WATER RESOURCE MANAGEMENT IN FLOOD-PRONE URBAN AREAS

LESSONS FROM ATLANTIC SUPERSTORMS

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To all those friends and family who have made this year possible.

To Nelson, Sarah, Elena, and Mo – for keeping me grounded.

To Time – and its ceaseless, panic-inducing advance.

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

This dissertation does not exceed the maximum word count of 15,000 words.

Man seems to insist on ignoring the lessons available from history.

Norman Borlaug

ABSTRACT

This report analyses the successes and failures of urban storm and flood preparation and response efforts, specifically investigating whether hurricane-prone US cities synthesise lessons from past storm events into current storm and flood risk management policies. A review of global literature describes the challenges of water resource management in flood-prone urban areas. Atlantic hurricanes provide a unique and challenging opportunity to investigate storm and flood risk management in those areas, although a host of engineering, political, social, and environmental factors complicate this effort.

The body of the discussion extends from analysis of three major hurricane cases: Katrina (2005), Ike (2008), and Sandy (2012). Trends in storm preparation and response across these cases provide insight into the larger US storm preparation and flood management system. The characterisation of that high-level political and social system suggests possible leverage points that could create a more proactive storm and flood preparation system, but merits further investigation into city-specific policies and the complex relationships between public institutions at different levels of government.

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1. INTRODUCTION: RESILIENT URBAN INFRASTRUCTURE

In the United States, hurricanes batter coastal populations and wreak havoc on their economies, industry, environment, and livelihood. The US states bordering the Atlantic Ocean and Gulf of Mexico, while not increasing in population as quickly as many other coastal nations, represent an immense distributed population centre at severe risk from the annual Atlantic hurricane season (US Census Bureau 2015). Given the extensive record of these catastrophic annual events, what – if anything – is being done to synthesise the lessons from past severe storms into improved city plans and more effective engineering organisational psychology? How will global climate change impact future planning efforts?

Since Hurricane Katrina's landfall in New Orleans in August 2005, US federal institutions have revised their planning frameworks and operational paradigms to account for lessons learned through the tragedy and loss of Katrina and other major storms. Storm preparation systems, as well as flood management and mitigation infrastructure, are now more technically sound than ever before. Despite this, institutional inefficiencies, a lack of proactive risk-based investment, and reluctant integration of climate change predictions continue to undermine efforts to protect coastal American cities from disaster.

This report will outline an investigative methodology and establish a global context for storm-induced urban flooding before analysing the legacy of three major storms: Hurricane Katrina (2005), Hurricane Ike (2008), and Hurricane Sandy (2012). It will then identify trends across these cases before discussing progress in the development of storm- and flood-resistant cities and the structural (and associated barriers to change) within the larger political, social, and environmental systems underpinning US storm protection efforts. Finally, the report will offer a variety of key recommendations for political, environmental, and social action in the creation of a more resilient and effective hurricane and flood preparation system in the United States.

1.1. METHODOLOGY

This report begins with a discussion of relevant literature on urban flood management and mitigation from around the world in order to synthesise a global perspective on risk evaluation and management efforts. Despite this report's focus on the US, water resource management and flood response protocol in other areas of the world will provide a useful metric for comparison when analysing US-centric institutions and systems.

Following the literature review, the first analysis-based portion of this report consists of a critical evaluation of US preparation for and response to three cases of major storm events since 2005. The cases and the trends across them will provide an initial set of results that will indicate exactly where US systems are falling short in preparation for and response to recent storm events. These results will also help identify ways in which the lessons from individual storms impact planning and response efforts for future storms. This will depend on the analysis of each case with respect to a consistent crisis timeline:

- Is there evidence of long-term capacity-building far in advance of a storm?
- Did public institutions predict and prepare for the storm's landfall?
- How were response efforts conducted immediately after storm landfall?
- How did the storm affect the city's infrastructure development and planning in the years after its landfall?

This report will then review current storm preparation and disaster management policies in several cities to characterise ways in which they do and do not reflect consideration and integration of lessons from past catastrophic events. This will provide the final component necessary for a broader discussion of the larger system of hurricane preparation and flood response within the US, which will characterise institutional mindset within the system. This discussion will examine how the system works, what barriers and constraints exist within the system, and whether US public institutions embody current engineering ideology. The conclusion will offer key recommendations for action based on leverage points from the described socio-political system.

1.2. KEY RESEARCH QUESTIONS

1. What are the key social, political, and engineering lessons from recent catastrophic storm and flood events in the US?
2. Do current storm and flood management protocols in coastal cities synthesise those lessons into more effective policy and practice?
3. How do US public institutions align incentives and balance short- and long-term engineering concerns with a consideration for public safety and storm and flood risk?
4. What is the most useful way to characterise the political, social, and environmental components of the US hurricane preparation and flood response system?
5. What barriers exist within the system, and does it contain leverage points that would support the implementation of new policies and practice?
6. Do US public institutions integrate the results of new academic research and climate change projections into their organisational philosophy?

2. LITERATURE REVIEW: A GLOBAL PERSPECTIVE

This report will examine the federal-level systems within the United States that contribute to the creation and maintenance of storm- and flood-resistant urban areas. The discussion following the storm case studies will focus on a characterisation of political, social, and environmental factors influencing system change within the US, but will benefit from an initial examination of the global body of urban flood risk and mitigation literature. Hurricanes are unique to the Atlantic Ocean, but typhoons and flood-inducing events in other parts of the world may provide a good indication of best engineering and political practice for catastrophic flood events elsewhere.

2.1. GLOBAL AT-RISK POPULATIONS

The planet's population continues to urbanise. This gradual shift, which has existed since the introduction of agriculture and which accelerated during mass industrialisation, incurs many benefits; the UN Habitat (2009) characterised city-dwelling populations as happier, healthier, and more economically prosperous than their rural peers. However, this same increase in urban density presents a host of additional challenges not present in rural areas: increased stresses on critical infrastructure systems, more problems in social administration, and increased distance from regions of agricultural productivity. Cohen (2006) described this mass urbanisation as particularly severe in developing countries, posing a constant challenge to infrastructure maintenance and the pursuit of sustainable urban systems.

Shifts towards the planet's coasts pose additional risk. Small and Nicholls (2003) conducted a global analysis of human settlement in coastal zones and found that the world's near-coastal population (within 100 km of a coastline) is more than three times as dense as the global average population density. This same at-risk zone also contains many of the world's fastest-growing cities and must rapidly build increased resilience, defined in depth by Klein and others (2002). Creel (2003) noted that coastal regions present unique opportunities for industry and trade, but that these benefits come at significant cost.

Hallegatte et al. (2013) described the implications of the demographic shift described by Klein, Nicholls, and Small; intense rain events and variable seasonal flows pose a dire threat to many of these rapidly developing cities. If these at-risk population centres are to persist and prosper, especially given climate change effects that Kalnay and Cai (2003) claim they accelerate, they will require the creation of uniquely resilient and sustainable urban infrastructure.

2.2. FLOOD PREPARATION AND RESPONSE

Flood preparation and response are the world is generally characterised by the location and immediate cause of the flood event, the threat posed by the flood, and any existing government preparation and response systems. The United Kingdom and Australia, although they do not experience hurricanes, offer useful perspectives on integrated flood risk management that may help in analysis of American systems.

In the United Kingdom, the Environment Agency is responsible for leading flood risk evaluation and management, cooperating closely with the Scottish Environment Protection Agency (SEPA) to manage risk in flood-prone areas. Hall and others (2003) conducted a review of the Environment Agency's (and DEFRA's) flood risk evaluation and management efforts, concluding that the organisation needed to work towards increased integration of disparate flood management systems with each other, but that the Environment Agency was actively revising its protocols towards this end.

In Australia, flood risk management is notionally the responsibility of the federal government through Geoscience Australia, most recently outlined in its National Flood Guidelines (2014). However, Box et al. (2013) describe the Australian flood risk management system as much more diffuse, involving the coordination of public and private actors across all levels of government. This perhaps helps to explain the severity of the 2010-2011 Brisbane floods, analysed with respect to societal resilience by Walters (2015) and in terms of future climate change projections by Smith and McAlpine (2014).

2.3. URBAN FLOOD MITIGATION SYSTEMS

Conventional flood "protection" and "prevention" methods involve the almost-exclusive use of hard "grey" infrastructure. The case studies presented in this report will discuss the legacy and consequences of pure-grey flood mitigation systems, but academic consensus indicates that new systems should involve a mixture of grey and "green" infrastructure components working in concert. Gill and others (2007) emphasised the importance of these green infrastructure components in cities threatened by climate change that – as described by Schreider, Smith, and Jakeman (2000) – will increase the frequency and magnitude of urban flood events in the future.

Bridges et al. (2015) of the US Army Corps of Engineers (USACE) described a variety of "green" coastal resilience system components, characterising them as "Natural and Nature-Based Features" (NNBFs) for use as part of a coastal community resilience "package." Though not named as such, many of these measures would fit within the system designs proposed in Blue-Green Cities approaches. Lawson, Fenner, and others (2014) defined methods that would reduce the need for grey infrastructure while including the additional benefit of recreating more natural (and therefore more resilient) water cycles within urban areas. However, the relative costs and benefits of components of such a system would likely require additional long-term analysis before their adoption by a politically pragmatic organisation like USACE.

2.4. RISK COMMUNICATION AND SIGNALLING

The implementation of any flood risk management system depends on a thorough understanding of both the risk that will be managed and the most effective ways to communicate and signal that risk to a population. Fischhoff (1995) offered a useful but general outline of risk perception and communication methods from a research perspective, but Ball (2002) leveraged Fischoff's outline into a more pertinent analysis of the role of human bias in environmental risk assessments. Berlemann (2016) outlined a more recent application of these frameworks in analysis of the effects of risk from hurricanes and other natural disasters on individual decisions.

Governments constantly work to establish risk for various events and communicate that risk to the public, often in the form of hard political and economic signals like insurance rates, taxes, and zoning controls. Charpentier and Le Maux (2014) discussed the ideal role of government insurance in the public perception of natural disaster risk – a dynamic that has been synthesised into actual insurance programs like “Flood Re” in the UK and the National Flood Insurance Program (NFIP) in the US (Flood Re 2016; FloodSmart 2016). Bagstad and others (2007) discussed the viability of a potential set of tax, subsidy, and altered NFIP insurance structures that would help optimise US Gulf Coast development. Linnenluecke and others (2011) instead used the NFIP as a means to explore optimal government investment levels and the proper balance between insuring and relocating businesses properties – a theme that this report’s discussion will explore.

3. CASE STUDIES

This study utilises three major hurricanes as case studies in order to extract lessons to examine storm defence and flood management practice in US cities: Hurricane Katrina (2005), Hurricane Ike (2008), and Hurricane Sandy (2012). These hurricanes represent the three most financially destructive storms since 2005, and their respective impacts on New Orleans, Galveston, and New York City are useful even in examining areas of significantly different geographies, economies, and political environments.

Tropical storms and hurricanes occur annually, typically in the North Atlantic "hurricane season" between June and November. However, the severity of a single hurricane season is highly unpredictable; a season might pass without even a single named storm (a tropical storm with 1 minute sustained wind speeds greater than 40 mph) or there might be multiple major hurricanes in a single season. The Saffir-Simpson Hurricane Wind Scale (SSHWS) defines hurricane intensity and "major" hurricane classification in the US. Table 1 shows each category and its required 1 minute sustained wind speed; hurricanes are continually tracked and reclassified against this scale throughout their existence (National Hurricane Center 2016).

Table 1: Saffir-Simpson Hurricane Wind Scale (SSHWS)

SSHWS Category	Sustained Wind Speed
1	74-95 mph (119-153 km/h)
2	96-110 mph (154-177 km/h)
3 (Major)	111-129 mph (178-208 km/h)
4 (Major)	130-156 mph (209-251 km/h)
5 (Major)	≥157 mph (≥252 km/h)

Because of the unpredictable nature of hurricane landfall, there is a high variability in their damage on a year-to-year basis. Table 2 shows a compiled account of total financial damage and deaths for all storms in the 2005-2015 seasons (Atlantic Oceanographic & Meteorological Laboratory 2016).

Table 2: Hurricane financial damage and associated fatalities

Season	Total Damage (USD)	Deaths
2005	$159 billion	2,280
2006	$500 million	14
2007	$3 billion	423
2008	$42 billion	1,047
2009	$57.8 million	9
2010	$12.357 billion	314
2011	$18.585 billion	114
2012	$75.9 billion	355
2013	$1.51 billion	47
2014	$233 million	17
2015	$648.7 million	89

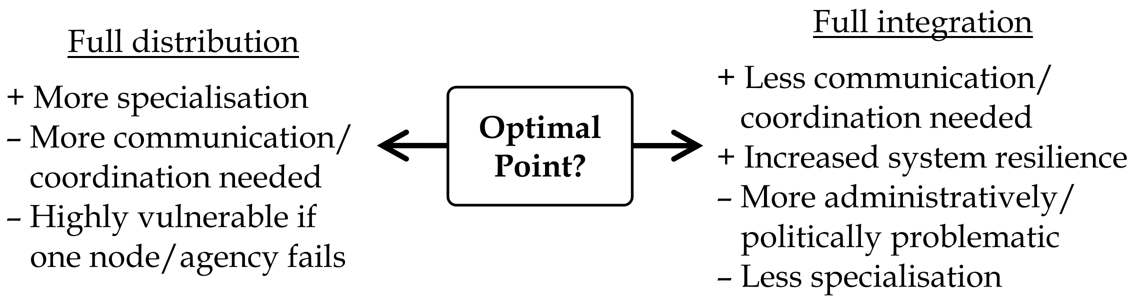
Hurricane preparation and response in the United States (and associated flood management efforts) rely on the coordinated actions of various federal, state, and local organisations. As will be shown in the following case studies, the relative success or failure of response and recovery efforts for a single storm is often defined by how well these agencies are able to communicate, share resources, coordinate their response efforts, and work to revise preparation and response protocols in advance of the next major storm.

Table 3 summarises typical areas of responsibility before, during, and after major storms according to published doctrine from FEMA's national planning frameworks (Department of Homeland Security 2013b). Actual roles in real crises sometimes differ, but this division of responsibilities among contributing organisations is often beneficial to the overall preparation and response efforts for hurricanes. Agency-specific missions that leverage unique resources and areas of expertise generally increase the effectiveness of operations in a given area.

Table 3: Major areas of storm preparation/recovery responsibility by agency

Organisation	*Before storm event*	*During storm event*	*After storm event*
Federal Emergency Management Agency **(FEMA)**	Evaluates geographic flood risk and labels at-risk areas	Prepares for and lead short-term relief (if state of emergency is declared)	Aids in managing evacuated populace Leads major short-term relief and rescue efforts
US Army Corps of Engineers **(USACE)**	Creates/maintains federal water infrastructure Works with state and local authorities on infrastructure design/construction	Supports FEMA relief efforts	Repairs deficient infrastructure Creates short-term infrastructure Supports FEMA relief efforts
National Oceanic and Atmospheric Administration **(NOAA)**	Evaluates long-term weather and storm trends	Tracks storms during landfall Updates storm warnings	No stated/ significant role
State and Local Authorities (Local Gov't, Emergency Response, etc.)	Establishes local building codes Communicates risk to public	Local response/ recovery efforts Aid in execution of evacuation efforts	Leads long-term recovery after FEMA's exit
US Congress	Appropriates funds for infrastructure creation to USACE	No stated/ significant role	Commissions investigations into any major failures Funds further risk evaluation efforts

However, as will be shown in discussion of the case studies, these institutional interrelationships often break down during intense storm events – precisely when the efficient operation of those institutional links is most needed. This breakdown in communications and collaboration has dire consequences in distributed systems used to prepare for and respond to hurricanes. Identification of the most operationally "optimal" position along this continuum will be vital throughout analysis and discussion of these case studies.



Reaching this optimal point may be difficult or impossible; movement along the axis of change may require institutional reorganisation that is unlikely within the constraints of the political environment. These three case studies include summaries of each event, but should also provide a more useful indication of the feasibility of large-scale change within US public institutions. The cases will discuss the preparation for and response to each storm, providing insight on the evolving roles of the institutions, actors, and planning processes associated with hurricane preparation and flood response in the US.

3.1. HURRICANE KATRINA

Date of landfall:	29 Aug. 2005 (Louisiana, Mississippi, Alabama)
Wind speed at landfall:	125 mph (200 km/h)
Category at landfall:	Category 3
Estimated damage:	$108 billion
Associated fatalities:	1,836 (all within US)
	(National Climatic Data Center 2005)

Hurricane Katrina, in the eleven years since its landfall, has solidified its initial reputation as an engineering and institutional failure. Single-point engineering failures led to cascading losses within the New Orleans Hurricane Protection System, and USACE and FEMA both opted for cheaper engineering options that did not provide the claimed level of safety to the city and its residents (Robertson & Schwartz 2015; Rogers et al. 2015). Local and state officials were not prepared to respond to the rapid flooding of the city and safety was deprioritised in favour of best-cost short-term solutions. Planning frameworks depended on system resilience that simply did not exist. This storm response – terrible though it was – set the stage for drastic changes to hurricane preparation and flood response across the United States (Baker 2014).

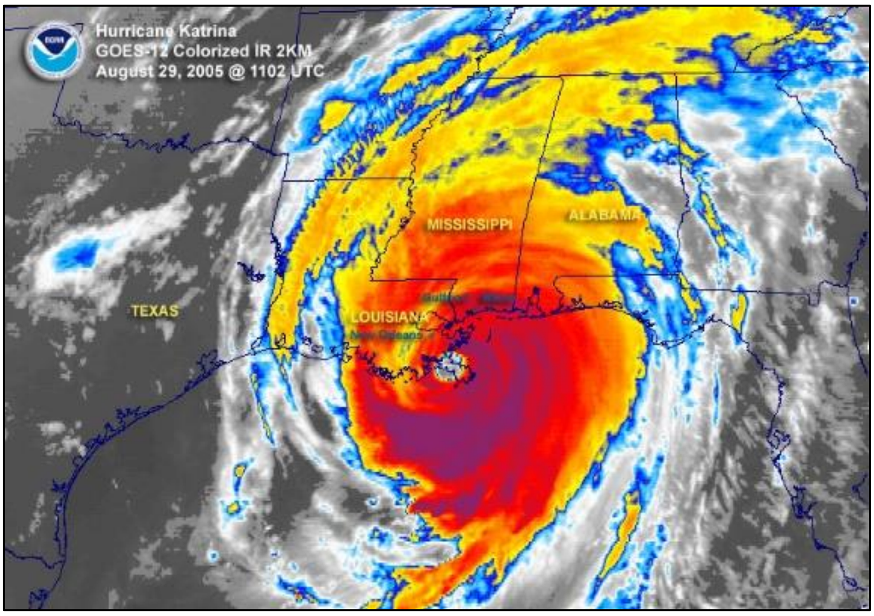


Figure 1: The eye of Hurricane Katrina approaches New Orleans (NOAA 2005)

Hurricane Katrina made landfall on the Gulf Coast shores of Louisiana, Alabama, and Mississippi on August 29, 2005. While the storm wrought havoc on all three states, its damage was most severe in southeast Louisiana on the Mississippi River delta and adjacent New Orleans. It was one of the most powerful Atlantic hurricanes of all time; as a Category 5 storm, it reached a minimum central pressure of 902 mb before making landfall as a strong Category 3 storm. Its storm surge flooded 80% of New Orleans (greater than 4.5 meters in some areas) as levees overtopped and breached (National Climatic Data Center 2005). Although there was early declaration of a federal state of emergency within Louisiana and greater than 80% evacuation of the city, more than one thousand people lost their lives in the wake of what were immediately deemed failures by local, state, and federal authorities (U.S. House of Representatives 2006). The city's hurricane protection "system" fell into disparate pieces during the massive storm and Katrina became the definition of "engineering failure" to the US populace (Andersen et al. 2007; Griffis 2007).

Response to Hurricane Katrina required the coordinated efforts of USACE, FEMA, and local emergency authorities, but the preparation and response efforts were widely criticized during and following the storm (Shane & Lipton 2005). The brunt of criticism focused on the perceived lack of initiative by federal, state, and local authorities in executing plans and policy. The US House of Representatives committee investigation on Katrina takes its title, *A Failure of Initiative*, from America's confrontation with "the vast divide between policy creation and policy implementation. The life-and-death difference between theory and practice" (U.S. House of Representatives 2006).

Immediately following the hurricane and in response to Congressional and media criticism of organisational failure, USACE conducted a review of the hurricane protection system in New Orleans and southeast Louisiana, which included the majority of the failed engineering systems. This report, the product of the USACE Interagency Performance Evaluation Taskforce (IPET), was reluctant to admit much blame on behalf of USACE efforts to prepare for major Gulf Coast storms, instead attributing overall system failure to a variety of small-scale failures among system components. Levees had been constructed using incorrect elevation data, system maintenance had been poor, and backup systems (pumps and generators) had been situated in places vulnerable to flooding, causing cascading system failures (US Army Corps of Engineers 2009; Seed et al. 2006; Rogers et al. 2015).

The IPET admitted higher-level shortcomings in storm modelling efforts, but identified the harms of political complications, lack of public acceptance of the communicated storm risk, and lack of a comprehensive water resources management policy. Commentary on USACE's internal leadership decisions and interagency coordination shortcomings were largely absent. While the report did involve good analysis of the relationships within the New Orleans hurricane protection system and the factors that had contributed to its structural failure, it was a somewhat incomplete and rather biased evaluation of one of the most destructive storms in modern US history (US Army Corps of Engineers 2009).

The negative response to a public draft of the IPET report prompted USACE to commission an independent engineering investigation into both the New Orleans Hurricane Protection System and into its own institutional handling and evaluation of the storm preparation and response. The American Society of Civil Engineers (ASCE) led this independent audit, releasing a 2007 report that forms a more coherent narrative of events before, during, and after the storm's landfall. The ASCE report confirmed several sections of the IPET report, primarily those dealing with storm modelling efforts and political obstacles that had impeded response efforts. High-water marks had been the only common metric available for storm effect modelling throughout New Orleans, limiting the suitability of infrastructure designs for a Katrina-calibre storm. Political turnover had forced greater focus on realising short-term engineering goals rather than creating long-term risk mitigation strategy or achieving life-cycle solutions throughout the electoral process (Andersen et al. 2007; US Army Corps of Engineers 2009).

Independent findings of the ASCE report reflected more human-centric areas of importance: communication of risk to the public in an understandable manner, the implementation of rigorous inspections and construction standards to combat human oversight, and the value of decisive institutional leaders. ASCE underscored the importance of quantifying storm and flood risk prior to landfall, but stressed that the most crucial portion of any risk analysis was the communication of that risk to the public. While 80% of the population of New Orleans evacuated prior to the storm's arrival, evidence suggests that at least a portion of the remaining 20% did not evacuate due to underappreciation of the storm's threat (Andersen et al. 2007; Guiney 2006).

Risk for Hurricane Katrina was largely disseminated to the New Orleans populace in relation to its category – "only" 3 at landfall. This may have led some to believe that the storm would be only a moderate threat, or at least much less destructive than a storm like Hurricane Camille (Category 5), which struck New Orleans in 1969. In reality, the Saffir-Simpson category of a storm is a poor predictor of hurricane damage, which is better characterised by storm size and storm surge magnitude – both exceptionally large for Katrina (Kantha 2013). Inconsistent, contradictory, and sometimes even dangerous warnings from local weather services also exacerbated response efforts. Some weather services, using stock messages designed for high wind and tornado circumstances, issued recommendations to take shelter in "an interior room of the lowest floor" of buildings – even in areas at severe risk for storm surge flooding (Guiney 2006).

Recent analysis of Hurricane Katrina confirms the findings of the ASCE report. The catastrophic events of Hurricane Katrina were the compound result of low-level engineering failures and oversights, higher-level planning failures and inefficiencies in interagency communication, and failure in the clear communication of storm and flood risk to the public. USACE and FEMA both bear responsibility for these failures, although local and state officials are also culpable for the adoption of plans and response protocols depending on non-existent system resilience (Robertson & Schwartz 2015; Baker 2014). Hurricane Katrina deserves its reputation as one of America's worst-ever natural disasters, but its legacy continues to influence modern storm planning and flood management efforts.

3.2. HURRICANE IKE

Date of landfall:	13 Sep. 2008 (Texas, Louisiana)
Wind speed at landfall:	110 mph (175 km/h)
Category at landfall:	Category 2
Estimated damage:	$37.5 billion
Associated fatalities:	195 (113 in the US, 74 in Haiti, 7 in Cuba, 2 in the Dominican Republic) (Berg 2009)

Hurricane Ike struck Galveston, Texas, on September 13, 2008. At the time of its landfall, it was a strong category 2 storm with sustained winds of 110 mph (175 km/h) – somewhat weakened by an earlier encounter with Cuba, but still strong enough to cause severe alarm along the Gulf Coast of Texas and Louisiana. Ike brought a 6.8 m storm surge, crippling local infrastructure, flooding large portions of Texas, and destroying many beachfront communities. Yet unlike Hurricane Katrina, Hurricane Ike involved the use of revised planning frameworks and response protocols involving close coordination among FEMA, USACE, and state and local officials. While the total response efforts were not wholly successful, small-scale engineering failures were relatively rare and the short-term response transitioned well into long-term recovery efforts.

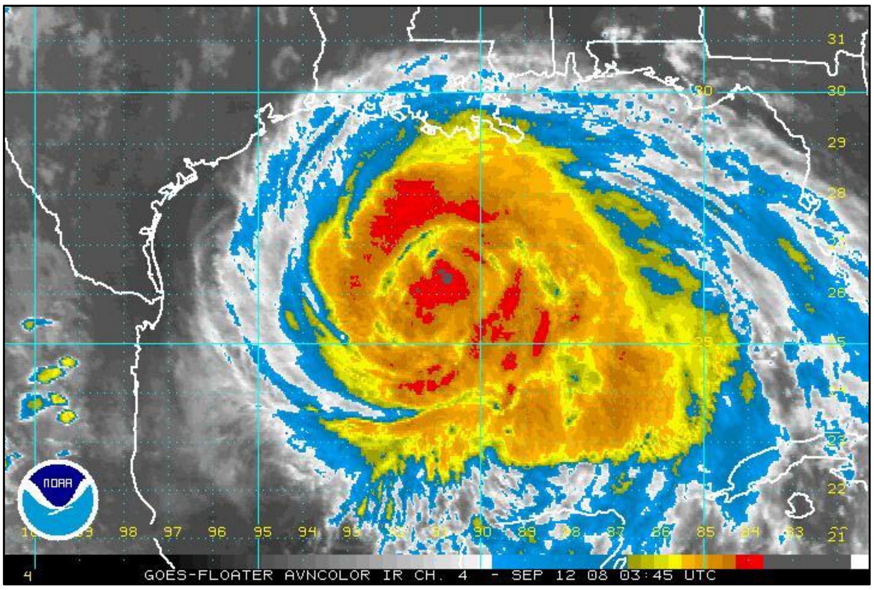


Figure 2: Hurricane Ike approaches the Gulf Coast of Texas (NOAA 2008)

On 7 September, analysing NOAA projections of strength and direction for the storm dubbed "Ike," the Galveston District Office of USACE activated its Emergency Operations Center (EOC). The EOC was staffed with quick-response personnel and supplies and soon opened redundant lines of communication with local, state, and federal officials (Tirpak 2009). Drawing upon post-Katrina revisions to FEMA National Planning Frameworks, USACE prepared for close coordination with FEMA during the anticipated emergency response stages following Ike's landfall (Berg 2009; Department of Homeland Security 2013a).

The storm wrought havoc as it swept over Haiti and Cuba on September 8, weakening from Category 4 to Category 1 but destroying buildings and crops in such large numbers that it would eventually become the costliest hurricane in Cuban history (Brown et al. 2010). Moving back over the warm waters of the Gulf of Mexico, it strengthened to Category 2 as it approached the coast of Texas. NOAA projections had anticipated the storm growing more concentrated and stronger than Category 2 during its time over the Gulf of Mexico, but disturbances in Ike's core led instead to the development of massive outer rain bands (Berg 2009). Ike grew quickly grew in size while sustaining Category 2 wind speeds as it approached the coast – a deceptive and unfortunate result of inaccurate storm projections.

On September 10, three days before landfall, the governor of Texas issued a state of emergency, officially requesting the support of federal authorities in the preparation for and response to Hurricane Ike. FEMA, with the support of USACE and the Texas Joint Hurricane Response Team, began preparations for provisioning critical supplies, generating emergency power, and providing impromptu shelter for evacuated residents (Tirpak 2009). The storm's arrival revealed a level of engineering resilience that had not existed during the impact of Hurricane Katrina in 2005. Three federal hurricane protection levees had been constructed along the Galveston shoreline after the impact of Hurricane Carla in 1961; although each sustained damage during the storm, they performed as designed without overtopping and significantly reduced the damage caused by Ike's storm surge (Tirpak 2009; Rego & Li 2010).

Despite these successes, long-lasting shore recovery and protection projects are required in order to rejuvenate the areas struck by the storm. Many coastal communities still have not rebounded to their pre-storm states, and FEMA faced some criticism in the weeks following the storm for its ongoing procurement of temporary housing for storm evacuees (Colley 2008). The project to restore Galveston will need to incorporate climate change projections showing increased risk from storm surges over the next century, but these projections have not yet been incorporated into updated infrastructure designs (Rego & Li 2010; Warner & Tissot 2012).

Although NOAA's predictions of the exact location of landfall contained a persistent degree of bias that had initially misled local residents as to the likelihood of Ike's landfall, the Galveston area benefited in this case from a history of strong hurricane impacts. The Great Storm of 1900, which killed more than 6,000 people in Texas, prompted USACE to create the first Galveston seawall and to raise the grade of local boundary islands. Subsequent storms, especially Hurricane Carla in 1961, had prompted the creation of more extensive levees and flood gates which added further resilience to the Galveston area (Tirpak 2009). Yet it was the influence of Hurricane Katrina, and the subsequent revision of planning frameworks and response procedures, that truly helped Galveston avoid a catastrophe on the order of that witnessed in New Orleans in 2005 (Colley 2008).

3.3. HURRICANE SANDY

Date of landfall:	29 Oct. 2012 (New Jersey, New York)
Wind speed at landfall:	70 mph (115 km/h)
Category at landfall:	Post-tropical cyclone
Estimated damage:	$75 billion
Associated fatalities:	233 (157 in the US, 54 in Haiti, 11 in Cuba, 2 each in Canada, the Dominican Republic, Jamaica, The Bahamas, and offshore, and 1 in Puerto Rico) (National Weather Service 2012)

Hurricane Sandy was more unexpected than a typical hurricane; it arrived late in the 2012 hurricane season, persisted long after its peak as a so-called "superstorm," and affected every state on America's East Coast from Florida north to Maine. It exerted the brunt of its force on the New York City metropolitan area, a region not usually affected by tropical storms. Extensive government preparation efforts and emergency funding mitigated loss of life due to storm effects, but Sandy's winds and storm surge damaged or destroyed more than 650,000 homes and crippled regional transportation systems (National Weather Service 2012). The storm tested the responsiveness of various institutions, highlighting systematic improvements developed after past storms and setting the conditions for future improvement to New York's infrastructure.

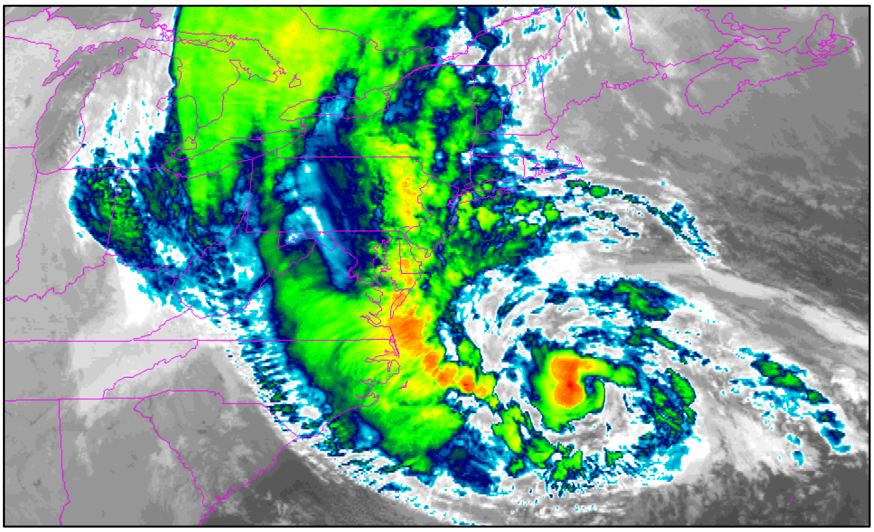


Figure 3: "Superstorm Sandy" moves north along the East Coast (NOAA 2012)

Hurricane Sandy formed in the Caribbean on 22 October 2012, crossing Jamaica and Cuba as it gathered strength in its initial movement northward. Although it was briefly a Category 3 major hurricane during its landfall in Cuba on October 25, it was a Category 1 storm for most of its existence. Despite this weakening as it travelled parallel to the East Coast, Sandy continued to grow in physical size as it neared the northeastern US. It turned westward off the coast of New Jersey on 29 October before making landfall with sustained winds of 70 mph (110 km/h) near Atlantic City, New Jersey (Blake et al. 2013).

The National Weather Service downgraded Sandy from a hurricane to a post-tropical cyclone just before its landfall due to its low wind speed. Its immediate wind and rain damage were relatively minor across New Jersey and New York, but its massive size created a monumentally damaging storm surge exceeding 12 feet (3.6 m) in many areas of New York. This surge alone was severe, but a coinciding astronomical high tide created a combined storm tide exceeding 14 feet (4.3 m) in some parts of Lower Manhattan and Long Island. This storm ride caused the brunt of Sandy's estimated $75 billion in damage (Gibbs & Holloway 2013; Blake et al. 2013).

The National Weather Service excelled technically in its prediction of Sandy's trajectory and strength (Folmer et al. 2015). Despite encountering communication problems with numerous Emergency Managers responsible for regional decision-making, the National Weather Service was able to issue timely warnings to both New York and New Jersey that enabled dissemination of calculated evacuation orders on 27 October (National Weather Service 2012). This evacuation order came a full two days before the arrival of the storm, giving adequate time for most residents of the prioritised evacuation zones to leave the area and seek FEMA assistance. Compliance with these evacuation orders was high, especially considering Sandy's projection at that time for a downgrade to the post-tropical cyclone classification (Gibbs & Holloway 2013).

Sandy was exceptionally damaging to New York's local and regional transportation infrastructure. The storm tide flooded underground roads, subway tunnels, and utilities throughout Lower Manhattan, blocking crucial access routes into the island and causing power outages. Although there were no critical infrastructure failures, the storm tide induced by Sandy was a 200-year flood event that exceeded the design capacity of many of New York's historic flood mitigation systems (US Army Corps of Engineers 2013). Flooded key transit routes hampered emergency response in the days following the storm, intensifying already-severe economic damage (Gibbs & Holloway 2013). Despite this, USACE was able to work in concert with FEMA to leverage some of its military assets to establish small-scale power generation and communications sites across Manhattan in the hours following the storm's landfall, easing the process of establishing a more substantial disaster relief presence through FEMA efforts (US Army Corps of Engineers 2015).

Long-term prospects for the recovery of New York appeared positive even in the immediate aftermath of Sandy. After some delay, Congress signed the 2013 Disaster Relief Appropriations Act into law in January 2013, dispensing more than $50 billion in federal relief funds to government agencies in the impacted areas (Hernandez 2013; 113th US Congress 2013; Department of the Interior 2013). The state and local governments in New York have been particularly effective in synthesising this massive recovery package into both short-term recovery and long-term resilience-building efforts, even exhibiting a high level of commitment to nature-based design features in new coastal protection projects (Special Initiative for Rebuilding and Resiliency 2013; Governor's Office of Storm Recovery 2014; Goldstein et al. 2014).

Hurricane Sandy's destruction should not be understated – it was one of the most destructive storms in US history – but it could have been significantly more damaging. Federal and local authorities communicated risk and administered the evacuation well, engineering systems were resilient up to their established design capacity, and post-disaster recovery efforts are constructive in tone and focused both on rebuilding lost social capital and on long-term resilience-building (Clay et al. 2016; US Army Corps of Engineers 2015). Future storm risk management systems will likely benefit from government efforts to communicate the long-term risk of living along New York's coasts, and should pursue a better balance and interconnectedness among natural, social, and built systems (National Research Council 2014; Mcdonnell et al. 2016; Wagner et al. 2016).

3.4. TRENDS WITHIN CASE STUDIES

The preparation and response strategies used by US cities and institutions in these case studies evolved considerably to respond to disasters throughout these three case studies. USACE, FEMA, NOAA, and other federal institutions all show evidence of critically revising their internal administration, developing new planning frameworks adjusting decision-making procedures (Department of Homeland Security 2016). It is more difficult to draw conclusions about state and local authorities in each of the cases, but New York officials seem to have been mindful of the lessons of Hurricane Katrina as they implemented evacuation orders before the arrival of Hurricane Sandy in 2012 (Gibbs & Holloway 2013). Overall, low-level systems administration improved from 2005-2012, while higher-level interagency efforts and political involvement in the storm preparation/response process do not seem to show significant improvement. This section identifies five broad trends – two positive and three negative – and will discuss each in turn.

Positive:

- Low-level engineering failures (i.e. failure of individual levees during the 2005 flooding of New Orleans) have become more uncommon.
- Individual responses to government evacuation orders and disaster response plans, as well as government execution of disaster response/recovery plans, have become more effective since 2005.

Negative:

- Interagency communication and coordination of preparatory and capacity-building efforts are still inefficient and often problematic.
- Engineering institutions, in concert with state and local governments, need to convey pre-disaster risk more effectively.
- Government institutions still resist operating with a proactive, preparation-focused mindset, instead relying on recovery stimulus funds.

Reduction in low-level engineering failures:

Hurricane Katrina was a shock to every level of disaster preparation and recovery in the US: to federal administrations and planning frameworks, to state-level authorities, and to the local communities and immediate physical infrastructure that bore the damage of the hurricane itself. However, its most glaring shortcomings existed in the streets – failed and overtopped levees and floodgates that had experienced water levels seemingly within their design parameters. Shoddy construction and maintenance standards set the conditions for these low-level engineering failures that in turn caused cascading failures in systems lacking redundancy and resilience (Guiney 2006; Rogers et al. 2015).

Hurricane Ike exhibited significant improvements over the standard set by Hurricane Katrina in infrastructure system resilience. Ike's significant storm surge flooded large portions of the barrier islands near Galveston, but federally-maintained levees and floodgates did not overtop or fail, protecting critical shipping infrastructure in Galveston Bay (Rego & Li 2010; Tirpak 2009). Hurricane Sandy in 2012 involved some examples of engineering infrastructure failure, but only after those systems had exceeded their service levels – indicating shortcomings in design capacity and funding allocation rather than in construction or maintenance of the systems (US Army Corps of Engineers 2015; US Army Corps of Engineers 2013; National Weather Service 2012).

Increased efficacy of evacuation and response plans:

On-paper evacuation rates within New Orleans during the Hurricane Katrina response were high – 80% on average across the zones with evacuation orders. However, a significant portion of the most vulnerable portions of the New Orleans population remained in catastrophically flooded portions of the city. The city's Hurricane Protection System failed, exposing the lack of a comprehensive flood response plan as relief convoys slowed to a trickle due to the lack of serviceable overland routes into the city (Guiney 2006)

By Hurricane Ike in 2008, FEMA had amended its evacuation and response protocols, working closely with USACE and local government organisations to support more evacuees and lead a more effective flood response. The changes were not perfect; FEMA still drew criticism for its longer-term evacuee support, but its initial population relief and distribution of emergency supplies was much more effective than its response during Katrina – perhaps due in part to closer coordination with USACE and more resilient local infrastructure (Colley 2008; Tirpak 2009). FEMA's response during Hurricane Sandy improved upon this mark; FEMA coordinated the evacuation from designated zones of New York, and close cooperation with local officials led to a successful evacuation (National Weather Service 2012; Department of Homeland Security 2016).

Inefficient interagency coordination and communication in preparation:

Although institutional responses became more efficient across the case studies, even Hurricane Sandy in 2012 exposed instances of miscommunication on project execution in the preparation phase before the storm's arrival. New York infrastructure projects funded by multiple cooperating institutions were mismanaged and left incomplete, and those projects that did secure funding did not necessarily reflect the construction priorities of expert organisations (US Army Corps of Engineers 2015). Similar examples exist in Katrina and Ike, especially between different levels of government. Poor coordination between federal agencies and local government confused storm preparation in Katrina, while Ike involved significant tension between FEMA and the state government in Texas (Andersen et al. 2007; Tirpak 2009; Berg 2009).

Some of the institutions highlighted in Table 3 – particularly USACE and FEMA – showed evidence of becoming more transparent in their self-evaluation and more willing to admit and identify their own faults. However, resolutions that depended on resource-sharing and closer cooperation in long-term storm preparation generally met friction in their execution. USACE, for instance, revised its engineering priorities after Katrina and has since advocated for increased use of nature-based coastal protection measures. These projects – whether by virtue of Congressional budget priorities or inability by USACE to present a compelling budgetary request – generally fail to achieve much funding (Bridges et al. 2015; US Army Corps of Engineers 2015).

Ineffective communication of long-term risk to the public:

Sound infrastructure and response plans will help mitigate financial damage from major storms and floods, but that damage will always be a threat given human tendencies to settle in risky storm- and flood-prone coastal areas (Small & Nicholls 2003). Accordingly, risk – both in how it is assessed and in how it is subsequently communicated to and perceived by an at-risk populace – is crucial in a storm and flood preparation context (Berlemann 2016; Linnenluecke et al. 2011).

Katrina post-storm documents lament the public underappreciation of the true risk associated with Katrina-strength hurricanes (Baker 2014; U.S. House of Representatives 2006). These documents place significant blame on FEMA, USACE, and NOAA's National Weather Service for their communications to the public just prior to the storm's landfall, but accord less attention to the public perception of risk in the years before Katrina (US Army Corps of Engineers 2009). Significant portions of the New Orleans population lived in areas of extreme flood risk, perhaps deriving a sense of safety from the "Hurricane Protection System" that eventually failed to protect them (Guiney 2006; Mittal 2005; Wiener 2007; Fussell & Lowe 2014; Lein et al. 2012).

Hurricanes Ike and Sandy both expose similar stories in Galveston and New York City. Those storm events show a better acceptance of the risk that was communicated immediately prior to storm landfall in the form of higher evacuation rates, but still exhibit mass habitation in areas of extreme flood risk in the years prior to the storms. Local governments spent much of the relief and recovery funding from the federal government to rebuild homes and businesses in similarly at-risk locations (Colley 2008; Special Initiative for Rebuilding and Resiliency 2013). This suggests a deeper need to convey long-term storm and flood risk more appropriately – to reduce the mass destruction of storm and flood events by encouraging local officials to think more deeply about city planning consequences (Imperiale & Vanclay 2016).

Prevalence of reactive policy mindset:

Each of the preceding trends, whether positive or negative, show greater focus by government institutions and by the public on *reaction* to storm and flood events rather than *proactive* capacity-building. Society cannot predict storms and flooding on a case-by-case basis, but modern storm predictions and risk analysis can give a highly accurate sense of which cities and areas at the most risk. Ideally, public institutions would respond to those prediction with proactive investment in mitigation infrastructure and response systems; investment before a storm is far more effective and efficient than recovery funding after the event (Ripley 2006; Sadowski & Sutter 2008; Reiman & Rollenhagen 2011). Identifying the basis for this trend, as well as the political, social, and environmental factors that create and sustain it, will form the basis for Section 4.2 of this study.

Concluding notes:

In all, the cases discussed here show a progressive shift from explicit, small-scale engineering failures towards more pervasive but subtle failures of larger administrative and political systems. Solutions involving "simple" science and engineering, the specialty of organisations like USACE and NOAA, cannot tackle current deficiencies in US responses to major storms and urban flooding. Details within these cases show that executive agencies (USACE, NOAA, FEMA, and others) can be on-message and wholly correct in their risk assessments, but limited in their institutional efficacy by poor communication and inefficiencies elsewhere in the nation's large-scale coastal management (Bridges et al. 2013).

Funding and political circumstances may bias the identification of these trends, particularly the positive ones. New York City has a local infrastructure development budget dwarfing that of New Orleans, and New York's impressive response to Hurricane Sandy might simply indicate greater budgetary and construction capabilities rather than positive change in higher-order hurricane preparation and flood response (Goldstein et al. 2014; Guiney 2006; National Weather Service 2012). However, independent federal agencies – primarily USACE and FEMA – played key roles in infrastructure management and zoning administration in all three cases, increasing the likelihood that the differences across the cases indicate higher-order reform rather than just differences in city resources (US Army Corps of Engineers 2015; Andersen et al. 2007; Department of Homeland Security 2013b). Discussion of these and other cities in Section 4.1 will lend further support to this assertion.

4. DISCUSSION

The historic hurricane cases and the trends across them point to the importance of constant re-evaluation of US storm preparation and flood mitigation and management systems. US public institutions must continuously re-evaluate these systems against historic events and new academic developments. A single system might seem perfectly adequate after one storm or flood event, only to undergo catastrophic failure in the next event because of myopic design consideration, poor management and maintenance, or simply sloppy communication (Guiney 2006).

This discussion section will examine current planning efforts in four cities – both with and without recent exposure to storm and flood events – before examining the complexities of US coastal management and city planning systems. These systems involve many of the infrastructure projects discussed in the case studies, but also include additional degrees of political, social, and environmental complexity (Department of Homeland Security 2013b). As will be shown, the reactive components of the US political cycle and bias inherent in human risk evaluation complicate ongoing efforts to develop urban storm and flood resilience (US Army Corps of Engineers 2015). The discussion will also introduce projections from climate change and differences in the future nature of major storms before concluding with an identification of potential leverage points that could enable greater efficiency within this complex system (Meadows 1999).

4.1. CURRENT TRENDS IN CITY PLANNING

The lessons from the major case studies, as well as the trends across those cases, provide a valuable body of knowledge for future city planning and disaster administration efforts in the US. Despite this, urban populations – especially those that have not experienced a recent major storm – often react with surprise when a major storm makes landfall (Reiman & Rollenhagen 2011). Is this simply the result of a short collective memory or does it point to deeper problems in institutional mindset within US public institutions? Current city planning should provide some indication of the source of this reactionary ideology. Specifically, planning policies should reflect the integration of knowledge from previous storms, showing the diffusion of those lessons even to different cities across the country (Ripley 2006).

Current city planning efforts in the following urban areas – New Orleans, New York, Miami, and Boston – contain a mixture of recognition, adoption, and even neglect of the lessons from previous storms. This suggests that the adoption and implementation of resilient planning policies is dependent not just on previous impacts by major storms, but also on the long-term economic and cultural aims of the city and its local planning officials (Bridges et al. 2013; Sadowski & Sutter 2008).

4.1.1. New Orleans

After Hurricane Katrina's destructive 2005 impact, the city of New Orleans leveraged federal relief funds to plan and conduct long-term revisions to its local storm and flood risk management policies. Its "Hurricane Protection System" became a "Storm Damage Risk Reduction System" and efforts to communicate everyday risk of severe storm and flood loss to its residents seemed to increase (Yarnal 2007; US Army Corps of Engineers 2009; Mittal 2005).

Yet these updated systems and policies seem to distract from a basic acknowledgement of the more fundamental problems in New Orleans: canalisation of the Mississippi River, decreased sediment deposition within its Delta, severe subsidence of urban areas, and widespread reluctance to implement more environmentally conscious risk mitigation efforts (Ripley 2006; Wamsley et al. 2013; Wiener 2007). Just as local New York management policies integrate the lessons of Hurricane Katrina, it seems that New Orleans must synthesise lessons from more modern major storms to confront the engineering reality of its urban existence.

4.1.2. New York City

Hurricane Sandy and its associated federal recovery funding spurred a massive increase in the momentum of development in storm preparation and flood mitigation infrastructure in New York City – likely due in part to the perception of New York being relatively safe from major hurricane damage before Sandy's landfall (US Army Corps of Engineers 2015). Immediate recovery efforts were extensive and new projects designed following the initial recovery period (2012-2014) have largely secured funding and local approval. "The Dryline," which broke ground in 2015, proposed the creation of a protective ribbon of public space along the south edge of Manhattan. Contrary to the suggestion of its name, the Dryline is designed as a blue-green infrastructure system compatible with managed exceedance flooding from storm surges (Lafarge Holcim Foundation 2016; Demuzere et al. 2014; Lawson et al. 2014). Similar coastal protection and infrastructure rejuvenation projects are beginning construction in other parts of the city (Hu 2016; Goldstein et al. 2014)

These new projects risk distracting attention from New York's aging stormwater and transportation management policy and practices. The Metropolitan Transit Authority (MTA), responsible for the maintenance of roadways and train lines in the city, continues to face budgetary shortages preventing critical missions (Metropolitan Transit Authority 2013). Elsewhere, current guidelines for construction of stormwater management systems are limited in their ability to be adapted into a larger urban green infrastructure system (NYC Department of Environmental Protection 2012; NYC Emergency Management 2015; Hoang & Fenner 2015). New York City as a whole seems to be on the right track in its commitment to change, but needs to remain aware of traditional investment areas that might be neglected in this process.

4.1.3. Miami

Miami rates among the most vulnerable US cities to hurricane-induced storm surge. Unlike New Orleans, this is not due to its coastal geography; Miami's relatively steep coastal shelf does not create favourable conditions for either an intense or lasting storm surge (South Florida Water Management District 2016). Miami's vulnerability stems from its unprecedented real estate investment and development in high-risk areas directly adjacent to the coast. Hurricane financial effects models estimate up to $80 billion in immediate property damage to Miami if hit directly by a major hurricane (Karen Clark & Company 2015; Pinelli et al. 2008).

Despite its vulnerable geographic position, Miami has not been struck by a major hurricane since the landfall of Hurricane Andrew (Category 5) in 1992. Andrew, as well as other hurricane impacts across the state, led to the implementation of relatively strict state-level buildings codes, local attitudes toward hurricane risk management in Miami have relaxed in the past decade (South Florida Water Management District 2016; Abtew & Iricanin 2008; Ripley 2006). Oceanfront development continues to accelerate and creep into areas of progressively higher risk, negating benefits from Miami's forgiving coastal morphology and perhaps confirming the notion that city-specific change is directly linked to recent disasters (City of North Miami Beach 2015; Sadowski & Sutter 2008).

4.1.4. Boston

Boston is generally considered a low-risk location for major hurricane impacts – not unlike New York City prior to the destruction caused by Hurricane Sandy in 2012. Is Boston also vulnerable to "surprise" by a storm and storm surge of Sandy's magnitude? Like Sandy in New York City, a similarly-sized storm could cause huge impressive financial damage in Boston; Boston has large amounts of waterfront construction and investment, and a significant number of its homes and businesses are considered by FEMA to be at high risk of flooding in a major storm event (Fernandes 2013; FloodSmart 2016; Hallegatte et al. 2013).

Sandy skirted through New England in 2012 after its landfall in New Jersey, and that brief impact may have been enough to jumpstart planning efforts in the Boston area (US Army Corps of Engineers 2015). Boston boasts a variety of well-researched and forward-thinking conceptual frameworks for coastal land management and flood mitigation, yet these frameworks rarely translate into local policy or investment. Instead, these and other planning documents from the city seem content to spread awareness of flood risk through case studies and pamphlets (Massachusetts Office of Coastal Zone Management 2008a; Massachusetts Office of Coastal Zone Management 2008b; Massachusetts Office of Coastal Zone Management 2008d). City planning officials even continue to resist federal changes in flood insurance premiums when FEMA updates its flood risk maps (Fernandes 2013; Massachusetts Office of Coastal Zone Management 2008c). Like Miami, it seems that Boston draws some sense of risk from hurricane damage, but not a sufficient level of risk to spur increased investment in city-wide storm preparation and flood management projects.

4.2. A LARGER SYSTEM AND ITS BARRIERS

It is abundantly clear from the cases and from current city planning that hurricane preparation, flood mitigation, and management efforts in the US exist within a much larger system. USACE often seems tempted to confine its analysis to an engineering and environmental reality, while NOAA relegates itself to scientific investigation and FEMA struggles to extricate itself from political mires. This organisational specialisation is sometimes helpful, but it also distracts from the operation of the larger system. Trends within the case studies corroborate this, showing the decline in low-level failures but the continued importance of managing high-level institutional relationships. Though tempted by their individual foci, these organisations and must contextualise their roles within a larger geopolitical system in order to serve their constituents effectively.

Most of the institutions within the US that have specified roles in high-level hurricane preparation and flood response (e.g. USACE, FEMA, NOAA) are federal-level organisations falling under the administration and direction of the executive branch of government – the Presidential cabinet secretaries. These so-called executive agencies each have independent missions, yet are funded by the US Congress in the annual Congressional budget. While an executive agency usually has an independent discretionary portion of its annual budget, Congressional appropriations often dictate exactly what that funding will be spent to research or build. If the US Congress wishes to dam a river, it appropriates funding to the USACE for that specific project and USACE is obliged to plan and execute the project. Those agencies are responsible for maintaining the project following construction, but often need to seek continual budgetary support from Congress in order to do so (Government Accountability Office 2016; 113th US Congress 2013; Department of the Interior 2014).

Although they do submit annual budget requests, executive agencies usually cannot execute projects without specific funding appropriations, and so are often at the administrative mercy of the US House of Representatives and Senate (US Army Corps of Engineers 2015). This top-down development-driven policy process was the hallmark of the rapid expansion into and development of the American West, and is only now slowly yielding to other forms of policy creation (Reisner 1986).

Social and environmental realities complicate efforts to change this system; it is immensely difficult to align political, social, and environmental incentives in a way that minimises total risk and loss in storm events. As a single example, individual responses to a major storm (in the form of voting and lobbying) are enormously powerful within the current political system. There is little reason for constituents to amend this system it in favour of one with less emphasis on constituent representation or with increased risk conveyance through "hard" measures like higher flood insurance premiums (Charpentier & Le Maux 2014; Bagstad et al. 2007; Sadowski & Sutter 2008). Leverage points may exist to change institutional paradigms, but will require greatly increased communication and coordination among all members of this complex system.

4.2.1. Political Complexity

As mentioned in previous sections, current hurricane preparation and flood management policy seems to be largely reactive – only ever scrutinised or updated following a major weather event in a city or region. This is likely due in part to the appropriations relationship between executive agencies and Congress. The US Congress operates on a short and volatile political cycle; full re-election of the US House of Representatives occurs every two years. Accordingly, Congress responds most immediately to regions and constituent bodies recently struck by crises. Response comes in the form of funding and appropriations to executive agencies, which in turn conduct their assigned projects in the affected areas. Congressional funding – an amount limited every year by the political bargaining process – is spent disproportionately in areas with recent crises. Figure 4 shows a large-scale representation of this relationship and a Congressional funding response limited to a single geopolitical area.

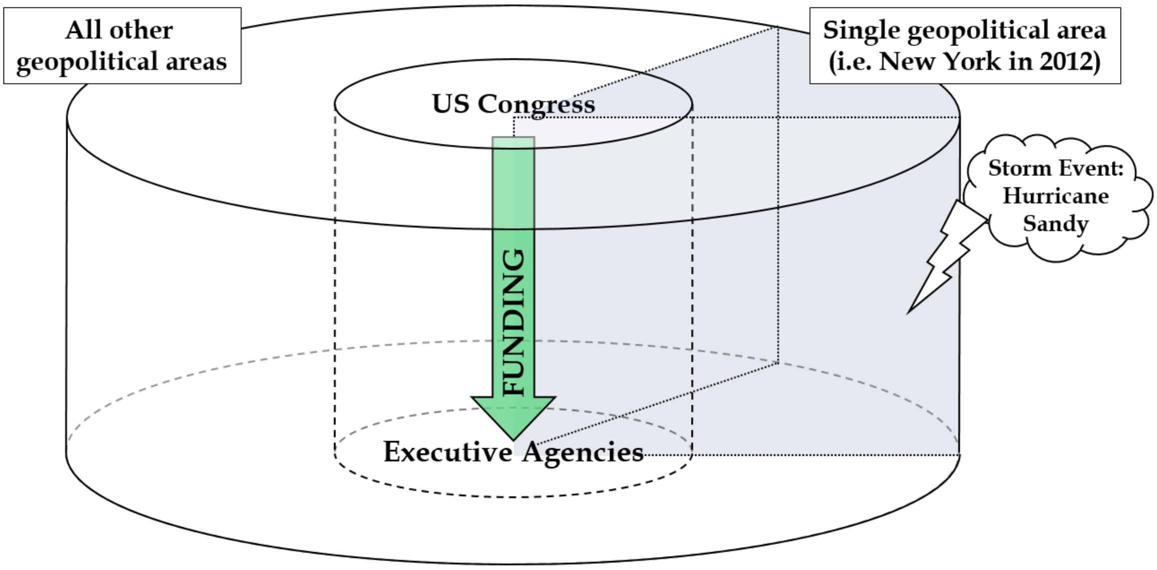


Figure 4: Congressional funding used to react to region-specific events

While this large-scale view is helpful to appreciate the generally reactive nature of Congressional spending, it is more useful to express this relationship as a reactive cycle involving Congress, executive agencies, agency projects and plans, and a regional body of constituents. If a storm event disrupts a regional subset of constituents (apparent as constituent protestations to their Congressional representatives), Congress reacts by initiating projects in that area, shown in a generalised form in Figure 5.

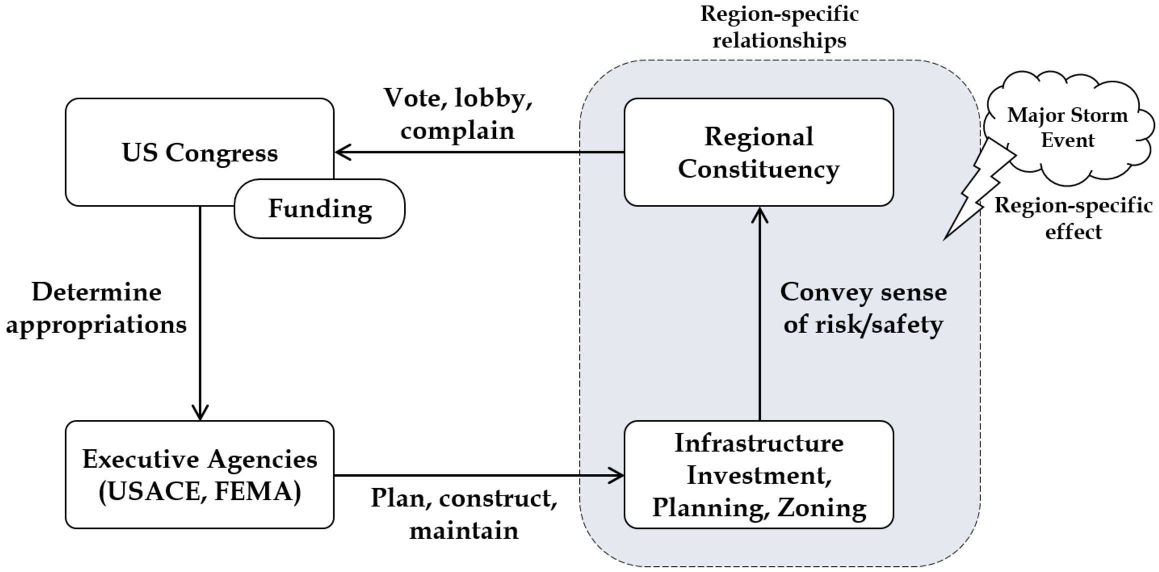


Figure 5: Cyclical funding relationships motivated by region-specific events

This cycle works in some instances, but is hugely inefficient in most areas of the US. American cities often do not have the necessary infrastructure and planning frameworks until after they are needed and executive agencies are not able to plan new projects before a catastrophic event.

The conventional response to this problem has involved the creation of specialised organisations with unique knowledge in a given field. Executive agencies periodically create new organisations within their own structure, hoping to leverage additional expertise from those organisations into more effective policy creation and implementation. These specialised organisations sometimes succeed (NOAA’s National Hurricane Center is highly trusted in its unique research and predictions) but more often creates excessive and unnecessary redundancies across all executive agencies, stretching a strained Congressional budget even further(U.S. House of Representatives 2006; 113th US Congress 2013; Department of the Interior 2013).

This problem is common across all issues addressed by the federal government in the US, but is particularly dire with respect to storm and flood infrastructure because the US does not have a comprehensive water resource management plan or a single agency in charge of water management (US Army Corps of Engineers 2015; Department of Homeland Security 2013b). Other world governments often concentrate responsibility for water resource management within a minimal number of agencies; the UK government's Environment Agency cooperates closely with the Scottish Environment Protection Agency in order to minimise redundancies (UK Environment Agency 2016; Forbes et al. 2015)

In the US, water resource management in disaster situations (i.e. after hurricanes and storm flooding) is notionally managed by FEMA's National Planning Framework, developed under the Department of Homeland Security. This framework contains subsidiary planning framework designed to address the various stages of a disaster:

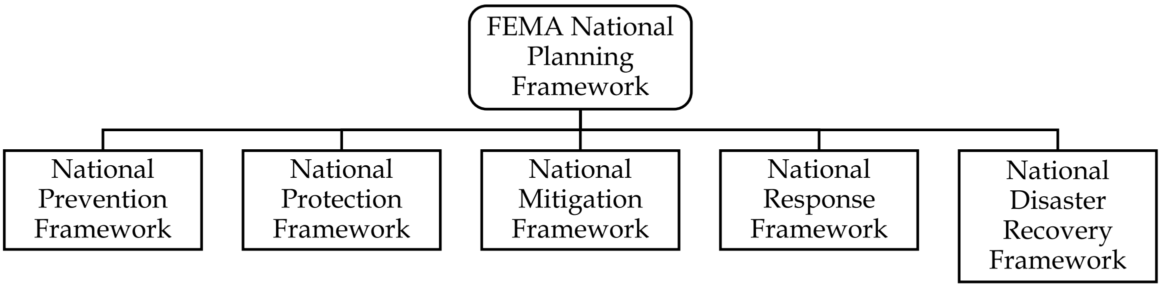


Figure 6: FEMA's National Planning Framework (Department of Homeland Security 2013b)

On the surface, this National Planning Framework looks as though it would be suitable for use before and after a significant natural disaster. Yet while FEMA has revised much of its internal organisation since its criticism following Hurricane Katrina, it still seems somewhat hampered both by its organisational mindset and by the structure of this planning framework. FEMA was created in 1978 to administer federal response to natural disasters, yet was reorganised into the Department of Homeland Security in 2003 (Executive Order 12127 1979; 107th Congress 2002). This reorganisation fundamentally changed the mission of FEMA, diverting a large portion of its resources to counter-terrorism and requiring a complete rewriting of its planning frameworks. The subsidiary planning frameworks in Figure 6 now focus most of FEMA's internal resources on terrorism mitigation, requiring FEMA to divide disaster management responsibility among itself and other executive agencies (Department of Homeland Security 2013b; Department of Homeland Security 2016).

This division of missions within FEMA has intensified the diffusion of water resource management and disaster preparation/response among a wide variety of various federal agencies, complicating their ability to work cooperatively during before and after disaster situations. Since there is not a central executive agency in charge of water resource management, these missions spread redundantly across multiple executive-level cabinet secretaries.

Table 4: Diffusion of water resource management responsibilities

Agency	*Selected missions related to water resource management*
FEMA (Dept. of Homeland Security)	• Leads natural disaster response efforts in a state of emergency • Models flood risk and establishes flood zone maps for use by states • Administers National Flood Insurance Program (NFIP)
USACE (Dept. of Defense)	• Plans, designs, and builds federal water resources infrastructure • Designs and builds hurricane and flood mitigation infrastructure in areas given Congressional mandates
NOAA (Dept. of Commerce)	• National Weather Service (NWS): Issues domestic weather warnings • National Ocean Service (NOS): Preserves/enhances domestic coasts • Office of Oceanic and Atmospheric Research (OAR): Researches long-term ocean/weather trends to understand atmospheric phenomena
Environmental Protection Agency (EPA)	• Office of Water (OW): Regulates water supply and treatment • Office of Land and Emergency Management (OLEM): Responds to waste sites created by natural disasters
Dept. of Agriculture	• Administers food banks, soup kitchens, and evacuee rations • National Water Management Center (NWMC): Models surface water hydrology, plans watershed-level projects
Dept. of the Interior	• WaterSMART Program: Advocates for water conservation • Bureau of Ocean Energy Management (BOEM): Responds to oceanfront disasters, special focus on sand resource management
(Department of Homeland Security 2013b; US Army Corps of Engineers 2015; National Weather Service 2012; Department of Agriculture 2016; Environmental Protection Agency 2016)	

Individually, it is common for these organisations to be “on message” with current best practice and academic discoveries in their areas of expertise. Yet the larger system of interdependent organisations described in this section is not on-message with respect to its funding and project selection structure. This structure hinders the analysis of new risk, limits the creation of new solutions and the maintenance of existing ones, and complicates the crucial process of cooperation across various levels and aspects of government. In all, political complexity supports a storm preparation and flood response system comprised of organisations with redundant missions and defined by a lack of proactive ideology.

4.2.2. Social Factors

The human factor introduced at the beginning of this discussion – individual response to major storm events and subsequent interaction with legislators – underscores the importance of social issues in storm defence engineering. A single individual's response to a storm can dictate whether an engineering project secures funding and proceeds. Clearly, engineers, scientists, and politicians must strive to understand this all-important human reality (Hernandez 2013; Hu 2016).

In the case of a major storm, the social factor is inseparable from an individual's sense of safety and security before, during, and after a storm. The causal loop diagram shown in Figure 7 illustrates personal sense of safety as the central tenet in the cycle of Congressional investment in infrastructure.

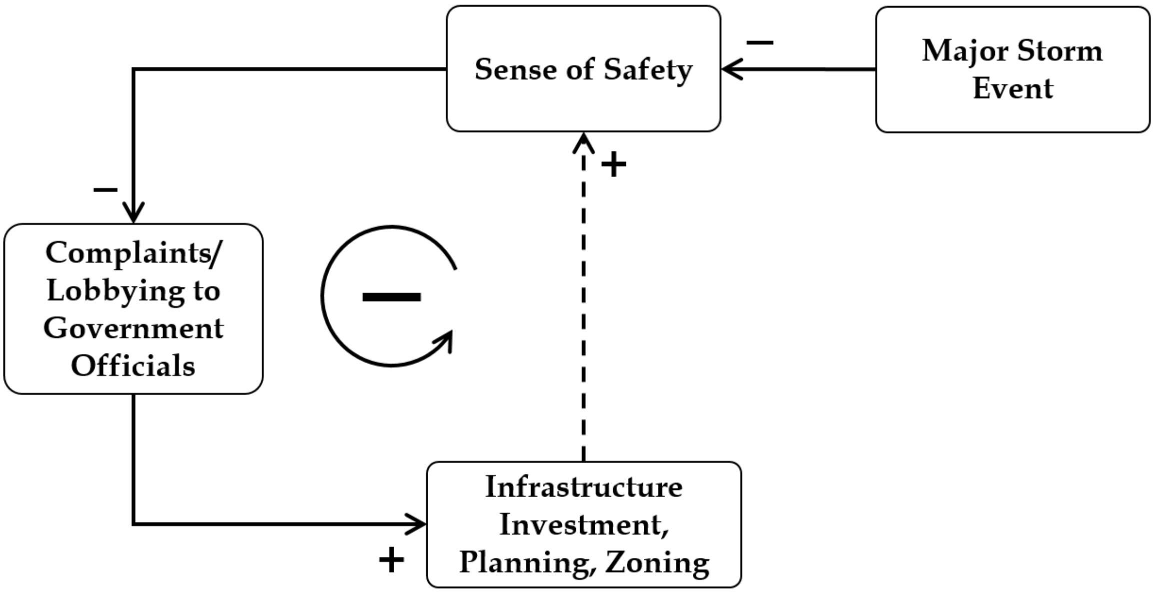


Figure 7: Causal loop diagram representation of individual safety

A population, passively drawing a weak but positive sense of safety from any ongoing infrastructure investment, has that sense of safety tested and often drastically eroded following a major storm event. All three case studies align with this model, though Hurricane Katrina is undoubtedly the most extreme example. The population of New Orleans had internalised a sense of safety from the numerous levees comprising the Hurricane Protection System, yet the effects of Katrina and the ensuing flooding and system failure deeply challenged that sense (Mittal 2005; Ripley 2006; Shane & Lipton 2005).

A decrease in personal sense of safety spurs an uptick in complaints and lobbying to legislators, which in turn (based on the reactive political system discussed in Sections 4.2 and 4.2.1) increases infrastructure investment and planning effort in affected communities. This final cause/effect relationship creates a negative feedback loop that seeks equilibrium according to the influence of a single external factor – the presence of destructive major storms. Reactionary investment and risk perception is engrained within the very structure of this loop. Where best, then, to attempt to influence the relationships in order to optimise investment and engineering efforts?

In the model in Figure 7, the loop stagnates if major storm influences disappear. This is not unlike the modern-day case of Miami and South Florida. As discussed in Section 4.1.3, Miami has not been struck by a major storm since Hurricane Andrew in 1992, and its city planning policies reflect a steadily-increasing sense of laxity and implied safety in the continued absence of major storms (Purdum 2002; South Florida Water Management District 2016). This implies that a singular external factor overly simplifies this loop.

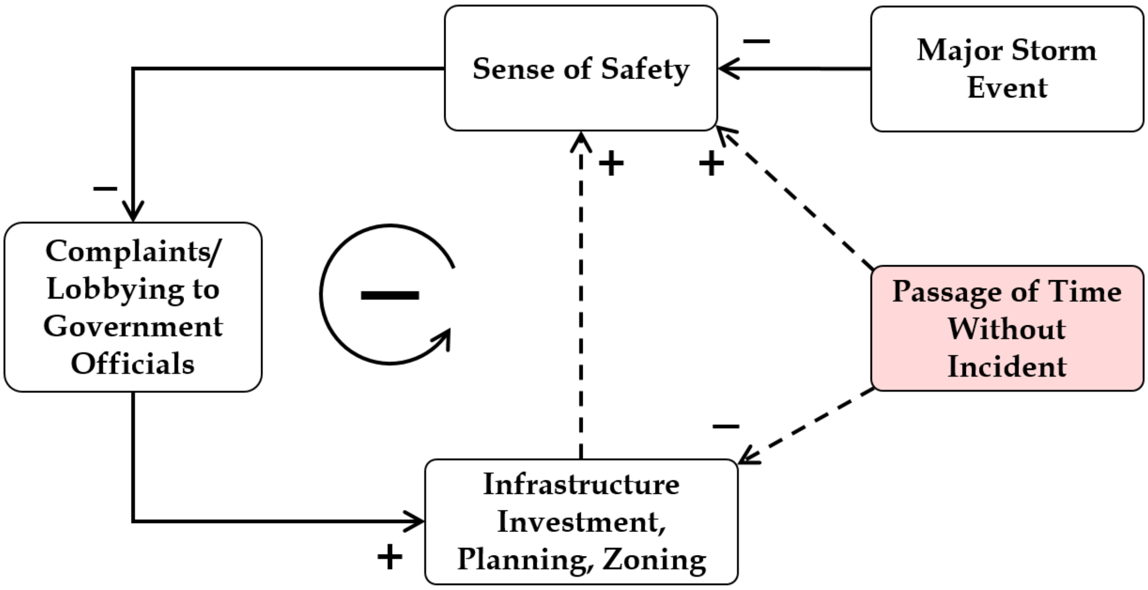


Figure 8: Revised causal loop diagram introducing the passage of time

In reality, it is not just the incidence of a major storm or flood event that affects personal sense of safety, but also the inverse – the passage of time without incident. Human fallacies and short-sightedness create confirmation bias in the continued absence of catastrophic events over a long timeframe (Reiman & Rollenhagen 2011; Berlemann 2016). An individual living near a levee or seawall might derive an internal sense of safety from that hard infrastructure, even if the infrastructure is not maintained or is not well-integrated in a local planning framework (Harrison & Williams 2016; Yarnal 2007).

Risk evaluation and communication processes provide two means of addressing these issues: "soft" methods in the form of more accurate and compelling communication of risk and "hard" methods in the form of politically-enforced adjustment of factors like zoning regulations, building codes, and flood insurance premiums (Bagstad et al. 2007).

More compelling communication of risk is often the responsibility of local government, but federal agencies can influence this process. As a single example, the scale used to classify hurricanes may be limiting the ability of NOAA and local officials to communicate the appropriate amount of hurricane risk to a threatened population. The Saffir-Simpson Hurricane Wind Scale was designed as a means of providing a concise classification system for meteorologists, yet it sees widespread use as an indicator of hurricane threat to the public. Hurricane Katrina (Category 3) and Hurricane Ike (Category 2) both created greater storm surges and wrought more damage than Hurricane Andrew (Category 5, impacting Miami) in 1992. Despite this, NOAA, the National Weather Service, and local meteorologists often disseminate a hurricane's category before any other information in conveyed. Alternative hurricane categorisation systems exist and are better able to describe the danger posed by winds and storm surge, but none have yet been adopted by the National Hurricane Center (Kantha 2013; National Climatic Data Center 2005; Berg 2009).

"Hard" methods of risk communication are more politically volatile, involving the careful adjustment of taxes, subsidies, and insurance in search of an economically-optimal balance between coastal development and storm risk mitigation (Charpentier & Le Maux 2014; Bagstad et al. 2007). As discussed in Section 4.1, the administration of building codes and zoning regulations is often the exclusive purview of state and local governments. Local governments are often reluctant to implement harsher building codes and zoning requirements due to the short-term economic benefits of lax regulations; changing this dynamic might require creation of unpopular new procedures and laws by the federal government. FEMA has a unique capability here to adjust its Flood Risk Maps and the associated insurance rates for those risk zones under the National Flood Insurance Program, which may be an effective avenue for positive change – especially for business entities more capable of detaching personal bias from their economically-driven business decisions (Pompe & Rinehart 2008; Kunreuther & Michel-Kerjan 2014; FloodSmart 2016).

Human bias and perception of risk complicates the already-nightmarish political environment of storm and flood risk mitigation. Understanding risk evaluation, communication, and internalisation is vital in identifying ways to optimise American coastal management policies. Future solutions will likely require the combination of “soft” solutions – more effective risk communication – with “hard” solutions: adjustment of taxes, subsidies, and insurance rates.

4.2.3. Environmental Features

Like the slow pace of change in the political and social components of the US storm preparation and flood mitigation system, the uptake of natural and nature-based features (NNBFs) in infrastructure systems has been slow. This is likely due to political influence on the development of coastal management systems more than any other factor. The funding and appropriations relationships between Congress and executive agencies discussed in Section 4.2.1 often result in engineering projects dictated by political rather than scientific considerations, misaligning incentives and impeding creation of comprehensive storm and flood mitigation systems (Bridges et al. 2013; Meerow et al. 2016).

NNBF measures like artificial wetlands, living shorelines, and overwash fans can never prevent the most severe effects of catastrophic storms and floods, but can help buffer and mitigate short-term damages while easing the post-disaster transition into recovery (US Army Corps of Engineers 2015; Bridges et al. 2015). This makes them a crucial component of a comprehensive storm preparation and flood mitigation systems – filling the voids in antiquated systems like the 2005 New Orleans Hurricane Protection System (US Army Corps of Engineers 2009; US Army Corps of Engineers 2013). Yet despite these benefits, environmentally-sound projects like NNBFs and the creation of blue-green infrastructure in urban areas often receive less funding than more conventional "grey" infrastructure solutions, perhaps due in part to the greater sense of personal security derived from conventional building methods (Demuzere et al. 2014; Lawson et al. 2014; Wamsley et al. 2013; Reiman & Rollenhagen 2011).

Expert institutions like USACE, NOAA, and FEMA publish regular reports encouraging the design and construction of NNBF-type projects, but face political resistance in funding acquisition for those projects (Bridges et al. 2013). Responsibility for this shortcoming must be split among all parties, underscoring the importance of system-wide leverage points that can increase political willingness to fund NNBF-type projects while simultaneously increasing the public sense of safety derived from those projects.

4.3. CLIMATE CHANGE IMPACTS

Climate change projections – both from "popular science" sources and from academic investigation – often point to a future of larger and more frequent severe weather events. Warming oceans and increased incidence of highly-destructive storms are often used to conclude that storms are growing "stronger" (Voiland 2013; Nature Conservancy 2016). The underlying message in these statements is instructive and should be heeded; cities should make additional preparations for severe storms and flood events. However, this does not adequately convey the difficult task of linking established climate change trends to storm frequency and intensity projections.

The ambiguity of hurricane "strength" provides the first complication. Depending on the source, storm "strength" is variously conflated as Saffir-Simpson category, physical storm size, total rainfall, minimum pressure, sustained wind speed, maximum storm surge, induced flooding, financial damage, or associated fatalities (Chylek & Lesins 2008; Voiland 2013). Understandably, "strength" is a term generally avoided by NOAA and other climactic agencies when predicting future storm trends. These organisations instead prefer to analyse storm formation rates and intensity as a function of sustained wind speed (Goldenberg et al. 2001).

The short historical data record for hurricanes is the key limiting factor in these predictions. Unlike the lengthy geologic records used to predict high-level climate change trends and global temperature change, comprehensive records of Atlantic hurricanes exist only for the past several decades, supplemented by anecdotal accounts before then (Chylek & Lesins 2008). Multi-decade ocean temperature shifts and weather cycles (particularly El Niño and La Niña) also have significant impact on hurricanes, further complicating efforts to identify how global climate change affects storm frequency and intensity (Goldenberg et al. 2001; Bell 2014).

While it is true that hurricanes have increased in average financial damage over the past several decades, this cost increase is likely more closely linked with ongoing population shift to coastal cities. Rapid coastal development and investment that creates more financially-massive targets for major storms (Karen Clark & Company 2015; US Census Bureau 2015). NOAA does acknowledge increased *frequencies* of tropical cyclone formation in the Atlantic from 1995-2012, but attributes this to a periodic multi-decadal storm cycle (the Atlantic Multidecadal Mode, AMM) rather than specific climate change effects (National Climatic Data Center 2005; Chylek & Lesins 2008). The AMM results from slowly-shifting, decades-long variations in seawater temperature in the portions of the Atlantic Ocean responsible for storm formation. Importantly, this cycle does not yet seem to correlate with the eventual intensity of those storms or the number of major hurricanes that make landfall in the US during a hurricane season (National Climatic Data Center 2005). This could change as NOAA continues to amass more data on hurricane formation throughout each season.

Even despite uncertain projections of storm frequency and intensity, both NOAA and USACE identify rising sea levels as the most pressing cause for concern in relation to the effects of future storms. The characteristics of the actual storms making landfall may be difficult to predict for the next century, but increased sea levels will magnify the effects of all storm surges (Hallegatte et al. 2013). USACE projections for the New York metropolitan area anticipate 100-year return period storm surge increases of more than 4 meters in the next century, significantly threatening areas of rapid development along New York and New Jersey coastlines (Maloney & Preston 2014; Nadal-Caraballo & Melby 2015).

The city planning preparations discussed in the preceding section largely ignore the projected impacts of climate change. These sea level rise projections have been anticipated and described in academia for at least two decades, but city planning and zoning regulations still lag in their acknowledgement and incorporation of those projections (Klein & Nicholls 1999; Nicholls 1995). Boston, for example, has published documents acknowledging sea level rise projections, but seeks only to aid in "understanding" those projections rather than synthesizing them into actionable changes in city planning efforts (Massachusetts Office of Coastal Zone Management 2013). Similarly, 35-year projections for the city of New Orleans forecast a potential loss of 1.21% of the city's GDP in simulation of storm effects based purely on socioeconomic factors. That GDP loss increases to 1.42% when sea level rise and city subsidence are included – factors unaccounted for in current city planning efforts (Hallegatte et al. 2013). There is still uncertainty surrounding the ways these storms will change in the future, but cities must begin planning for the increased storm surge magnitude unilaterally predicted by current sea level rise projections (Linnenluecke et al. 2011).

4.4. POTENTIAL SYSTEM LEVERAGE POINTS

The system described in this section – complex though it is – does seem to contain several potential leverage points that would support system-wide revisions to US coastal management policies (Meadows 1999). However, it is difficult to quantify the degree to which the use of a single leverage point would be effective. Wide differences in state and local decision-making and planning policies among US cities vulnerable to hurricane-induced flooding complicate any specific calculations of effects. These general suggestions would provide a good basis for a close examination of specific system dynamics in any city discussed in this report.

Weaken the link between Congressional budgeting and agency projects:

A weaker relationship between the fickle nature of Congressional budgeting and the funded projects of US executive agencies could manifest as a reduction in the percentage of executive agency budgets that is non-discretionary. While this is politically optimistic, it would enable greater discretion by agencies like USACE and NOAA to select missions and projects that align with their own expert knowledge, while also decreasing political bias on the selection of engineering projects (U.S. House of Representatives 2006; US Army Corps of Engineers 2015; Andersen et al. 2007).

Decrease executive agency redundancies to reduce necessary funds.

The redundant water resources management roles described in Table 4 point to inefficiencies and redundancies in the funding for those organisations. A reduction in the overlap of agency roles could reduce budget requirements for storm preparation and flood management (making the first leverage point more politically viable) while also allowing for increased specialisation in a streamlined set of agency roles and reducing confusion in interagency coordination (Department of Homeland Security 2013b; Department of the Interior 2014; Department of the Interior 2013).

Divorce personal sense of safety from passage of time without a crisis:

As discussed in Section 4.2.2, human bias in risk assessment leads to a developed sense of safety in the continued absence of a major disaster event. Better "soft" communication of long-term passive risk to individuals living in zone of high flood risk could decrease the magnitude of damage associated with severe storms and flooding (Sadowski & Sutter 2008; Berlemann 2016). This could exist in the form of updated risk categories for hurricanes and more common discussion of at-risk flood zones in urban areas (Kantha 2013; FloodSmart 2016).

Introduce stricter building codes, zoning regulations, and insurance rates:

"Soft" communication of risk might be ineffective, necessitating the introduction of "hard" measures. Strict building codes, more stringent coastal and urban zoning regulations, and adjustments to storm and flood insurance premiums all introduce an economic factor that could affect an individual's or business's behaviour (Charpentier & Le Maux 2014; Bagstad et al. 2007; Pompe & Rinehart 2008). However, these measures must be balanced carefully to minimise negative externalities; increases in flood insurance premiums, for instance, might have a disproportionately severe negative impact on poorer portions of a population (Fussell & Lowe 2014; Lein et al. 2012).

5. CONCLUSIONS

This report investigated the key lessons in storm preparation and flood management practice from major Atlantic hurricanes of the twenty-first century. A review of at-risk coastal populations and flood risk management systems around the world created a basis for the study of urban storm response and flood management, but three major cases helped synthesise that literary foundation into a useful analysis of US policy and practice.

The cases described in Section 3 – Hurricane Katrina (2005), Hurricane Ike (2008), and Hurricane Sandy (2012) – indicated that storm response and flood risk management policies in coastal US cities largely underestimate the severity and infrastructure demands of major storm events, tending to ignore the high-level institutional lessons of past storms. Low-level engineering failures have decreased in frequency since Hurricane Katrina struck New Orleans, but all three cases pointed to a reactionary political and social system of investment in urban storm and flood management infrastructure.

A brief examination of current city planning policies in Section 4.1 highlighted the importance of constant risk assessment in systems riddled with human bias. A more comprehensive characterisation of federal political systems and public institutions in Section 4.2 showed structural barriers to change that continue to entrench a reactionary mindset within public institutions at all levels. Some individual institutions – specifically FEMA, USACE, and NOAA – proved to be "on message" with current best practice and are capable evaluators of urban flood risk, but remain hindered in their operation by misaligned political, social, and environmental incentives elsewhere in this system. Global climate change, particularly rising sea levels and their impact on storm surge magnitude, underscored the dire need for reform within this system.

Despite barriers within the system, several leverage points discussed in Section 4.4 suggest a potential for crucial system-wide reform. Politically, increased budgetary autonomy for the specialised public institutions described in Tables 3 and 4 would encourage the implementation of more proactive engineering projects based on continual risk assessment. A complementary reduction in redundant roles among these agencies would encourage useful specialisation and reduce interagency coordination problems and unnecessary budgeting. Introduction of risk communication and signalling methods – in both "soft" and "hard" forms – would help individuals and businesses internalise storm and flood risk, leading to better low-level decision-making in coastal communities.

These recommendations aside, the analysis presented here has some shortcomings. The case studies and discussion in this report adopted a federal scope in the examination of US storm preparation and flood mitigation systems. This scope carried throughout the report, and the discussion suggests generalised high-level recommendations for the nation and its at-risk cities. Many of these recommendations could not be analysed with any degree of specificity because of their additional dependence and state and local policies and practice. The US, a federal republic, conveys significant powers and planning authority to its states, limiting the usefulness of any federal-level recommendations.

Further studies could supplement this federal framework by conducting city-specific examinations of public policy and engineering efforts. Section 4.1 of this report offers several cursory discussions of current city planning efforts, but a full investigation of a single city would involve a systems model with specific attention to that city's state and local building codes, zoning regulations, and development priorities. Miami, for instance, might prove to be an especially compelling case given the amount of time since its last major hurricane landfall.

Finally, as mentioned in this report's discussion, the US still lacks a comprehensive and unifying framework for water resource management. Further research and investigation into the resource management systems of other countries would provide ample material for the suggestion of a new water resource management framework for the United States. Such a framework might require the wholescale dismantling and reorganisation of public institutions responsible for water management, but would help the US abandon reactive institutional ideologies in favour of a more forward-looking and sustainable national water policy.

6. REFERENCES

107th US Congress, 2002. *Public Law 107-296*, United States Congress. Available at: https://www.gpo.gov/fdsys/pkg/PLAW-107publ296/html/PLAW-107publ296.htm.

113th US Congress, 2013. *Disaster Relief Appropriations Act*, United States.

Abtew, W. & Iricanin, N., 2008. Hurricane effects on South Florida water management system: A case study of Hurricane Wilma of October 2005. *Journal of Spatial Hydrology*, 8(1), pp.1–21. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-56849114485&partnerID=40&md5=6776122cd6fdaa09c190bd229ce4d860.

Andersen, C.F. et al., 2007. *The New Orleans Hurricane Protection System: What Went Wrong and Why: A Report by the American Society of Civil Engineers Hurricane Katrina External Review Panel*, Available at: http://www.asce.org/uploadedFiles/Publications/ASCE_News/2009/04_April/ERPreport.pdf.

Atlantic Oceanographic & Meteorological Laboratory, 2016. Current Hurricane Data Sets. Available at: http://www.aoml.noaa.gov/hrd/data_sub/hurr.html.

Bagstad, K.J., Stapleton, K. & D'Agostino, J.R., 2007. Taxes, subsidies, and insurance as drivers of United States coastal development. *Ecological Economics*, 63(2), pp.285–298.

Baker, C.R., 2014. Breakdowns of accountability in the face of natural disasters: The case of Hurricane Katrina. *Critical Perspectives on Accounting*, 25(7), pp.620–632.

Ball, D.J., 2002. Environmental risk assessment and the intrusion of bias. *Environment International*, 28(6), pp.529–544.

Bell, G., 2014. Impacts of El Niño and La Niña on the hurricane season. *National Oceanic and Atmospheric Administration*. Available at: https://www.climate.gov/news-features/blogs/enso/impacts-el-ni%C3%B1o-and-la-ni%C3%B1a-hurricane-season.

Berg, R., 2009. *Tropical Cyclone Report: Hurricane Ike*, Available at: http://www.nhc.noaa.gov/data/tcr/AL092008_Ike.pdf.

Berlemann, M., 2016. Does hurricane risk affect individual well-being? Empirical evidence on the indirect effects of natural disasters. *Ecological Economics*, 124, pp.99–113.

Blake, E.S. et al., 2013. *Tropical Cyclone Report: Hurricane Sandy*, Available at: http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf.

Box, P., Thomalla, F. & Honert, R. Van Den, 2013. Flood risk in Australia: Whose responsibility is it, Anyway? *Water (Switzerland)*, 5(4), pp.1580–1597.

Bridges, T. et al., 2013. *Coastal Risk Reduction and Resilience: Using the Full Array of Measures*, Available at: http://www.corpsclimate.us/docs/USACE_Coastal_Risk_Reduction_final_CWTS_2013-3.pdf.

Bridges, T.S. et al., 2015. Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. *US Army Corps of Engineers - Engineer Research and Development Center*, (January), pp.1–447.

Brown, D.P. et al., 2010. Atlantic Hurricane Season of 2008. *Monthly Weather Review*, 138(5), pp.1975–2001. Available at: http://journals.ametsoc.org/doi/abs/10.1175/2009MWR3174.1.

Charpentier, A. & Le Maux, B., 2014. Natural catastrophe insurance: How should the government intervene? *Journal of Public Economics*, 115, pp.1–17.

Chylek, P. & Lesins, G., 2008. Multidecadal variability of Atlantic hurricane activity: 1851-2007. *Journal of Geophysical Research Atmospheres*, 113(22), pp.1–9.

City of North Miami Beach, 2015. *FEMA Flood Zones: City of North Miami Beach*, Available at: http://www.citynmb.com/flood.

Clay, P.M., Colburn, L.L. & Seara, T., 2016. Social bonds and recovery: An analysis of hurricane Sandy in the first year after landfall. *Marine Policy*.

Cohen, B., 2006. Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. *Technology in Society*, 28(1), pp.63–80.

Colley, J., 2008. *Hurricane Ike: Impact Report*, Available at: https://www.fema.gov/pdf/hazard/hurricane/2008/ike/impact_report.pdf.

Creel, L., 2003. *Ripple Effects: Population and Coastal Regions*, Available at: http://www.prb.org/pdf/RippleEffects_Eng.pdf.

Demuzere, M. et al., 2014. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. *Journal of environmental management*, 146, pp.107–15. Available at: http://www.sciencedirect.com/science/article/pii/S0301479714003740.

Department of Agriculture, 2016. National Water Management Center. Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/nwmc/.

Department of Homeland Security, 2013a. *National Response Framework: Second Edition*, Available at: https://www.fema.gov/media-library-data/20130726-1914-25045-1246/final_national_response_framework_20130501.pdf.

Department of Homeland Security, 2016. *National Response Framework: Third Edition*, Available at: http://www.fema.gov/media-library-data/1466014682982-9bcf8245ba4c60c120aa915abe74e15d/National_Response_Framework3rd.pdf.

Department of Homeland Security, 2013b. *Overview of the National Planning Frameworks*, Available at: http://www.fema.gov/media-library-data/20130726-1914-25045-2057/final_overview_of_national_planning_frameworks_20130501.pdf.

Department of the Interior, 2014. *Comparison of 2012, 2013, and 2014 Budget Authority*, Washington.

Department of the Interior, 2013. *Hurricane Sandy disaster relief supplemental appropriations spending plan*, Washington.

Environmental Protection Agency, 2016. The Office of Water. Available at: https://www.epa.gov/aboutepa/about-office-water.

Executive Order 12127, 1979. *Federal Emergency Management Agency*, Federation of American Scientists. Available at: https://fas.org/irp/offdocs/eo/eo-12127.htm.

Fernandes, D., 2013. FEMA's new flood map reaches deep into city. *Boston Globe*.

Fischhoff, B., 1995. Risk perception and communication unplugged: Twenty years of process. *Risk Analysis*, 15(2), pp.137–145.

Flood Re, 2016. Flood Re - Affordable Home Insurance. Available at: http://www.floodre.co.uk/.

FloodSmart, 2016. Understanding Flood Maps. Available at: https://www.floodsmart.gov/floodsmart/pages/understanding_flood_maps/understanding_flood_maps.jsp.

Folmer, M.J. et al., 2015. Satellite tools to monitor and predict Hurricane Sandy (2012): Current and emerging products. *Atmospheric Research*, 166, pp.165–181.

Forbes, H., Ball, K. & McLay, F., 2015. *Natural Flood Management Handbook*, Scottish Environment Protection Agency.

Fussell, E. & Lowe, S.R., 2014. The impact of housing displacement on the mental health of low-income parents after Hurricane Katrina. *Social Science & Medicine*, 113, pp.137–144.

Geoscience Australia, 2014. National Flood Guidelines. Available at: http://www.ga.gov.au/scientific-topics/hazards/flood/nfrip/national-flood-guidelines.

Gibbs, L.I. & Holloway, C.F., 2013. *Hurricane Sandy After Action Report and Recommendations to Mayor Michael R. Bloomberg*, Available at: http://www.nyc.gov/html/recovery/downloads/pdf/sandy_aar_5.2.13.pdf.

Gill, S.E. et al., 2007. Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, 33, pp.115–133.

Goldenberg, S.B. et al., 2001. The Recent Increase in Atlantic Hurricane Activity: Causes and Implications. *Science*, 293(5529), pp.474–479. Available at: http://www.sciencemag.org/content/293/5529/474\nhttp://www.ncbi.nlm.nih.gov/pubmed/11463911\nhttp://www.sciencemag.org/content/293/5529/474.full.pdf.

Goldstein, W., Peterson, A. & Zarrilli, D.A., 2014. *One City, Rebuilding Together: A Report on the City of New York's Response to Hurricane Sandy and the Path Forward*, Available at: http://www1.nyc.gov/assets/home/downloads/pdf/reports/2014/sandy_041714.pdf.

Government Accountability Office, 2016. *Army Corps and FEMA Have Made Little Progress in Carrying Out Required Activities*, Washington.

Governor's Office of Storm Recovery, 2014. *New York Rising: 2012-2014*, Available at: https://www.stormrecovery.ny.gov/sites/default/files/uploads/gosr_report_letter_full_high.pdf.

Griffis, F.H. (Bud), 2007. Engineering failures exposed by Hurricane Katrina. *Technology in Society*, 29(2), pp.189–195.

Guiney, J.L., 2006. *Service Assessment: Hurricane Katrina*, Available at: http://www.nws.noaa.gov/om/assessments/pdfs/Katrina.pdf.

Hall, J.W. et al., 2003. Integrated Flood Risk Management in England and Wales. *Natural Hazards Review*, 4(3), pp.126–135. Available at: <Go to ISI>://WOS:000208496800003.

Hallegatte, S. et al., 2013. Future flood losses in major coastal cities. *Nature Climate Change*, 3(9), pp.802–806. Available at: http://www.nature.com/nclimate/journal/v3/n9/full/nclimate1979.html.

Harrison, C.G. & Williams, P.R., 2016. A systems approach to natural disaster resilience. *Simulation Modelling Practice and Theory*, 65, pp.11–31.

Hernandez, R., 2013. Congress Approves $51 Billion in Aid for Hurricane Victims. *New York Times*, p.A21.

Hoang, L. & Fenner, R. a., 2015. System interactions of stormwater management using sustainable urban drainage systems and green infrastructure. *Urban Water Journal*, 9006(April), pp.1–20. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84930168639&partnerID=tZOtx3y1.

Hu, W., 2016. New York City to Get $176 Million From U.S. for Storm Protections. *New York Times*, pp.19–21. Available at: http://www.nytimes.com/2016/01/19/nyregion/new-york-city-to-get-176-million-from-us-for-storm-protections.html.

Imperiale, A.J. & Vanclay, F., 2016. Experiencing local community resilience in action: Learning from post-disaster communities. *Journal of Rural Studies*, 47, pp.204–219.

Kalnay, E. & Cai, M., 2003. Impact of urbanization and land-use change on climate. *Nature*, 423(May), pp.528–531. Available at: http://www.nature.com /nature/journal/v423/n6939/full/nature01675.html.

Kantha, L., 2013. Classification of hurricanes: Lessons from Katrina, Ike, Irene, Isaac and Sandy. *Ocean Engineering*, 70, pp.124–128.

Karen Clark & Company, 2015. *Most Vulnerable US Cities to Storm Surge Flooding August 2015*, Available at: http://www.karenclarkandco.com/ news/publications/pdf/KCC_StormSurge_20150820.pdf.

Klein, R.J.T. & Nicholls, R.J., 1999. Assessment of Coastal Vulnerability to Climate Change. *Ambio*, 28(2), pp.182–187.

Klein, R.J.T., Nicholls, R.J. & Thomalla, F., 2002. The Resilience of Coastal Megacities to Weather-Related Hazards. *Building Safer Cities: The Future of Disaster Risk*, pp.101–120.

Kunreuther, H. & Michel-Kerjan, E., 2014. Chapter 11 – Economics of Natural Catastrophe Risk Insurance. In *Handbook of the Economics of Risk and Uncertainty*. pp. 651–699.

Lafarge Holcim Foundation, 2016. The Dryline: Urban flood protection infrastructure, New. Available at: https://www.lafargeholcim-foundation.org/projects/the-dryline.

Lawson, E. et al., 2014. Delivering and evaluating the multiple flood risk benefits in Blue-Green cities: An interdisciplinary approach. *WIT Transactions on Ecology and the Environment*, 184, pp.113–124.

Lein, L. et al., 2012. The basement of extreme poverty: Katrina survivors and poverty programs. In University of Texas Press, pp. 47–62.

Linnenluecke, M.K., Stathakis, A. & Griffiths, A., 2011. Firm relocation as adaptive response to climate change and weather extremes. *Global Environmental Change*, 21(1), pp.123–133.

Maloney, M.C. & Preston, B.L., 2014. A geospatial dataset for U.S. hurricane storm surge and sea-level rise vulnerability: Development and case study applications. *Climate Risk Management*, 2, pp.26–41.

Massachusetts Office of Coastal Zone Management, 2008a. *Case Study: A Cape Cod Community Prevents New Residences in Floodplains*, Available at: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/.

Massachusetts Office of Coastal Zone Management, 2008b. *Case Study: Massachusetts Communities Reduce Storm Risk in Developed Areas*, Available at: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/.

Massachusetts Office of Coastal Zone Management, 2008c. *Introduction to No Adverse Impact (NAI) Land Management in the Coastal Zone*, Available at: http://www.mass.gov/eea/docs/czm/stormsmart/ssc/ssc1-nai.pdf.

Massachusetts Office of Coastal Zone Management, 2008d. *No Adverse Impact and the Legal Framework of Coastal Management*, Available at: http://www.mass.gov/eea/docs/czm/stormsmart/ssc/ssc2-legal.pdf.

Massachusetts Office of Coastal Zone Management, 2013. Sea Level Rise: Understanding and Applying.

Mcdonnell, S. et al., 2016. *A Managed-Participatory Approach to Community Resiliency: A Case Study of New York State's Response to Extreme Weather Events*, New York. Available at: http://stormrecovery.ny.gov/sites/default/files/crp/community/documents/2016-06-Managed-Participatory_Approach.pdf.

Meadows, D.H., 1999. *Leverage Points: Places to Intervene in a System*, The Sustainability Institute.

Meerow, S., Newell, J.P. & Stults, M., 2016. Defining urban resilience: A review. *Landscape and Urban Planning*, 147, pp.38–49.

Metropolitan Transit Authority, 2013. Fix&Fortify: Sandy Recovery Work. Available at: http://web.mta.info/nyct/service/FloodMitigationWorkBeginsat7DowntownStations.htm.

Mittal, A., 2005. *Lake Pontchartrain and Vicinity Hurricane Protection Project*, United States Government Accountability Office, Washington.

Nadal-Caraballo, N.C. & Melby, J.A., 2015. North Atlantic Coast Comprehensive Study Phase I: Statistical Analysis of Historical Extreme Water Levels with Sea Level Change. *Journal of Coastal Research*, 32(1), pp.35–45.

National Climatic Data Center, 2005. *Hurricane Katrina*, Available at: http://www.ncdc.noaa.gov/extremeevents/specialreports/Hurricane-Katrina.pdf.

National Hurricane Center, 2016. Saffir-Simpson Hurricane Wind Scale. Available at: http://www.nhc.noaa.gov/aboutsshws.php.

National Research Council, 2014. *Reducing Coastal Risk on the East and Gulf Coasts*, National Academy of Sciences.

National Weather Service, 2012. *Service Assessment: Hurricane/Post-Tropical Cyclone Sandy, October 22-29, 2012*, National Oceanographic and Atmospheric Administration.

Nature Conservancy, 2016. Climate Change Impacts: Stronger Storms and Hurricanes. Available at: http://www.nature.org/ourinitiatives/urgentissues/global-warming-climate-change/policy/index.htm.

Nicholls, R.J., 1995. Coastal megacities and climate change. *GeoJournal*, 37(3), pp.369–379.

NOAA, 2016. National Oceanic and Atmospheric Adminstration - Geostationary Satellite Server. Available at: http://www.goes.noaa.gov/.

NYC Department of Environmental Protection, 2012. Guidelines for the Design and Construction of Stormwater Management Systems.

NYC Emergency Management, 2015. *New York City's Risk Landscape: A Guide to Hazard Mitigation*, New York. Available at: https://www1.nyc.gov/assets/em/downloads/pdf/hazard_mitigation/nycs_risk_landscape_a_guide_to_hazard_mitigation_final.pdf.

Pinelli, J.-P. et al., 2008. Validation of a probabilistic model for hurricane insurance loss projections in Florida. *Reliability Engineering & System Safety*, 93(12), pp.1896–1905.

Pompe, J.J. & Rinehart, J.R., 2008. Mitigating damage costs from hurricane strikes along the southeastern U.S. Coast: A role for insurance markets. *Ocean & Coastal Management*, 51(12), pp.782–788.

Purdum, E.D., 2002. *A Water Resources Manual from Florida's Water Management Districts*, Florida Water Management Districts.

Rego, J.L. & Li, C., 2010. Storm surge propagation in Galveston Bay during Hurricane Ike. *Journal of Marine Systems*, 82(4), pp.265–279.

Reiman, T. & Rollenhagen, C., 2011. Human and organizational biases affecting the management of safety. *Reliability Engineering & System Safety*, 96(10), pp.1263–1274.

Reisner, M., 1986. *Cadillac Desert*, New York: Viking.

Ripley, A., 2006. Why we don't prepare for disaster. *Time Magazine*, August.

Robertson, C. & Schwartz, J., 2015. Decade After Katrina, Experts Point Finger More Firmly at the Army Corps. *New York Times*, p.13. Available at: http://www.nytimes.com/2015/05/24/us/decade-after-katrina-pointing-finger-more-firmly-at-army-corps.html?_r=0.

Rogers, J.D. et al., 2015. Interaction between the US Army Corps of Engineers and the Orleans Levee Board preceding the drainage canal wall failures and catastrophic flooding of New Orleans in 2005. *Water Policy*, 17(4), pp.707–723.

Sadowski, N.C. & Sutter, D., 2008. Mitigation motivated by past experience: Prior hurricanes and damages. *Ocean & Coastal Management*, 51(4), pp.303–313.

Schreider, S.Y., Smith, D.I. & Jakeman, A.J., 2000. Climate Change Impacts on Urban Flooding. *Climatic Change*, 47(1), pp.91–115. Available at: http://dx.doi.org/10.1023/A:1005621523177.

Seed, R.B. et al., 2006. *Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005*, National Science Foundation.

Shane, S. & Lipton, E., 2005. Government Saw Flood Risk but Not Levee Failure. *New York Times*, pp.1–7. Available at: http://www.nytimes.com/2005/09/02/us/nationalspecial/government-saw-flood-risk-but-not-levee-failure.html?_r=0.

Small, C. & Nicholls, R., 2003. A Global Analysis of Human Settlement in Coastal Zones. *Journal of Coastal Research*, 19(3), pp.584–599. Available at: http://www.jstor.org/stable/4299200?seq=1#page_scan_tab_contents.

Smith, I. & McAlpine, C., 2014. Estimating future changes in flood risk: Case study of the Brisbane River, Australia. *Climate Risk Management*, 6, pp.6–17.

South Florida Water Management District, 2016. *Managing Flood Water Before and After the Storm*, Available at: http://www.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/bts_before_after_storm.pdf.

Special Initiative for Rebuilding and Resiliency, 2013. *A Stronger, More Resilient New York: Coastal Protection*, New York. Available at: http://www.nyc.gov/html/sirr/html/report/report.shtml.

Tirpak, S.M., 2009. United States Army Corps of Engineers, Galveston District: Operational experiences and response to Hurricane Ike. *Shore & Beach*, 77(2), pp.60–70. Available at: http://www.swg.usace.army.mil/ Portals/26/docs/PAO/Lessons from Ike.pdf.

U.S. House of Representatives, 2006. *A Failure of Initiative: Final Report of the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina*, Available at: http://www.gpoacess.gov/congress/index.html.

UK Environment Agency, 2016. Environment Agency - GOV.UK. Available at: https://www.gov.uk/government/organisations/environment-agency.

UN Habitat, 2009. State of the World's Cities 2008/2009: Harmonious Cities. Available at: http://mirror.unhabitat.org/pmss/ listItemDetails.aspx?publicationID=3387.

US Army Corps of Engineers, 2013. *Hurricane Sandy Coastal Projects Performance Evaluation Study: Disaster Relief Appropriations Act, 2013*, Available at: http://www.nan.usace.army.mil/About/Hurricane_Sandy/Coastal-Projects-Performance-Evaluation-Study/.

US Army Corps of Engineers, 2015. *North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk: Main Report*, New York. Available at: http://www.nad.usace.army.mil/CompStudy.aspx\npapers2://publication/uuid/0D60A4AD-72B5-4C28-B3D2-FB5C3E9A929F.

US Army Corps of Engineers, 2009. *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System: Final Report of the Interagency Performance Evaluation Task Force*, Available at: https://ipet.wes.army.mil/.

US Census Bureau, 2015. Estimates of the Annual Rates of the Components of Residential Population Change. Available at: http://www.census.gov/popest/data/state/totals/2015/index.html.

Voiland, A., 2013. In a Warming World, the Storms May Be Fewer But Stronger. *NASA Earth Observatory*. Available at: http://earthobservatory.nasa.gov/Features/ClimateStorms/.

Wagner, M., Merson, J. & Wentz, E.A., 2016. Design with Nature: Key lessons from McHarg's intrinsic suitability in the wake of Hurricane Sandy. *Landscape and Urban Planning*.

Walters, P., 2015. The problem of community resilience in two flooded cities: Dhaka 1998 and Brisbane 2011. *Habitat International*, 50, pp.51–56.

Wamsley, T.V. et al., 2013. Mississippi Coastal Improvements Program ; Evaluation of Barrier Island Restoration Efforts Engineer Research and Development (September).

Warner, N.N. & Tissot, P.E., 2012. Storm flooding sensitivity to sea level rise for Galveston Bay, Texas. *Ocean Engineering*, 44, pp.23–32.

Wiener, A.J., 2007. Epilogue: After Katrina, lessons not only to be learned, but to be used. *Technology in Society*, 29(2), pp.257–260.

Yarnal, B., 2007. Vulnerability and all that jazz: Addressing vulnerability in New Orleans after Hurricane Katrina. *Technology in Society*, 29(2), pp.249–255.