florida City to Englewood including Florida Bay	TS Watch Issued
25-Aug	1500	Grand Bahama, Bimini, and Berry Islands in the NW Bahamas	TS Warning modified to
25-Aug	2100	Florida City to Jupiter Inlet including Lake Okeechobee	Hurricane Warning modified to
25-Aug	2100	Jupiter Inlet to Vero Beach, Key West to Ocean Reef & Florida City to Longboat Key including Florida Bay	TS Warning Issued
25-Aug	2100	Longboat Key to Anclote Key	TS Watch Issued
25-Aug	2300	Grand Bahama, Bimini, and Berry Islands in the NW Bahamas	TS Warning discontinued
26-Aug	0300	Vero Beach to Titusville	TS Watch discontinued
26-Aug	0300	Jupiter Inlet to Vero Beach	TS Warning discontinued
26-Aug	0500	Deerfield Beach to Florida City	Hurricane Warning changed to TS Warning
26-Aug	0500	Deerfield Beach to Jupiter and Lake Okeechobee	Hurricane Warning discontinued

26-Aug	0500	Dry Tortugas to Ocean Reef including Florida Bay, Florida City to Longboat Key	TS Warning modified to
26-Aug	1500	Florida City to Longboat Key, all Florida Keys and Florida Bay	TS Warning modified to
26-Aug	2100	All	TS Watch discontinued
26-Aug	2100	Florida City to Longboat Key	TS Warning discontinued
27-Aug	0900	Dry Tortugas to Seven Mile Bridge	TS Warning modified to
27-Aug	1500	Dry Tortugas to Key West	TS Warning modified to
27-Aug	1500	Morgan City to Pearl River	Hurricane Watch issued
27-Aug	2100	All	TS Warning discontinued
27-Aug	2100	Intracoastal City to FL/AL border	Hurricane Watch modified
28-Aug	0300	Morgan City to FL/AL border including Lake Pontchartrain	Hurricane Warning Issued
28-Aug	0300	FL/AL border to Destin	TS Warning Issued
28-Aug	0300	Intracoastal City to Morgan City	TS Warning Issued
28-Aug	0300	FL/AL border to Destin	Hurricane Watch modified to
28-Aug	0900	Destin to Indian Pass and Intracoastal City to Cameron	TS Warning Issued
29-Aug	1500	All	Hurricane Watch discontinued
29-Aug	2100	Pearl River to FL/AL Border including Lake Ponchartrain	Hurricane Warning changed to TS Warning
29-Aug	2100	Cameron to Pearl River and FL/AL border to Destin	Hurricane and TS Warnings discontinued
30-Aug	0300	All	TS Warning discontinued

(III) Visual images of Hurricane Katrina

(a) Search & rescue operation (UH60 helicopter)

(b) Lost Bascule Span (Bay St Louis Bridge)

(c)Transportation route inundated during Katrina

(d) Lower 9th Ward, New Orleans (Rare News, 2015)

(e) Oil spillage around homes in Louisiana

(Source: Louisiana Dept. Env Quality)

(f) Inundated areas in New Orleans (Source: NOAA)

Figure B1 Visual view of damages from Hurricane Katrina

Case Study 2: Hurricane Sandy (2012)

(I) Predicted path of Hurricane Sandy

Table B3 Hurricane Sandy's track/path predicted by NHC/NOAA. (Data extracted from NHC/NOAA)

Date	Time (UTC)	Wind speed (knots)	wind speed (in mph)	Stage	Location	Distance (in nautical miles)	Structure Change
21-Oct	1800	25	28.8	low			
22-Oct	1200	30	34.56	tropical depression			
22-Oct	1800	35	40.32	tropical storm			
23-Oct	0000	40	46.08				
23-Oct	1800	45	51.84				
24-Oct	0000	55	63.36				
24-Oct	0600	60	69.12				
24-Oct	1200	65	74.88	Category 1 hurricane			
24-Oct	1800	75	86.4				
24-Oct	1900	75	86.4	**First landfall as Category 1 hurricane**	Bull Bay, Jamaica		
25-Oct	0000	85	97.92	Category 3 hurricane			
25-Oct	0525	100	115.2	**Second landfall as Category 3 hurricane**	10 nautical miles near Cuba		
25-Oct	0900	95	109.44	Category 3 hurricane			
25-Oct	1800	90	103.68				
26-Oct	0000	75	86.4				
26-Oct	0600	70	80.64				
26-Oct	1200	65	74.88				
27-Oct	0000	60	69.12	tropical storm	Northward from Great Abaco	125 n mi	
27-Oct	1200	70	80.64	Category 1 hurricane			rapid intensification
28-Oct	0000	65	74.88	Category 3 hurricane	100 miles southeast of North Carolina		
29-Oct	0000	70	80.64				bend in the track towards the north. Sandy encountered blocking pattern over North Atlantic
29-Oct	0600	80	92.16				

29-Oct	1200	85	97.92		Southeast of Atlantic City, New Jersey	220 n mi	reached peak intensity
29-Oct	1800	80	92.16				
29-Oct	2100	75	86.4	extra-tropical			
29-Oct	2330	70	80.64	**Third landfall as extra-tropical**	Brigantine, NJ		
30-Oct	0000	70	80.64	extra-tropical			
30-Oct	0600	55	63.36				
30-Oct	1200	50	57.6				
30-Oct	1800	40	46.08				
31-Oct	0000	35	40.32				
31-Oct	1200	30	34.56				
31-Oct	1800			dissipated			

(II) Watch-warnings issued Hurricane Sandy

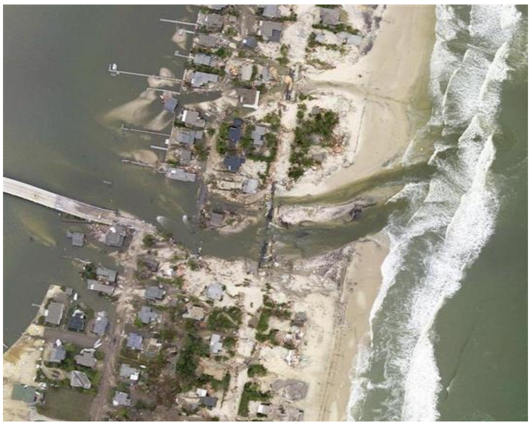
Table B4 Watch warnings issued by National Hurricane Centre (NHC) for Hurricane Sandy

Date	Time (UTC)	Location	Action
22-Oct	1500	Jamaica	TS Watch Issued
23-Oct	0900	Jamaica	TS Warning Issued
23-Oct	1500	Jamaica	Hurricane Watch issued
23-Oct	0900	Haiti	TS Watch Issued
23-Oct	1500	South-eastern and Central Bahamas	TS Watch Issued
23-Oct	1500	Camaguey and Guantanamo	Hurricane Watch issued
23-Oct	1800	Haiti	TS Watch to Warning
23-Oct	2100	Camaguey and Guantanamo	Hurricane Warning Issued
23-Oct	2100	North-western Bahamas	TS Watch Issued
24-Oct	0300	Central Bahamas	TS Warning Issued
24-Oct	0900	Jupiter Inlet to Ocean Reef	TS Watch Issued
24-Oct	0900	Ocean Reef to Craig Key	TS Watch Extended
24-Oct	1200	North-western Bahamas	TS Warning Issued
24-Oct	1500	Central and North-western Bahamas	Hurricane Watch
24-Oct	2100	Central and North-western Bahamas	Hurricane Warning
24-Oct	2100	Sebastian Inlet to Flagler Beach	TS Watch Issued
24-Oct	2100		Hurricane Watch discontinued
25-Oct	0300	South-eastern Bahamas	TS Watch to Warning
25-Oct	0300	Lake Okeechobee	TS Warning Issued
25-Oct	0300	Ragged Island	Hurricane Warning Issued
25-Oct	0900	Jamaica	Hurricane Watch discontinued
25-Oct	1500	Haiti	TS Warning discontinued

25-Oct	1500	Camaguey and Guantanamo	Hurricane Watch discontinued
26-Oct	0300	Central Bahamas	Hurricane Watch to TS Warning
26-Oct	0300	South-eastern Bahamas	TS Warning discontinued
26-Oct	0300	Ragged Island	Hurricane Watch discontinued
26-Oct	0300	North-western Bahamas	Hurricane Warning Issued
26-Oct	0600	Andros Island	TS Warning Issued
26-Oct	0900	Savannah River to Oregon Inlet	TS Watch Issued
26-Oct	1500	The north-western Bahamas except Great Abaco and Grand Bahama	Hurricane Watch to TS Warning
26-Oct	1500	Ocean Reef to Craig Key	TS Watch Discontinued
26-Oct	1500	Bermuda	TS Watch Issued
26-Oct	1500	Central Bahamas	TS Warning discontinued
26-Oct	1500	Andros Island	TS Warning discontinued
26-Oct	1800	Great Abaco and Grand Bahama Island	Hurricane warning to TS warning
26-Oct	1800	The north-western Bahamas except Great Abaco and Grand Bahama	TS Warning discontinued
26-Oct	2100	St Augustine to Fernandina beach	TS Watch Issued
26-Oct	2100	Lake Okeechobee	TS Warning discontinued
26-Oct	2100	South Santee River to Duck	TS Watch Issued
27-Oct	0000	St Augustine to Fernandina beach	TS Watch Discontinued
27-Oct	1500	Sebastian Inlet to St Augustine	TS Warning discontinued
27-Oct	2100	Bermuda	TS Watch to warning
27-Oct	2100	Great Abaco and Grand Bahama Island	TS Warning discontinued
28-Oct	0300	South Santee River to Duck	TS watch discontinued
29-Oct	1500	Bermuda	TS Warning discontinued
29-Oct	2100		TS Warning discontinued

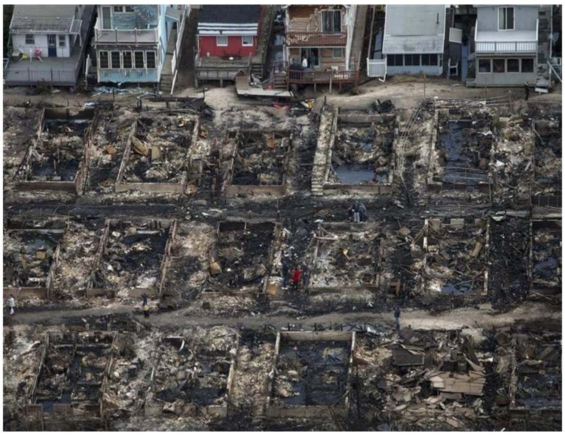
(III) Visual images of Hurricane Sandy

(a) Aerial photographs of the NASA Wallops facility and coastline (left) is a before the image was taken on Aug 2012, and (right) an after-image was taken in Nov 2012 post-Hurricane Sandy (Source: NASA)



(b) New inlet that was cut across the barrier island of the Jersey coastal town Mantoloking just north of w Hurricane Sandy made landfall in Ocean (Source: NOAA

(c) Homes flooded after Hurricane Sandy landfall on the southern New Jersey coastline on Oct 30, 2012 in Tuckerton, NJ (Source U.S. Coast Guard via GettyImages)



(d) Burned houses are seen next to those which survived in Breezy Point, New York City borough of Queens. (Pic: Reuters_Adrees Latif)

(e) Storm surge flooding in NJ by Hurricane Sandy in Oct 2012, Credit U.S. Air Force photo by Master Sgt Mark C. Olsen

(g) Boardwalk of Seaside Heights NJ, damaged by Hurricane Sandy (Source AP/Mike Groll)

(h) Street damaged by storm surge in Ortley Beach, NJ (Source: Tim Larsen / Governor’s office /Reuters)

Figure B2 Visual view of damages from Hurricane Sandy (2012)

Case Study 3: Cyclone Nargis (2008)

(I) Predicted path/track of Cyclone Nargis

Table B5 Cyclone Nargis's track/path compiled from cyclone report of Myanmar govt.

Date	Time (UTC)	windspeed (mph)	Cyclone's stage	Location	Structural Change
25-Apr			Tropical depression		
27-Apr			Severe depression		
28-Apr	0000		Cyclone Storm	Both Indian Meteorological Department (IMD) and US Joint Typhoon Warning Centre (JTWC) Updated by the Indian Meteorological Department (IMD) 550 km east of Chennai, India	
28-Apr			Category 1 Cyclone	Identified by JTWC as Category 1 in SSWHS	
29-Apr		100			Wind speed was identified as 160 km/h (100 mph)
01-May				Took a diversion and turning towards eastward	Rapid intensification took place at this time
02-May		135		Approaching towards the Coast of Myanmar	Peak intensity achieved with 1-minute sustained winds of 215 km/h (135 mph)
02-May			**First landfall as Category 3 cyclone**	Ayeyarwady Delta region approx. 250 km southwest of Yangon (Rangoon) as Cat 3	
03-May			**Second landfall as Category 4 cyclone**	Yangon	The cyclone weakened to Category 1
03-May			extra-tropical		

(II) Visual images of Cyclone Nargis

(a) Aerial view of Irrawaddy delta affected by cyclone Nargis (Source: BBC)

(b) Coastal communities of the delta region flooded during Nargis (Photo: Agency France-Presse / Rappler)

(c) Damage in the Dedaye region by cyclone Nargis Pararas-Carayannis (2008)

(c) Flooded villages near airport in Yangon during cyclone Nargis (Source: Reuters/Telegraph)

(e) Impact of storm surge flooding in the delta region of Myanmar (Source: Humanitarian coalition)

Figure B3 Visual view of damages from Cyclone Nargis (2008)

Case Study 4: Super-Typhoon Haiyan (Yolanda) (2013)

(I) Predicted path of Super-Typhoon Haiyan

Table B6 Super-typhoon Haiyan's track/path predicted by PAGASA

Date	Time (UTC)	Wind speed (kph)	Wind speed (in mph)	Stage	Location	Structural Change
03-Nov				Tropical depression	Western Pacific	
05-Nov				Tropical storm		
06-Nov		195	121	Category 3 Typhoon	Typhoon entered the Philippine Area of Responsibility (PAR) from East of Mindanao	
07-Nov		215	134	Category 4 Typhoon		Intensified and moved West Northwest towards Eastern Visayas and continued to intensify
08-Nov	2040	235	195	**First landfall Category 5 Typhoon**	Guiuan, Eastern Samar	
08-Nov	2300		195	**Second landfall Category 5 Typhoon**	Tolosa, Leyte	
08-Nov	0140			**Third landfall Category 5 Typhoon**	Daanbantayan, Cebu	
08-Nov	0240			**Fourth landfall Category 5 Typhoon**	Bantayan Island, Cebu	
08-Nov	0400			**Fifth landfall Category 5 Typhoon**	Concepcion, Iloilo	
08-Nov	1200			**Sixth landfall Category 5 Typhoon**	Busuanga, Palawan	
08-Nov				Category 2 Typhoon		Weakened slightly and continued towards the West

09-Nov	0730		Category 2 Typhoon		Philippine Sea Further weakened over the West Philippine Sea and exited PAR towards Vietnam
10-Nov			extra-tropical		

(II) Visualization of the damage from Super-Typhoon Haiyan

(a) Before image Anibong, Coast of Tacloban (b) After-image of Anibong, Coast of
Tacloban

(c) Pontoons & moorings in coastal Tacloban (d) After-image of coastal Tacloban
devastated

(e) Before-image of Tacloban Port (BBC News, 2013) (f) An After-image of Tacloban port post-landfall

(g) Aerial view of destroyed houses in Leyte Province, City of Tacloban (Source: Ted Aljibe/AFP/GettyImages)

(g) Tacloban City destroyed by Typhoon Haiyan (Source: Reuters)

(g) Impact on Super-typhoon Haiyan on Samar province central Philippines (Pic: Erik De Castro /Reuters)

(h) City of Guiuan, post Typhoon Haiyan_Bryan Denton for The NY times

Figure B4 Visual view of damages from Super-Typhoon Haiyan (2013)

Case Study5: Hurricane Matthew (2016)

(i) Predicted path of Hurricane Matthew

Table B7 Hurricane Matthew's path/ track predicted by NHC/NOAA

Date	Time (UTC)	Wind speed (kt)	Wind speed (mph)	Stage	Location	Distance (in n mi)	Structural Change
28-Sep	1200	50	57.6	**Tropical storm**			
29-Sep	0000	55	63.36				
29-Sep	1200	60	69.12				
29-Sep	1800	65	74.88	Category 1 hurricane			
30-Sep	0000	70	80.64	Category 2 hurricane			
30-Sep	0600	85	97.92				
30-Sep	1200	100	115.2	Category 3 hurricane			
30-Sep	1800	120	138.24	Category 4 hurricane			**Rapid intensification**
01-Oct	**0000**	**145**	**167.04**	Category 5 hurricane	North of Punta Gallinas (peak intensity)	80	
01-Oct	0600	140	161.28				
01-Oct	1200	135	155.52	Category 4 hurricane			
01-Oct	1800	130	149.76				
02-Oct	0600	125	144				
02-Oct	1200	130	149.76				
02-Oct	**1800**	**135**	155.52		South of Tiburon, Haiti	105	**re-intensification**
03-Oct	0000	130	149.76				
03-Oct	0600	125	144				
04-Oct	0000	130	149.76				
04-Oct	1200	125	144	**First landfall as Category 4 hurricane**	Les Anglais, Haiti		
04-Oct	1800	120	138.24				
05-Oct	0000	115	132.48	**Second landfall as Category 4 hurricane**	Juaco, Cuba		
05-Oct	0600	110	126.72	Category 3 hurricane			
05-Oct	1200	105	120.96				
06-Oct	0600	110	126.72				

06-Oct	1200	125	144		Southwest of Nassau, Bahamas	25	
07-Oct	0000	115	132.48	**Third landfall as Category 4 hurricane**	West end, Grand Bahamas		
07-Oct	0600	110	126.72	Category 3 hurricane	East of Vero Beach	35	
07-Oct	1200	105	120.96				
07-Oct	1800	100	115.2				
08-Oct	0000	95	109.44	Category 2 hurricane	East-northeast of Jacksonville Beach, Florida	50	
08-Oct	0600	85	97.92		Offshore of Georgia Coast	50	
08-Oct	1200	80	92.16				
08-Oct	1500	75	86.4	**Fourth landfall as Category 2 hurricane**	south of McClellanville, South Carolina		nearly parallel to the coast of South Carolina
08-Oct	1800	70	80.64		offshore of the coast of South Carolina		
09-Oct	1200	65	74.88	Category 1 hurricane	Offshore of the coast of North Carolina		lost its tropical characteristics and became extratropical
10-Oct	0000	40	46.08	extra-tropical	east of Cape Hatteras, North Carolina	200	extratropical low merged with the frontal system

(ii) **Storm surge inundation levels**

Table B8 Storm surge inundation levels from Hurricane Matthew

State & County	Estimated Storm surge Inundation Height (in ft) above ground level
Cuba	
The south-eastern coast of Guantanamo Province	10-13ft
North-eastern Coast of Guantanamo Province	>11.00
Santiago de Cuba Province	16.00
Holguin Province	3-5ft

Coast of Camaguey Province	<3.00
Bahamas	
the south coast of New Providence and Grand Bahama Island	8.00
United States	
Florida	
Brevard County	3-4ft
Fernandina Beach	6.96
Summer haven and Matanzas	3.00
Fort Matanzas	6.40
Marineland and Matanzas Inlet	
Jacksonville	7.00
Volusia County	4-6ft
Nassau County	3-5ft
Anastasia Island	>2.00
St. Augustine Beach and Castillo de San Marcus	>4.00
Cape Canaveral	1-2ft
Coast of St. Johns River	
Racy point	4.60
Georgia	
Coast of Georgia	3-5ft
Ft. Pulaski Monument	7.70
National park Service ground, Fort Pulaski	
South Carolina	3-5ft
Georgia-South Carolina Border (Ft. Pulaski)	
Charleston	6.20
North Carolina	6.06
Cape Hatteras (North-South Carolina border)	2-4ft
Cape Fear River	2.00
Coast on the sound side of the Outer Banks	4-6ft
Coast Guard Station, Hatteras Island	
North of Cape Hatteras	1-3ft
Virginia, Maryland, and Delaware	
Hampton Road area	2-4ft

(III) Hurricane watch-warning issued by NHC

Table B9 Hurricane Matthew's watch-warning issued by NHC

Date	Time (UTC)	Location	Action
28-Sep	1500	Guadeloupe and Martinique	TS Warning Issued
28-Sep	1500	St Lucia	TS Warning Issued
28-Sep	1500	Barbados, Dominica, St. Vincent & Grenadine Islands	TS Warning Issued
28-Sep	2100	Aruba, Bonaire, and Curacao	TS Watch Issued
29-Sep	0300	Barbados, Dominica, St. Vincent & Grenadine Islands	TS Warning discontinued
29-Sep	0300	Dominica, St. Vincent & Grenadine Islands	TS Warning Issued
29-Sep	0900	Guadeloupe and Martinique	TS Warning discontinued
29-Sep	0900	St Lucia	TS Warning discontinued
29-Sep	0900	Dominica, St. Vincent & Grenadine Islands	TS Warning discontinued
29-Sep	0900	St. Vincent & Grenadine Islands	TS Warning Issued
29-Sep	0900	All	TS Warning discontinued
29-Sep	2100	Colombia/Venezuela border to Riohacha	TS Watch Issued
30-Sep	0600	Aruba, Bonaire, and Curacao	TS Warning discontinued
30-Sep	0600	Aruba and Curacao	TS Watch Issued
30-Sep	1200	Aruba and Curacao	TS Warning discontinued
30-Sep	1200	Aruba	TS Watch Issued
30-Sep	1500	Colombia/Venezuela border to Riohacha	TS Watch to Warning
30-Sep	1500	All	TS Warning discontinued
30-Sep	2100	Southern Haiti/ Dominican Republic to Port-au-Prince	TS Warning Issued
30-Sep	2100	Jamaica	Hurricane Watch Issued
01-Oct	1500	All	TS Watch & Warning Discontinued
01-Oct	1500	Southern Haiti/ Dominican Republic to LeMole- St. Nicholas	Hurricane Watch Issued
01-Oct	2100	Jamaica	Hurricane Watch to Warning

01-Oct	2100	Southern Haiti/ Dominican Republic to LeMole- St. Nicholas	Hurricane Watch to Warning
01-Oct	2100	LeMole- St. Nicholas to northern border Haiti/Dominican Republic	Hurricane Watch Issued
01-Oct	2100	Camaguey to Guantanamo	Hurricane Watch Issued
02-Oct	0600	Puerto Plata to northern border Haiti/Dominican Republic	TS Watch Issued
02-Oct	0600	Southern Haiti/ Dominican Republic to Barahona	TS Warning Issued
02-Oct	0900	LeMole- St. Nicholas to northern border Haiti/Dominican Republic	Hurricane Watch discontinued
02-Oct	0900	Turks & Caicos and South-eastern Bahamas	Hurricane Watch Issued
02-Oct	0900	Southern border Haiti/ Dominican Republic to LeMole- St. Nicholas	Hurricane Watch discontinued
02-Oct	0900	Haiti	Hurricane Warning Issued
02-Oct	0900	Las Tunas to Guantanamo	Hurricane Warning Issued
03-Oct	0300	South-eastern Bahamas	Hurricane Watch to Warning
03-Oct	0300	Turks & Caicos and Central Bahamas	Hurricane Watch discontinued
03-Oct	2100	Turks & Caicos	Hurricane Watch Issued
03-Oct	2100	North-western Bahamas	Hurricane Watch Issued
04-Oct	0900	Turks & Caicos	Hurricane Watch to TS Warning
04-Oct	0900	South-eastern Bahamas to North-western Bahamas	Hurricane Watch to Hurricane Warning
04-Oct	0900	South-eastern Bahamas to North-western Bahamas	Hurricane warning modified
04-Oct	1500	Seven Mile Bridge to Deerfield Beach	TS Watch Issued
04-Oct	1500	Jamaica	TS Warning discontinued
04-Oct	1500	Deerfield Beach to Volusia/Brevard County Line	Hurricane Watch Issued
04-Oct	2100	Seven Mile Bridge to Golden Beach	TS Watch modified to
04-Oct	2100	Golden Beach to Volusia/ Brevard County Line	Hurricane Watch modified
05-Oct	0300	Seven Mile Bridge to Golden Beach	TS Watch to Warning

05-Oct	0300	Chokoloskee to Ocean Reef	TS Warning Issued
05-Oct	0300	Golden Beach to Volusia/Brevard County Line	Hurricane Watch discontinued
05-Oct	0300	Sebastian Inlet to Flagler/Volusia County Line	Hurricane Watch Issued
05-Oct	0300	Golden Beach to Sebastian Inlet	Hurricane Warning Issued
05-Oct	0900	Sebastian Inlet to Fernandina Beach	Hurricane Watch modified
05-Oct	1500	Haiti	Hurricane Warning changed to TS Warning
05-Oct	1500	All	TS Watch discontinued
05-Oct	1500	southern border Haiti/ Dominican Republic to Barahona	TS Warning discontinued
05-Oct	1500	Flager/Volusia County Line to Fernandina Beach	Hurricane Watch modified
05-Oct	1500	Golden Beach to Flager/Volusia County Line	Hurricane Warning modified
05-Oct	1800	Turks & Caicos	TS Warning discontinued
05-Oct	2100	Chokoloskee to Suwannee River	TS Watch Issued
05-Oct	2100	Haiti	TS Warning discontinued
05-Oct	2100	Cuba	Hurricane Watch discontinued
05-Oct	2100	Cuba	Hurricane Warning discontinued
05-Oct	2100	Flager/Volusia County Line to Savannah River	Hurricane Watch modified
06-Oct	0300	Flager/Volusia County Line to Savannah River	Hurricane Watch discontinued
06-Oct	0300	Fernandina Beach to Edisto Beach	Hurricane Watch Issued
06-Oct	0300	Golden Beach to Fernandina Beach	Hurricane Warning modified
06-Oct	0900	Fernandina Beach to Edisto Beach	Hurricane Watch discontinued
06-Oct	0900	Altamaha Sound to South Santee River	Hurricane Watch Issued
06-Oct	0900	Golden Beach to Altamaha Sound	Hurricane Warning modified
06-Oct	1200	Central Bahamas to North-western Bahamas	Hurricane Warning modified
06-Oct	1500	Chokoloskee to Anclote River	TS Watch modified

06-Oct	1500	Anclote River to Suwanee River	TS Warning Issued
06-Oct	1500	Edisto Beach to South Santee River	Hurricane Watch modified
06-Oct	1500	Golden Beach to Edisto Beach	Hurricane Warning modified
06-Oct	2100	South Santee River to Surf City	TS Warning Issued
06-Oct	2100	All	Hurricane Watch discontinued
06-Oct	2100	Golden Beach to South Santee River	Hurricane Warning modified
07-Oct	0000	Englewood to Anclote River	TS Watch modified to ???
07-Oct	0000	Chokoloskee to Ocean Reef	TS Warning discontinued
07-Oct	0000	Seven Mile Bridge to Boca Raton	TS Warning modified
07-Oct	0000	Boca Raton to South Santee River	Hurricane Warning modified
07-Oct	0300	Ocean Reef to Boca Raton	TS Warning modified
07-Oct	0900	Anna Maria Island to Anclote River	TS Watch modified
07-Oct	0900	Boca Raton to Jupiter Inlet	TS Warning modified
07-Oct	0900	Jupiter Inlet to South Santee River	Hurricane Warning modified
07-Oct	1200	Jupiter Inlet to Sebastian Inlet	TS Warning modified
07-Oct	1200	North-western Bahamas	Hurricane Warning discontinued
07-Oct	1200	Sebastian Inlet to South Santee River	Hurricane Warning modified
07-Oct	1500	All	TS Watch discontinued
07-Oct	1500	Surf City to Duck	TS Warning modified
07-Oct	1500	Sebastian Inlet to Cocoa Beach	TS Warning modified
07-Oct	1500	Anna Maria Island to Anclote River	TS Warning discontinued
07-Oct	1500	Surf City to Cape Lookout	Hurricane Watch Issued
07-Oct	1500	Sebastian Inlet to South Santee River	Hurricane Warning discontinued
07-Oct	1500	Cocoa Beach to Surf City	Hurricane Warning Issued
07-Oct	2100	Sebastian Inlet to Cocoa Beach	TS Warning discontinued
07-Oct	2100	Volusia/Brevard County Line to Flagler/Volusia County Line	TS Warning Issued
07-Oct	2100	Flagler/Volusia County Line to Surf City	Hurricane Watch modified

08-Oct	0000	Volusia/Brevard County Line to Flagler/Volusia County Line	TS Warning discontinued
08-Oct	0300	Flagler/Volusia County Line to Fernandina Beach	TS Warning Issued
08-Oct	0300	Fernandina Beach to Surf City	Hurricane Warning modified
08-Oct	0900	Flagler/Volusia County Line to Fernandina Beach	TS Warning discontinued
08-Oct	0900	Altamaha Sound to Surf City	Hurricane Warning modified
08-Oct	1800	Edisto Beach to Surf City	Hurricane Warning modified
08-Oct	2100	South Santee River to Surf City	Hurricane Warning modified
09-Oct	0300	Surf City to Duck	Hurricane Watch modified
10-Oct	0300	Little River Inlet to Surf City	Hurricane Warning modified
11-Oct	0900	Cape Fear to Duck	TS Warning modified
12-Oct	0900	All	Hurricane Warning discontinued
13-Oct	1500	All	Hurricane Watch discontinued
14-Oct	1800	Surf City to Duck	TS Warning modified
15-Oct	2100	All	TS Warning discontinued

(IV) Visual damage of Hurricane Matthew

(a) Homes and businesses in Lumberton, Nort` Carolina cutting roads and bridges (Source: AP/Photo /Chuck Burton)

(b) City of Lumberton water treatment facility surrounded by floodwater both rainfall and storm surge (AP/Photo /Mike Spencer)

(c) Communities in Lumberton submerged in Hurricane Matthew (Source: Reuters / Chris Keane)

(d) Bridge collapsed by storm surge in Haiti (Source photo Tim Schandordff_Mission Network.net)

(e) West coast of Haiti impacted by Hurricane Matthew (Source: Reuters)

(f) City of Flagler beach and roads damaged from storm surge hurricane Matthew (Source: CDR emergency management

(g) West coast of Haiti impacted by Hurricane Matthew (Source: Reuters)

(h) A house in Lumberton, NC submerged in Hurricane Matthew impacted by (Source: Reuters/ Chris Keane)

Figure B5 Visual view of damges from Hurricane Matthew (2016)

Case Study 6: Hurricane Maria (2017)

(i) Predicted path of the Hurricane Maria

Table B10 Hurricane Maria's path/track predicted by NHC/NOAA

Date	Time (UTC)	Wind speed (kt)	wind speed (mph)	Stage	Location	Structure Change
16-Sep	1200	30	34.56	tropical depression		
16-Sep	1800	40	46.08	tropical storm		
17-Sep	0000	45	51.84			
17-Sep	0600	55	63.36			
17-Sep	1200	60	69.12			
17-Sep	1800	65	74.88	Category 1 hurricane		
18-Sep	0000	75	86.4			
18-Sep	0600	80	92.16			
18-Sep	1200	100	115.2	Category 3 hurricane		
18-Sep	1800	110	126.72			
19-Sep	0000	145	167.04	Category 5 hurricane		
19-Sep	0115	145	167.04	**First Landfall as Category 5 hurricane**	Dominica	rapid intensification
19-Sep	0600	135	155.52	Category 4 hurricane		weakened and quickly regained strength
19-Sep	1200	140	161.28			
19-Sep	1800	145	167.04			
20-Sep	0000	150	172.8			
20-Sep	0300	150	172.8			
20-Sep	0600	140	161.28			
20-Sep	1015	135	155.52	**Second Landfall as Category 5 hurricane**	Near Yabuca, Puerto Rico	
20-Sep	1200	115	132.48			
20-Sep	1800	95	109.44	Category 2 hurricane		
21-Sep	0000	95	109.44			
21-Sep	0600	100	115.2	Category 3 hurricane		
21-Sep	1200	100	115.2			Rapid intensification
21-Sep	1800	105	120.96			
22-Sep	0000	110	126.72			
22-Sep	0600	110	126.72			
22-Sep	1200	110	126.72			
22-Sep	1800	110	126.72			
23-Sep	0000	105	120.96			
23-Sep	0600	100	115.2			

23-Sep	1200	100	115.2	
23-Sep	1800	100	115.2	
24-Sep	0000	100	115.2	
24-Sep	0600	95	109.44	Category 2 hurricane
24-Sep	1200	95	109.44	
24-Sep	1800	90	103.68	
25-Sep	0000	85	97.92	
25-Sep	0600	75	86.4	Category 1 hurricane
25-Sep	1200	70	80.64	
25-Sep	1800	70	80.64	
26-Sep	0000	70	80.64	
26-Sep	0600	65	74.88	
26-Sep	1200	65	74.88	
26-Sep	1800	65	74.88	
27-Sep	0000	65	74.88	
27-Sep	0600	65	74.88	
27-Sep	1200	65	74.88	
27-Sep	1800	65	74.88	
28-Sep	0000	65	74.88	
28-Sep	0600	60	69.12	tropical storm
28-Sep	1200	60	69.12	
28-Sep	1800	55	63.36	
29-Sep	0000	55	63.36	
29-Sep	0600	50	57.6	
29-Sep	1200	50	57.6	
29-Sep	1800	50	57.6	
30-Sep	0000	50	57.6	
30-Sep	0600	50	57.6	
30-Sep	1200	50	57.6	
30-Sep	1800	45	51.84	extra tropical

(ii) Hurricane watch Warning issued by NHC

Table B11 Hurricane Maria's watch warning issues by NHC

Date	Time (UTC)	Location	Action
16-Sep	1500	St. Lucia	Tropical Strom Watch Issued
16-Sep	1500	Martinique	TS Watch
16-Sep	1500	Guadeloupe	TS Watch
16-Sep	1500	Dominica	TS Watch Issued
16-Sep	1800	Barbados	TS Watch Issued
16-Sep	1800	St. Vincent & Grenadine	TS Warning Issued

16-Sep	2100	Antigua/Barbuda/St. Kitts/nevis/Montserrat	Hurricane Watch Issued
17-Sep	0000	Guadeloupe	TS Watch Changed to Hurricane Watch
17-Sep	0300	Saba/St. Eustatius	Hurricane Watch Issued
17-Sep	0300	St. Maarten	Hurricane Watch Issued
17-Sep	0300	Anguilla	Hurricane Watch Issued
17-Sep	0900	Dominica	TS Watch Changed to TS Warning
17-Sep	1200	St. Martin/St. Barthelemy	Hurricane Watch Issued
17-Sep	1500	St. Lucia	TS Watch Changed to TS Warning
17-Sep	1500	Dominica	Hurricane Watch changed to the hurricane warning
17-Sep	1800	Martinique	TS watch changed to TS warning
17-Sep	1800	Guadeloupe	Hurricane Watch changed to the hurricane warning
17-Sep	2100	Antigua/Barbuda	TS Warning Issued
17-Sep	2100	Saba/St. Eustatius	TS Warning Issued
17-Sep	2100	Antigua/Barbuda/St. Kitts/Nevis/Montserrat	Hurricane Watch discontinued
17-Sep	2100	U.S. Virgin Islands	Hurricane Watch Issued
17-Sep	2100	The British Virgin Islands	Hurricane Watch Issued
17-Sep	2100	St. Kitts/Nevis/Montserrat	Hurricane Warning Issued
18-Sep	0000	Martinique	TS Warning changed to Hurricane Warning
18-Sep	0900	Puerto Rico/Vieques/Culebra	Hurricane Watch Issued
18-Sep	1200	St. Lucia	TS Warning changed to Hurricane Warning
18-Sep	1200	St. Maarten	TS Warning Issued
18-Sep	1500	U.S. Virgin Islands	Hurricane Watch changed to the hurricane warning
18-Sep	1500	The British Virgin Islands	Hurricane Watch changed to the hurricane warning
18-Sep	1500	Anguilla	TS Warning Issued
18-Sep	1800	Barbados	TS watch discontinued
18-Sep	2100	Puerto Rico/Vieques/Culebra	Hurricane Watch changed to the hurricane warning
18-Sep	2100	St. Lucia	Hurricane warning changed to TS warning
18-Sep	2100	Puerto Plata to Northern DR/Haiti Border, Dominican Republic	TS watch issued
18-Sep	2100	Isla Saone to Puerto Plata, Dominican Republic	Hurricane watch issued
19-Sep	0000	Martinique	Hurricane warning changed to TS warning
19-Sep	1200	St. Vincent/Grenadines	TS watch discontinued

19-Sep	1200	St. Lucia	TS warning discontinued
19-Sep	1800	Puerto Plata to Northern DR/Haiti Border, Dominican Republic	TS Watch Changed to TS Warning
19-Sep	1800	Guadeloupe	Hurricane warning changed to TS warning
19-Sep	1800	Martinique	TS warning discontinued
19-Sep	1800	Cabo Engano to Punta Palenque, Dominican Republic	TS Warning Issued
19-Sep	1800	Isla Saona to Coba Engano, Dominican Republic	Hurricane watch modified to
19-Sep	1800	Cabo Engano to Punta Plata, Dominican Republic	Hurricane Warning Issued
19-Sep	2100	Antigua/Barbuda	TS warning discontinued
19-Sep	2100	Turks and Caicos Islands/South-eastern Bahamas	Hurricane Watch issued
19-Sep	2100	Dominica	Hurricane Warning discontinued
20-Sep	0000	Anguilla	TS warning discontinued
20-Sep	0000	Anguilla	Hurricane Watch discontinued
20-Sep	0000	St. Kitts/Nevis/Montserrat	Hurricane Warning discontinued
20-Sep	0600	Saba/St. Eustatius	TS Warning changed to Hurricane Watch
20-Sep	0600	Saba	TS Warning issued
20-Sep	0900	Turks and Caicos Islands/South-eastern Bahamas	Hurricane Watch changed to the hurricane warning
20-Sep	0900	Guadeloupe	TS warning discontinued
20-Sep	0900	Saba/St. Eustatius	Hurricane Watch discontinued
20-Sep	1200	St. Martin/St. Barthelemy	Hurricane Watch changed to TS warning
20-Sep	1500	Saba	TS warning discontinued
20-Sep	1500	St. Maarten	TS warning discontinued
20-Sep	1500	St. Martin/St. Barthelemy	TS warning discontinued
20-Sep	1500	St. Maarten	Hurricane Watch discontinued
20-Sep	2100	U.S. Virgin Islands	Hurricane Warning discontinued
20-Sep	2100	The British Virgin Islands	Hurricane Warning discontinued
21-Sep	0300	Puerto Rico/Vieques/Culebra	Hurricane Warning discontinued
21-Sep	1200	Central Bahamas	TS watch issued
21-Sep	1500	Cabo Engano to Andres/ Boca Chica, Dominican Republic	TS Warning modified to
21-Sep	1500	All	Hurricane Watch discontinued
21-Sep	2100	Cabo Engano to Andres/ Boca Chica, Dominican Republic	TS warning discontinued

22-Sep	1200	Central Bahamas	TS warning discontinued
22-Sep	1500	Puerto Plata to Northern DR/Haiti Border, Dominican Republic	TS Watch Changed to TS Warning
22-Sep	1500	Cabo Engano to Puerto Plata, Dominican Republic	TS warning discontinued
22-Sep	2100	Turks and Caicos Islands/South-eastern Bahamas	Hurricane Warning discontinued
23-Sep	0900	All	Hurricane warning changed to TS warning
23-Sep	2100	Surf City to North Carolina/Virginia Border	TS warning discontinued
23-Sep	2100	Pamlico Sound	TS Watch issued
23-Sep	2100	Albemarle Sound	TS Watch issued
23-Sep	0900	Pamlico Sound	TS Watch Changed to TS Warning
23-Sep	0900	Albemarle Sound	TS Watch Changed to TS Warning
23-Sep	0900	Duck to North Carolina/Virginia Border	TS Watch modified to
23-Sep	0900	Cape Lookout to Duck	TS warning Issued
23-Sep	2100	All	TS watch discontinued
23-Sep	2100	Cape Lookout to Duck	TS warning discontinued
25-Sep	2100	Bogue Inlet to North Carolina/Virginia Border	TS Warning Issued
27-Sep	1500	Ocracoke Inlet to North Carolina/Virginia Border	TS Warning modified to
27-Sep	2100	Cape Hatteras to North Carolina/Virginia Border	TS Warning modified to
28-Sep	0000	All	TS warning discontinued

(III) Storm surge watch-warnings

Table B12 storm surge watch-warning issued by NHC

Date	Time	Location	Action
24-Sep	2100	Cape Lookout to Duck, North Carolina	SS Watch issued
26-Sep	1500	Ocracoke Inlet to Cape Hatteras	SS Watch changed to SS Warning
27-Sep	1500	West of Ocracoke Inlet	SS Watch discontinued
27-Sep	2100	All	SS Watch discontinued
27-Sep	2100	All	SS Warning discontinued

(IV) Visual damages of Hurricane Maria

(a) Telecommunication poles damaged by Hurricane Maria (Source: Carlos Giusti/AP)

(b) Aerial view of flooding in Puerto Rico from Maria (Source: Ricardo Arduengo /AFP/Getty)

(c) Storm surge in communities of Juana Matos, Catana Puerto Rico during Hurricane Maria (Source: Ricardo Arduengo/AFP/Getty Images /abc News)

(d) Effects of storm surge in Palo Verde rice plantation are in Montecristi province the Dominican Republic (Source: © 2017 World Vision

(e) Damage to the Guajataca Dam, Quebradillas, Puerto Rico from Hurricane Maria's aftermath (Source: Alvin Baez/Reuters)

Figure B6 Visual view of damages from Hurricane Maria (2017)

APPENDIX C

Screenshots of Atlas.*ti* Coding

A sample case for which the process of analysis and categorisation of Atlas.*ti* coding is shown below. Atlas.*ti* version 8 is used for this research. The software is an emerging method for computer assisted qualitative data analysis (Friese, 2020). Based on the preliminary literature review, the documents required for data collection and further analysis is imported to the software. Once the documents were imported, then further codes were created for analysis and to draw output.

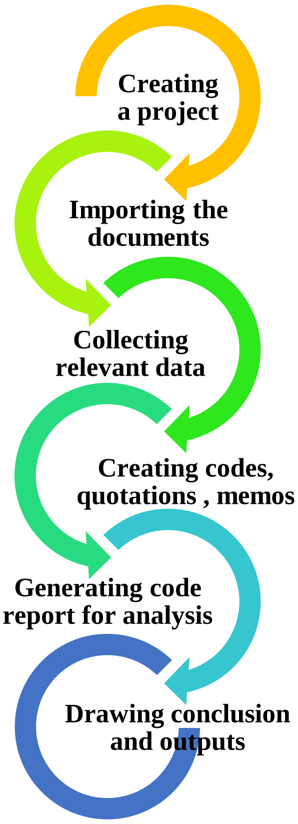


Figure C1 Workflow of Atlas.*ti*

Each document within a project will include several codes (key activities) which are called codes (smart codes). Importing graphic files, images, interviews, and newspaper articles were another advantage of using the Atlas.*ti* software (Friese, 2020).

Case Study: Super-Typhoon Haiyan

Step1: Document importing

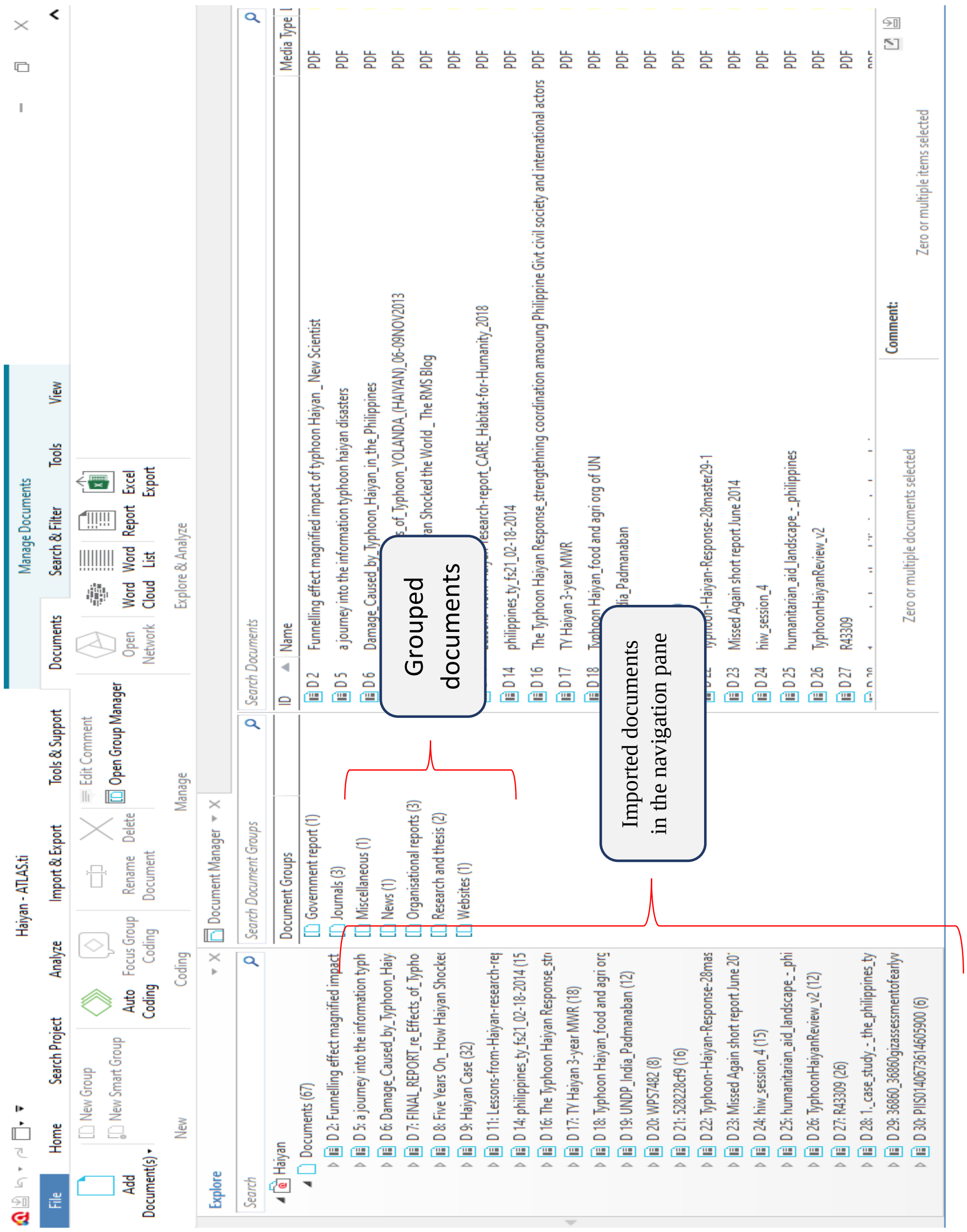


Figure C2 Importing documents to Atlas.*ti* and grouping

Figure C2 shows how the imported documents can be viewed in the navigation pane. The imported documents were further grouped as government documents, journals, newpaper artciles, organisation report, research and websites. These are the sources of evidence listed in Chapter 4.

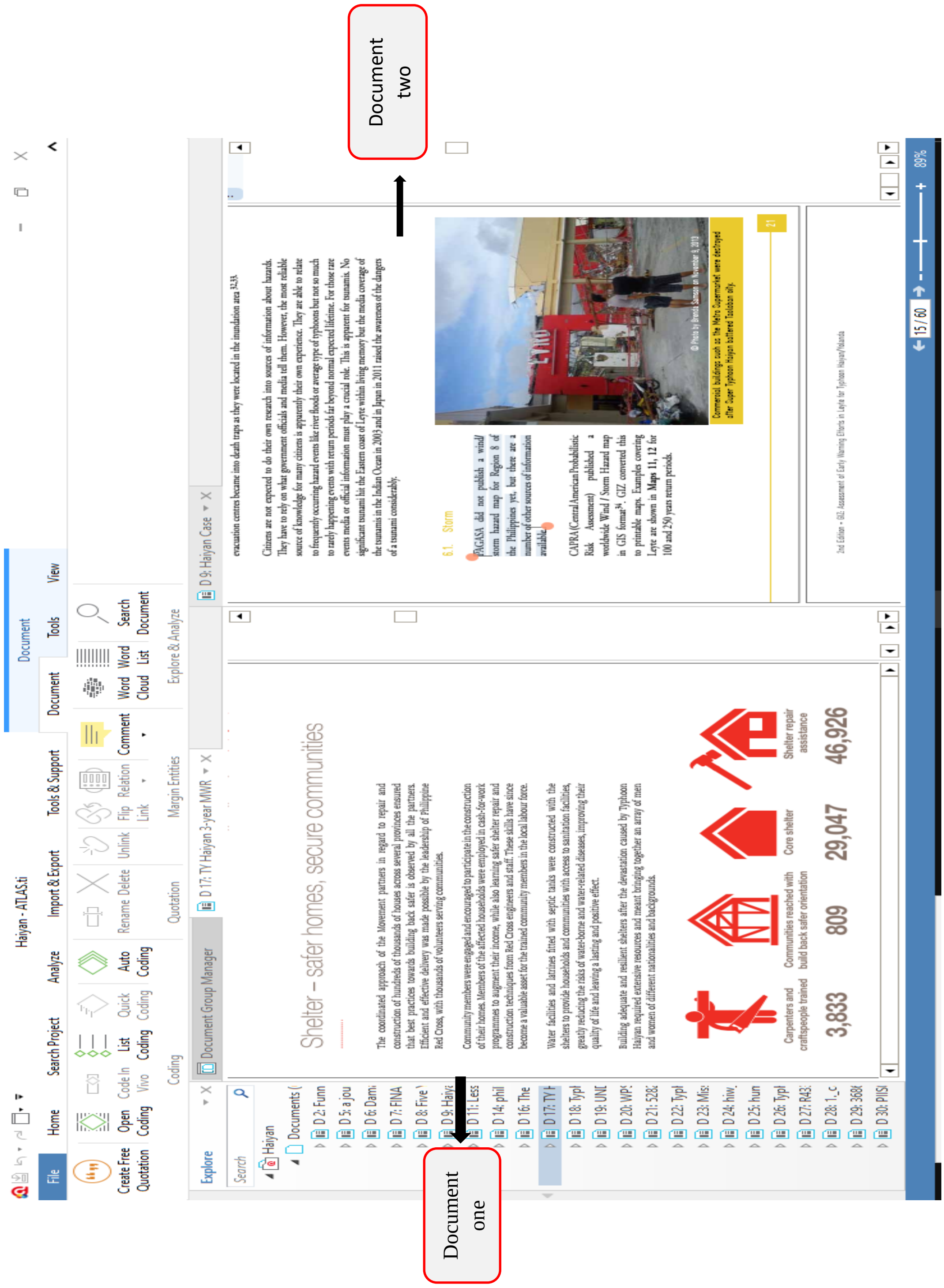


Figure C3 Viewing multiple documents for comparison

Viewing multiple documents side-by-side allows comparison of similar documents as shown in Figure C3.

Step 2: Systematic document search

Each document is search for the key words – which are the list of activities or related key activities that are addressed via the case study as shown in Figure C4.

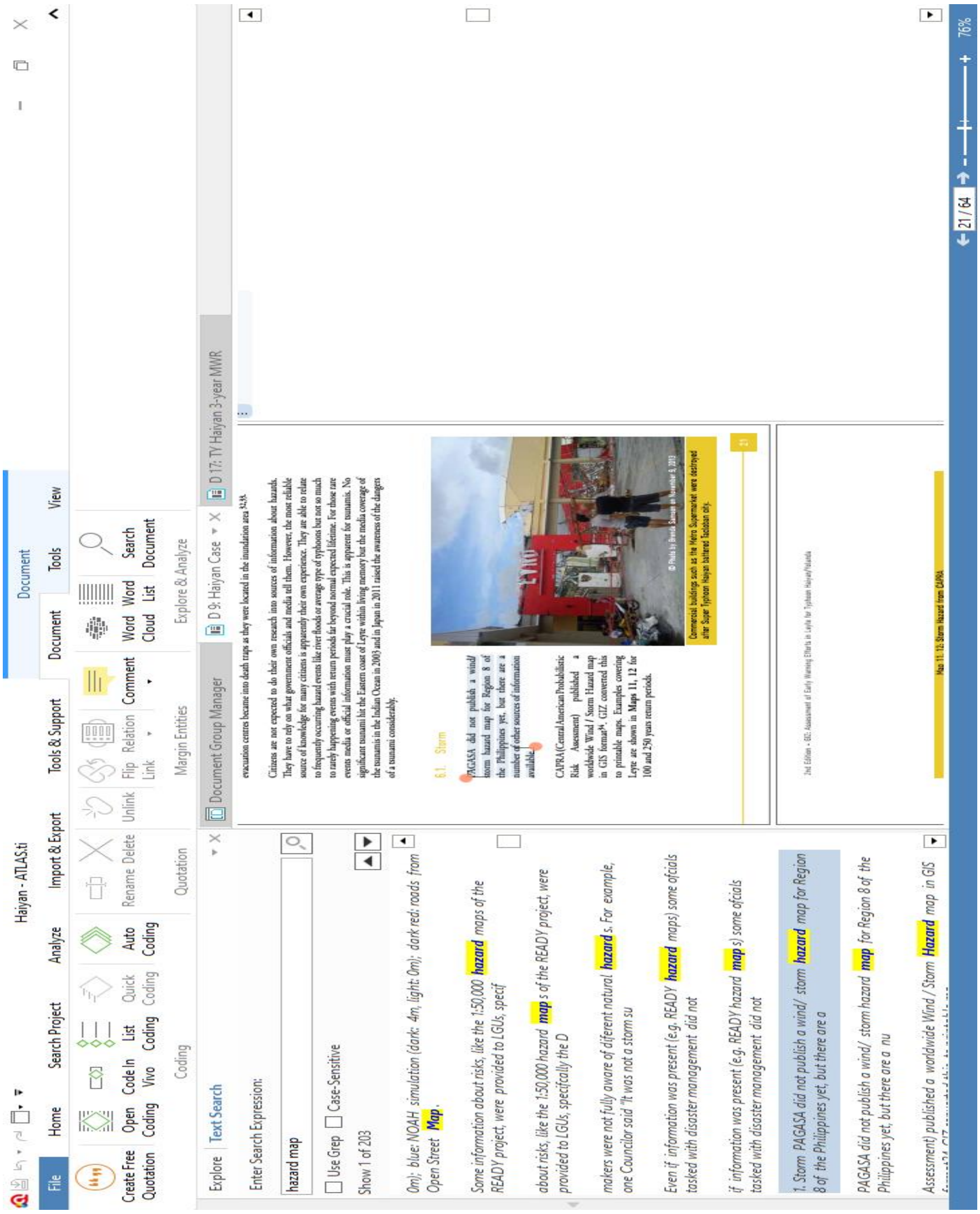


Figure C4 Document search by key word/key activity

Step 3: Creating a coding

Once the data segment which are the key word or key activity as stated in step 2 is searched, the selected segment of information is then converted as a 'new code' using the 'open coding' as shown below Figure C5 (a).

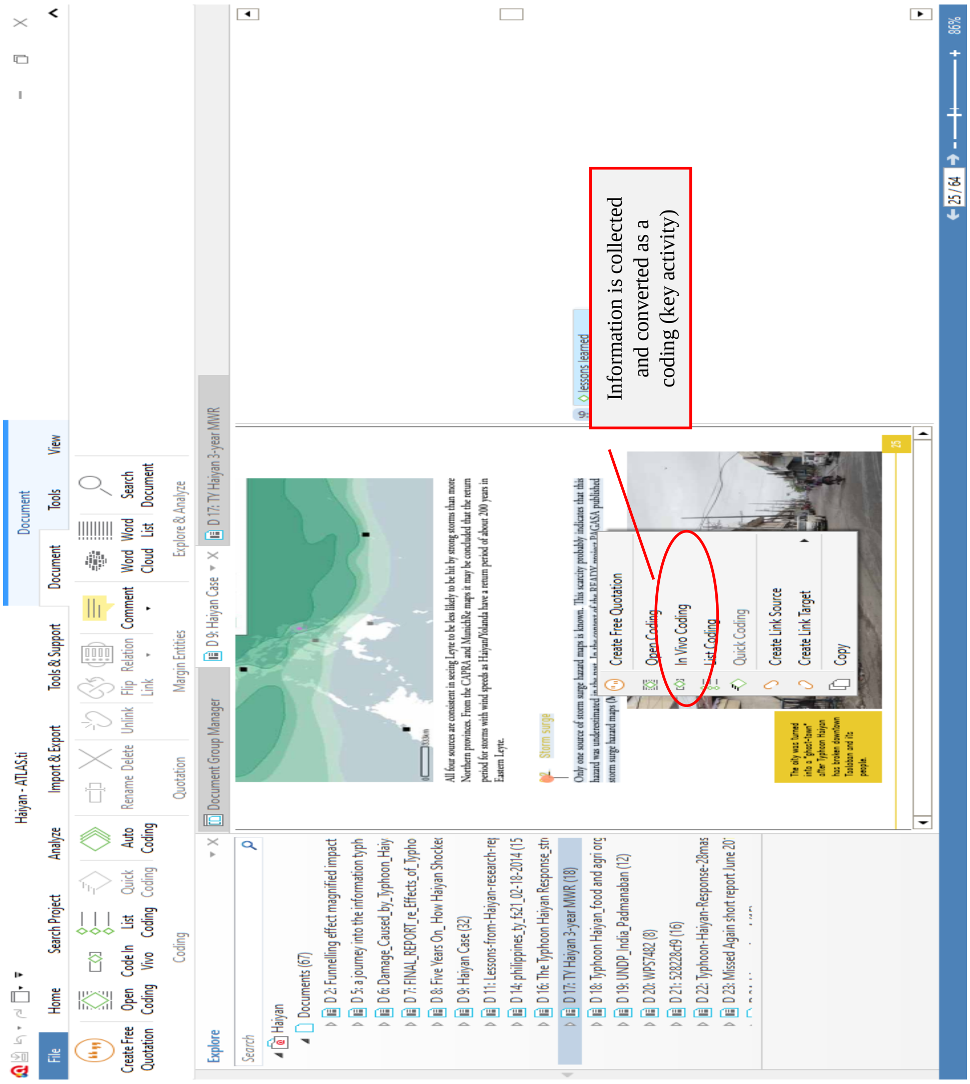


Figure C5(a) creation of new coding

Figure C5 (b) shows how a new coding is now created.

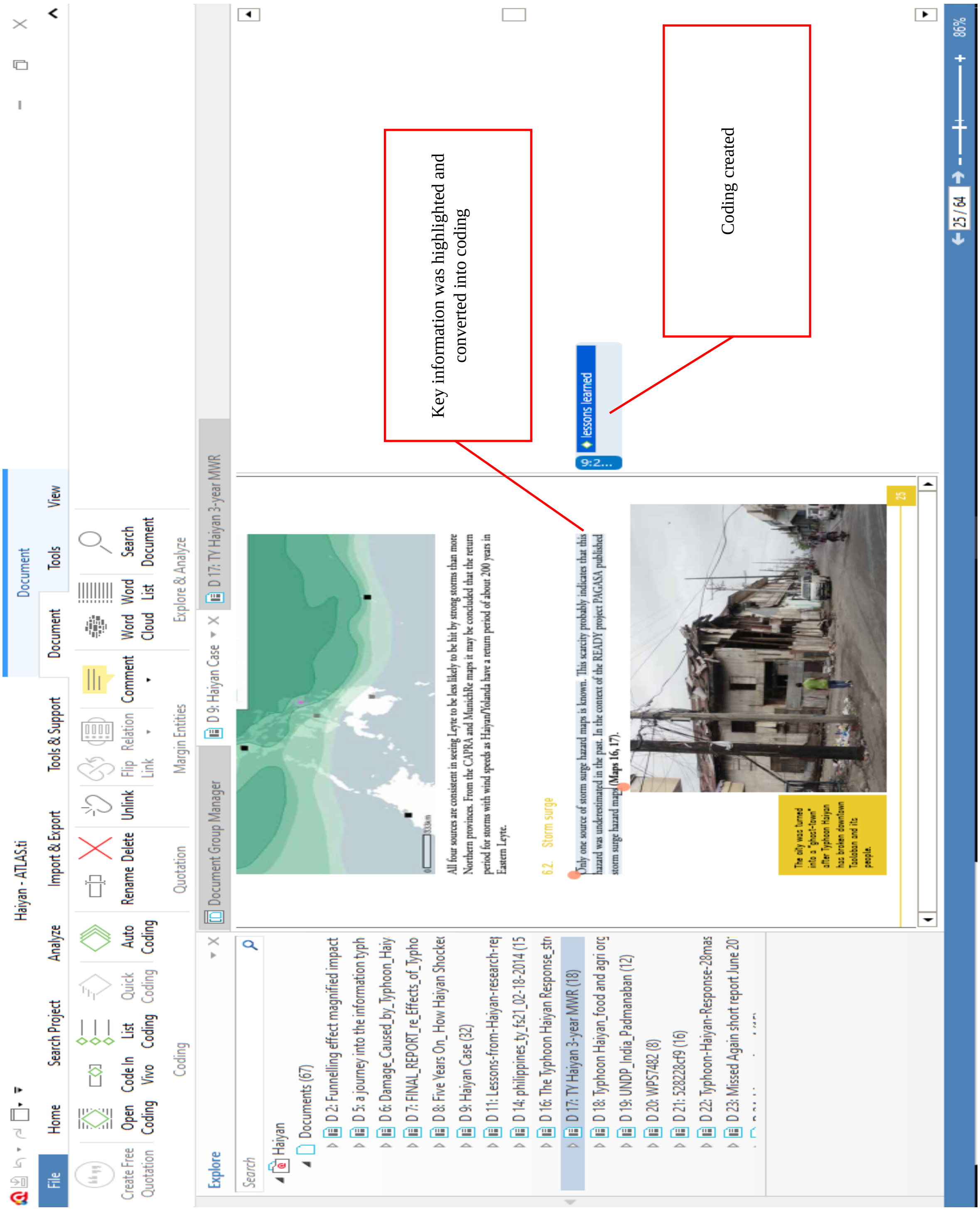


Figure C5(b) creation of new coding

Step 4: Code grouping

Each coding is then grouped under corresponding code group which are the four key themes (i) preparedness (ii) response (iii) recovery (iv) mitigation.

Figure C6 Grouping the coding

Figure C6 shows how the codes were grouped into four main code groups for case study Typhoon Haiyan. Creation of the codes and their code group were carried out for all the six case studies. This step of grouping the code was essential to cross-case analysis of each case study.

Step 5: Generating code report

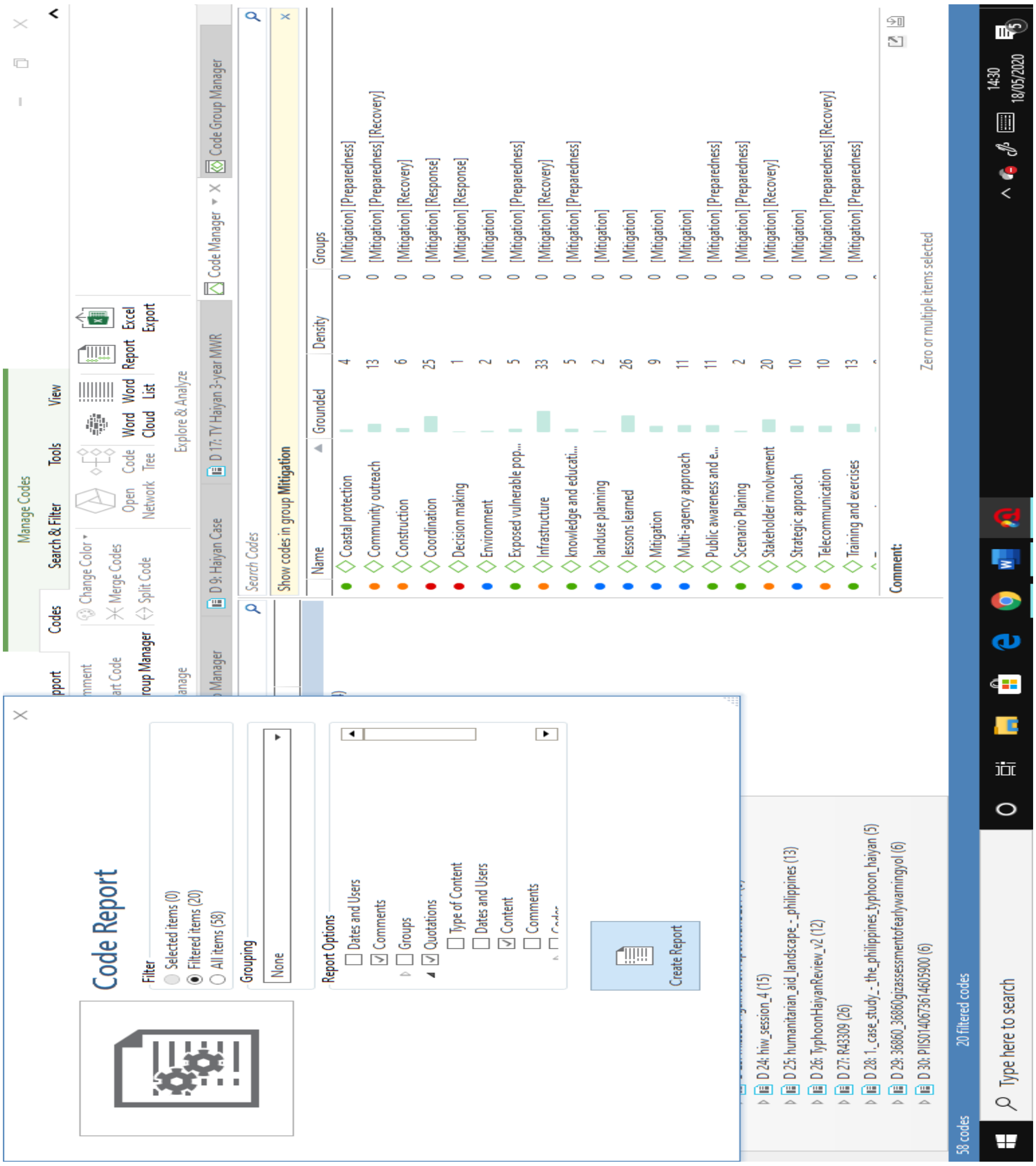


Figure C7 Generating code report

As a final step a code report is generated as shown in Figure C7. These code reports were greatly beneficial in designing the case study chapters 5, 6, and 7. For each case study a code report is generated. Sample codes were also provided in Chapter 8 which supported the analysis. In addition, these code reports further benefited during the identification of commonalities and differences which became the fundamental for the development of the DAMSS framework and defining the guidelines for best practices.