Hurricane Harvey Report

A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region

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Publication date
2017

Document Version
Final published version

Citation (APA)
Sebastian, T., Lendering, K., Kothuis, B., Brand, N., Jonkman, B., van Gelder, P., Godfroij, M., Kolen, B., Comes, T., Lhermitte, S., Meesters, K., van de Walle, B., Ebrahimi Fard, A., Cunningham, S., Khakzad, N., & Nespeca, V. (2017). *Hurricane Harvey Report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region*. Delft University Publishers.

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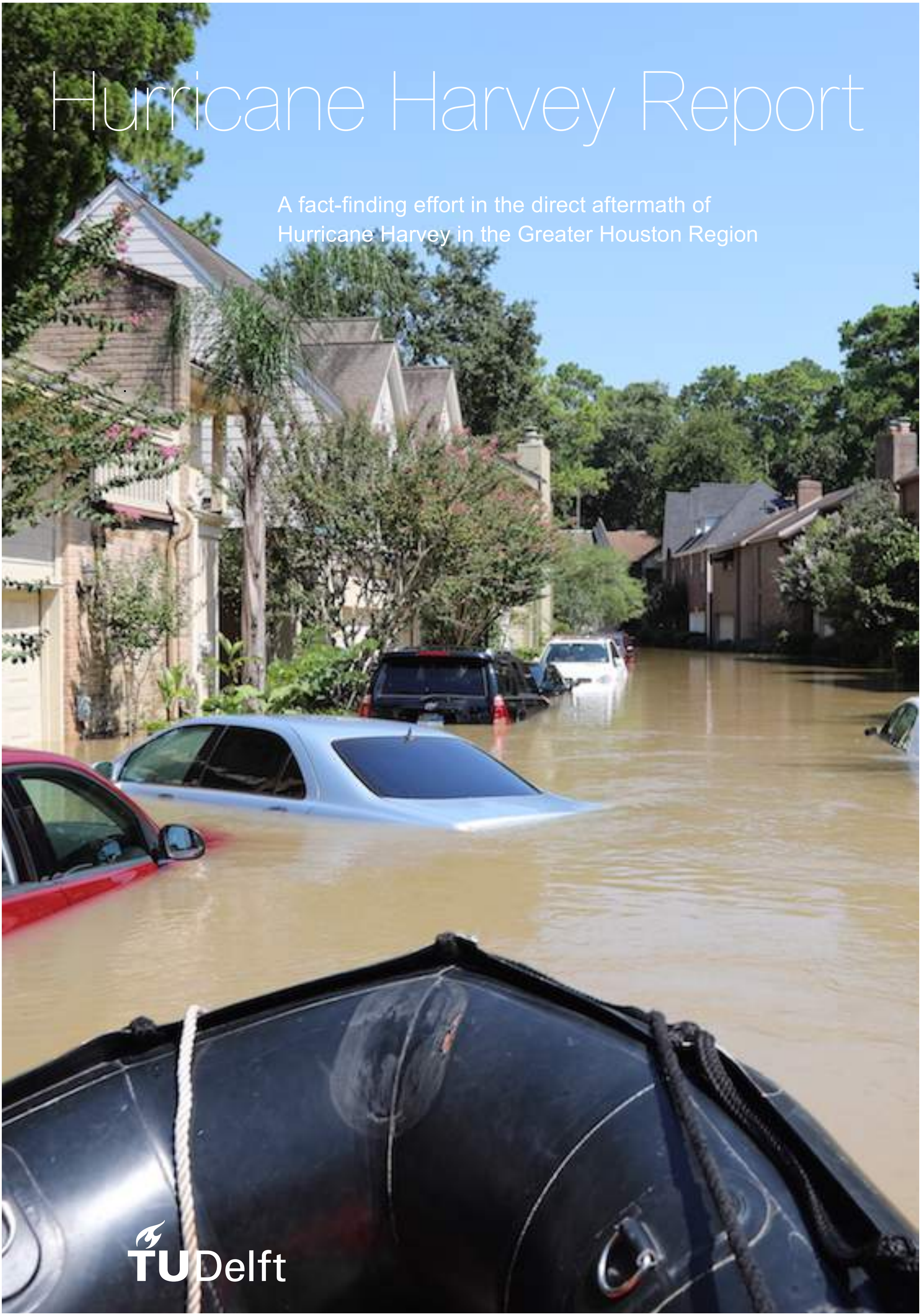

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The Harvey Hackathon
and the publication of this report
were funded by DIMI and DSyS

TU Delft | Deltas, Infrastructures & Mobility Initiative

TU Delft | Delft Safety & Security Institute

Image on cover: USAR VA Task Force 2 Houston (Courtesy of FEMA).

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Phase I Report
October 19, 2017

Keywords: Hurricane Harvey, floods, fact-finding, Houston, Texas, rainfall, impacts, damage, emergency response, land use planning, flood risk

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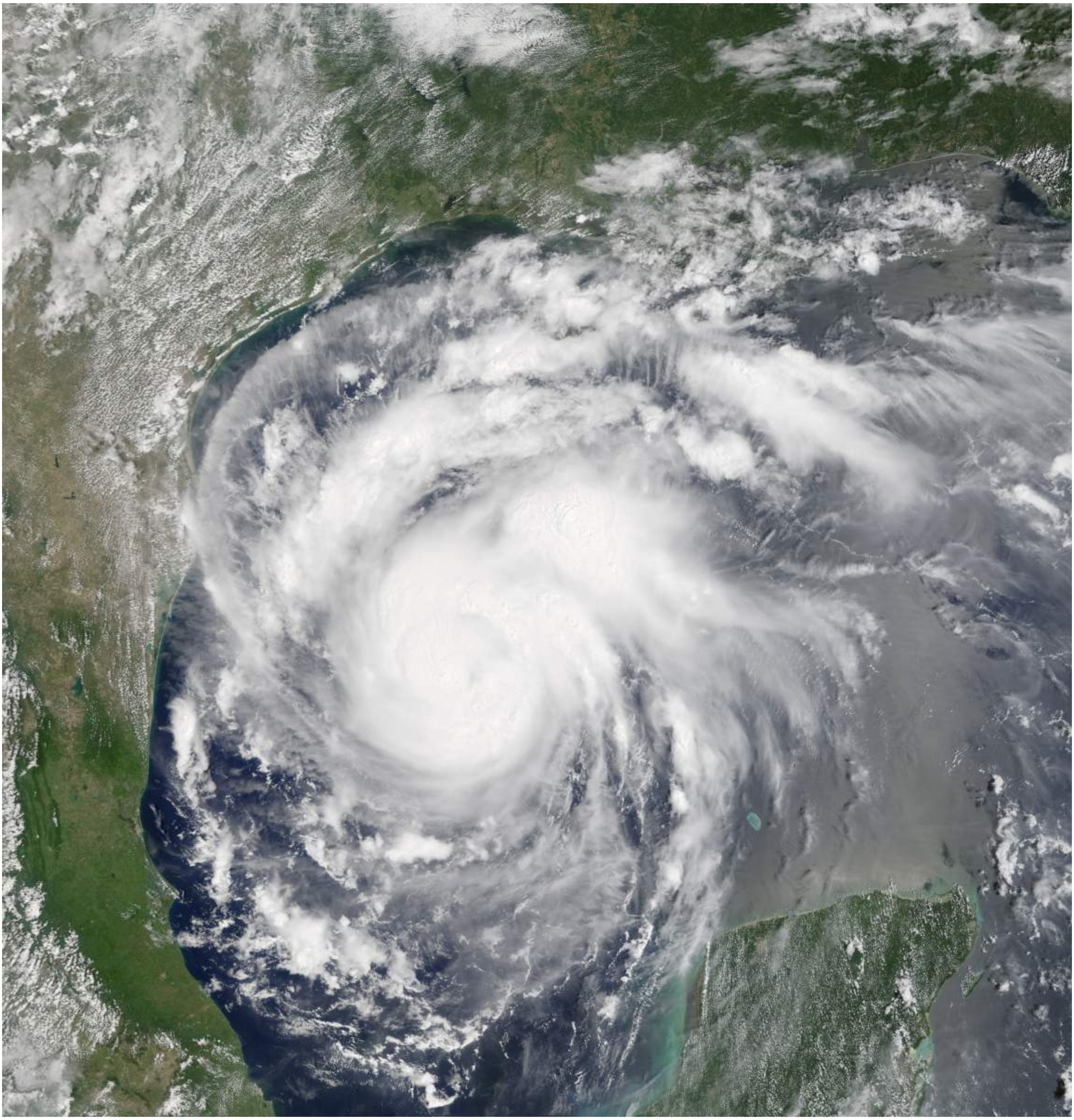

Hurricane Harvey from space August 24, 2017 (Image courtesy of NASA)

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Members of FEMA's Urban Search and Rescue Nebraska Task Force One perform one of many water rescues in the aftermath of Hurricane Harvey (Image courtesy FEMA News photo).

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31 August 2017, extensive flooding in a residential area in Southeast Texas (Image courtesy: Air National Guard - Staff Sgt. Daniel J Martinez)

Preface

The Netherlands and the U.S. share many important bonds, one of which is our relationship to water. The Dutch aided New Orleans and New York during the Hurricane Katrina and Superstorm Sandy recoveries, and continue to collaborate on water challenges in Miami, Norfolk, Boston, San Francisco, St. Louis, and Galveston. In turn, the Dutch learn from the U.S. more about emergency management and disaster response.

Climate change adds two crucial dimensions – uncertainty and extremes – to this work, both in the U.S. and in the Netherlands. We both must prepare for sea-level rise, and adapt our cities to extreme precipitation and water scarcity in our natural landscapes, farms and aquifers. Indeed, in the Netherlands we wonder whether our future holds the severe droughts recently experienced in the Western United States, or the whipsaw flood-and-drought water levels in the Mississippi River in 2011 and 2012.

Collaboration is useful, even necessary, to make us smarter and more resilient, separately and collectively. For example, faculty, researchers and students at Delft University of Technology have been working closely with Texas A&M University at Galveston and Rice University since Hurricane Ike in 2008. This international team of dedicated professionals has enhanced our technical and academic understanding of water forces along the Texas coast and around Galveston Bay. They have jointly developed a workable, cost-effective solution to coastal flooding in those regions.

System-wide, watershed-based approaches, comprehensive risk assessment and integrated planning are the foundation of Dutch water management policies, and they are relevant to the U.S., too. Hurricane Harvey gives us an opportunity to explore how extreme rainfall has impacted America's fourth largest city, how smart recovery will prepare Houston for future risks, and what lessons from Harvey – in flood protection design and operation, risks to human life, economic and critical infrastructure, and emergency management – are applicable to the Netherlands.

Part of that exploration is the Harvey Hackathon, the results of which are found in the following pages. While this report is interim, the breakdown of Harvey and its impacts upon the water system, residents, industry, and critical infrastructure in Houston form a solid foundation upon which to build. Assessments of the emergency response during Harvey provide key lessons for Dutch policymakers and practitioners. The report's Main Findings should be required reading for anyone wanting to understand Harvey and provide a direction of the way forward. The report also posits areas for fruitful joint-research that will benefit policymakers, planners and technicians in both countries.

Henry Ford noted that "Coming together is a beginning; keeping together is progress; working together is success." I commend TU Delft, its faculty and student body for demonstrating through the Harvey Hackathon and the Delta Infrastructures and Mobility Initiative the crucial relevance of international collaborative research. Your actions prove that "working together is success."

Henne Schuwer
Ambassador of the Kingdom of the Netherlands to the US

Dale Morris
Senior Economist
Royal Netherlands Embassy

Houston Interstate 10 floods during hurricane Harvey, August 28 (Image courtesy Katharine Anarde)

Executive Summary

On August 25, 2017, Hurricane Harvey made landfall near Rockport, Texas as a Category 4 hurricane with maximum sustained winds of approximately 200 km/hour. Harvey caused severe damages in coastal Texas due to extreme winds and storm surge, but will go down in history for record-setting rainfall totals and flood-related damages. Across large portions of southeast Texas, rainfall totals during the six-day period between August 25 and 31, 2017 were amongst the highest ever recorded, causing flooding at an unprecedented scale. More than 100,000 residential properties are estimated to have been affected in southeast Texas. It is likely that Harvey will rank among the costliest storms in U.S. history.

In the wake of Hurricane Harvey, Delft University of Technology has initiated a Harvey Research Team to undertake a coordinated multidisciplinary investigation of the events with a focus on the greater Houston area. This 'fact-finding' research is based on information available from public sources during and in the first weeks after the event. Results are therefore preliminary, but aim to provide insight into lessons that can be learned for both Texas and the Netherlands. As part of the investigations, a hackathon with more than 80 participants was organized to collect and analyze available public information.

Houston was especially hard hit by flooding. During the event, all 22 watersheds in the greater Houston area experienced flooding. Many of Houston's creeks and bayous exceeded their channel capacities, reaching water levels never before recorded. Across large portions of Harris County, rainfall totals exceeded the 1000-year return period. In addition, the water from the two reservoirs protecting downtown Houston (Addicks and Barker) were opened on August 28 to prevent catastrophic damages to the dams and further flooding in upstream communities. The releases exacerbated flooding in the areas downstream of the dams and an estimated 4,000 homes in neighborhoods downstream of the dams were impacted by flooding.

The consequences of the event in the greater Houston area have been characterized in terms of economic damages, loss of life and impacts on critical infrastructure, airports and industry. In total, more than 100,000 homes were affected more than 70 fatalities were reported in the greater Houston area. The event highlighted the vulnerability of industrial facilities, as several cascading impacts (releases of toxic materials and explosions) were reported.

Emergency response has been assessed. No large-scale mandatory evacuation was ordered before or during Harvey. However, it appeared that several local evacuations were ordered for areas with specific risks and circumstances. During the event, many people were trapped by rising waters necessitating a major rescue operation. In total, more than 10,000 rescues were made by professional and volunteer rescuers. Social media played an important role during the event and recovery, as an additional source of information, to inform emergency managers and as a means to organize community response e.g. for clean-up. Also, messages were conveyed through social media, e.g. a report of a levee breach that appeared to be incorrect afterwards.

Major flooding is a problem that has multiple causes from both physical and social origin. Based on the investigations, recommendations for future research and lessons for flood management have been formulated. A better understanding of the issues studied in this report is expected to contribute to a knowledge basis for further in-depth investigations and future directions for flood risk reduction.

Army Sgt. speaks with a family in Orange, TX, after assisting a local to safety. (Image courtesy: US Army, photo by Spc. Austin T. Boucher).

Acronyms

ARC	American Red Cross
BFE	Base Flood Elevation
CDEMA	Caribbean Disaster Emergency Management Agency
CDT	Central Daylight Time (CDT = GMT - 5 hours)
CEG	Civil Engineering and Geosciences
CMS	Centers for Medicare and Medicaid Services
CSR	Corporate Social Responsibility
CTBS	Center for Texas Beaches and Shores
DG ECHO	Directorate General for European Civil Protection and Humanitarian Aid
DoD	Department of Defense
DoE	Department of Energy
DoT	Department of Transportation
ERCC	European Response and Coordination Center
EPA	Environmental Protection Agency
FAS	Flood Alert System
FEMA	Federal Emergency Management Association
FIRM	Flood Insurance Rate Map
FWS	Flood Warning System
GDP	Gross Domestic Product
GLO	General Land Office
HCFCD	Harris County Flood Control District
HCFWS	Harris County Flood Warning System
HCOEM	Harris County Office of Emergency Management
HHS	Department of Human Health Services
HOU	William P. Hobby Airport
HUD	Department of Housing and Urban Development
IAH	George Bush Intercontinental Airport Houston
IMAT	Incident Management Assistance Team
IPCC	Intergovernmental Panel on Climate Change
LID	Levee Improvement District
LIDAR	Laser Imaging Detection And Ranging
MSL	Mean Sea Level
MUD	Municipal Utility District
NASA	National Aeronautics and Space Administration
NAVD	North American Vertical Datum
NFIP	National Flood Insurance Program
NGO	Non-Governmental Organizations
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priority List
NRCC	National Response Coordination Center
NWS	National Weather Service
SBA	Small Business Administration
SBTF	Standby Task Force
SFHA	Special Flood Hazard Area
SSPEED	Severe Storm Prediction, Education, and Evacuation from Disaster Center
TCEQ	Texas Commission on Environmental Quality

TMC	Texas Medical Center
TSARP	Tropical Storm Allison Recovery Project
TWC	Texas Workforce Commission
TXDoT	Texas Department of Transportation
ULI	Urban Land Institute
USACE	United States Army Corps of Engineers
USAR	Urban Search And Rescue
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VFW	Veterans of Foreign Wars

Introduction

1

1.1. Context

On August 25, 2017, Hurricane Harvey made landfall as a Category 4 hurricane near Rockport, Texas. Harvey's extreme winds and storm surge caused devastation along the Texas coast. As Harvey moved slowly inland, meteorologists predicted that Harvey would drop between 900-1000 mm (35-40 in) of rain during the following week in coastal Texas. In some areas these expectations were exceeded, particularly in the greater Houston area. As a result, unprecedented flooding occurred over an area the size of the Netherlands. Houston, the fourth largest city in the U.S., was especially hard hit, prompting massive emergency response ranging from local grass-roots efforts to formal disaster management. Initial reports place the damages from Hurricane Harvey among the top five historical events in the United States. More than 20,000 people were forced to seek emergency shelter during the event and an estimated 120,000 structures have been affected by flooding.

Extreme flood events such as Harvey are tragic, but also very rare events. As such they are important opportunities to learn. Therefore, it has been decided to set up an interdisciplinary research team at Delft University of Technology (from here on referred to as TU Delft) to conduct research in response to Hurricane Harvey. Similar but smaller-scale and more disciplinary efforts have been initiated by TU Delft after other flood disasters, such as Hurricane Katrina (2005), river floods in Thailand (2011) and Germany (2013) and the tsunami in Japan (2012).

Another reason to set up this investigation was the fact that TU Delft has been involved in multidisciplinary research and design efforts in Texas since the year 2012 – see textbox 1.1 for more information.

Textbox 1.1: The ‘Texas Case’

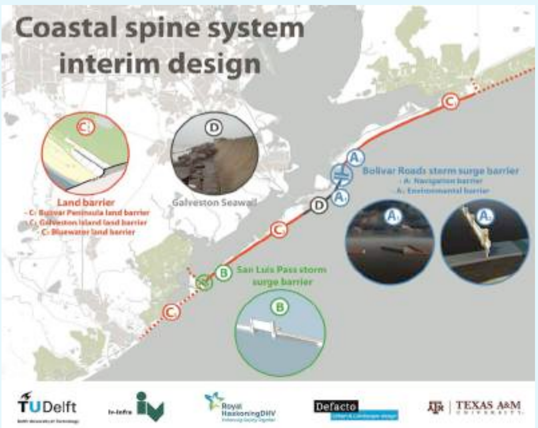
The ‘Texas Case’: Flood Risk Reduction in the Houston-Galveston Bay Region

Since 2012, numerous faculty, staff and students from different faculties and departments at TU Delft have been involved in research and design in Texas with a specific focus on the Houston – Galveston Bay area. In collaboration with academic partners from Texas - Texas A&M University and Rice University – research has focused on several themes related to flood risk reduction in Galveston Bay, including civil infrastructure design, land use and urban planning, governance and coastal engineering. For example, civil engineers from TU Delft were involved in the initial design of the coastal spine (or ‘Ike Dike’) for the protection of the area against storm surge. Students have also been involved in investigations into the preliminary designs for a proposed storm surge barriers in the Bolivar Roads and Houston Ship Channel, multi-functional land barriers, and nature-based solutions to reduce wind setup in Galveston Bay. Some designs were made in collaboration with experts from the Dutch private and public sector (Royal HaskoningDHV, IV Infra, Defacto and Rijkswaterstaat).

As part of the multidisciplinary efforts, several courses and workshops have been organized at TU Delft. For example, a multi-disciplinary Delta Interventions Studio hosted within the Faculty of Architecture brought together students from the departments of hydraulic engineering, urban planning and policy analysis. Additionally, in the Contested Issues Game Structuring (CIGaS) workshops brought researchers from The Netherlands and Texas together with a wide range of stakeholders to assess local values and interests as a basis for future strategies for Galveston Bay.

Since the year 2015, TU Delft has also participated as a partner institution in the Coastal Flood Risk Reduction Program, an International Research and Education Program (PIRE) funded by the U.S.’ National Science Foundation (NSF) (PI: Dr. Samuel Brody). As part of this multi-million dollar program, each summer 15 to 20 U.S. students are given the opportunity to travel to The Netherlands to conduct place-based research comparing Dutch and Texas flood risk reduction measures and strategies – creating a basis for further research and collaboration between the partner institutions.

The success of our collaboration with Texas over the past five years is perhaps best summarized by the following figures: 25+ MSc theses; 12 faculty research projects; 7 technical reports; 1 book and 2 book sections; 3 PhD exchanges; 10+ faculty-exchange visits; 15+ collaborative workshops, symposia and seminars. In addition, the Texas case is included in three Dutch National Science Foundation (NWO) research programs in which TU Delft is involved. Interim results of the exchange and research have been summarized in the publication “Delft Delta Design: the Houston Galveston Bay Region, Texas, USA” (Kothuis et al., 2015).



1.2. Objective

Hurricane Harvey resulted in widespread, never-before-seen flooding across Houston and surrounding areas. This report attempts gives an overview of Harvey's impacts in the region, while also focusing on several 'hot spots': locations that have experienced damage from flooding during recent flood events. At these hot spots, Harvey's extreme weather caused significant flooding, damages to housing and/or industry, human impacts (e.g., evacuations) and/or casualties. The events are studied from a multi-disciplinary perspective, considering the specializations of hydraulic structures, flood management, emergency response, safety and security and urban planning. To facilitate this research, first, a 'fact finding' investigation was undertaken during and in the immediate aftermath of the event (4-8 weeks).

The 'fact finding' includes efforts to collect data and information on the meteorology, the hydrologic and hydraulic response of the system, the emergency management and disaster response, and the impacts of the event on critical and hydraulic infrastructure. The Harvey Hackathon (Chapter 7), activating over a hundred students and researchers from multiple disciplines in a full day flash-event to gather data on the hurricane and its impact, was helpful to collect a large batch of initial information creating first insights on Harvey's effects and sprouting multiple questions for further academic research. This report constitutes the results of the 'fact finding'. It aims to provide a basis for longer-term research focusing on specific research topics more in-depth and to provide a basis for "research by design" for flood risk reduction in the affected areas.

1.3. Reading Guide

This report contains a description of Harvey's storm characteristics (Chapter 2), and a brief overview of Houston and its relationship to flooding (Chapter 3). This is followed by a description of Harvey's flood impacts in Houston and its surrounding areas (Chapter 4), damages and fatalities caused by flooding (Chapter 5), emergency decision-making and response (Chapter 6) and the data collection event Harvey Hackathon (Chapter 7). Finally, Chapter 8 describes the main findings, future research needs and lessons learned from the event.

Hurricane Harvey making landfall in Texas, August 25, 2017 (Image courtesy: NASA).

Hurricane Harvey

2

2.1. Hurricane Formation

Tropical cyclones form over the tropical latitudes where sea surface temperatures exceed 27 degrees Celsius. The hot waters cause water to evaporate and as the warm air rises, it cools and condenses, fueling the formation of clouds and thunderstorms. This process releases latent energy, causing the surrounding air to become even warmer, additional evaporation, and the atmospheric pressure at the sea surface to drop. Westerly winds blow toward the storm while the earth rotates clockwise, causing the thunderstorms to rotate counter-clockwise around the low pressure center called the eye (Figure 2.1).

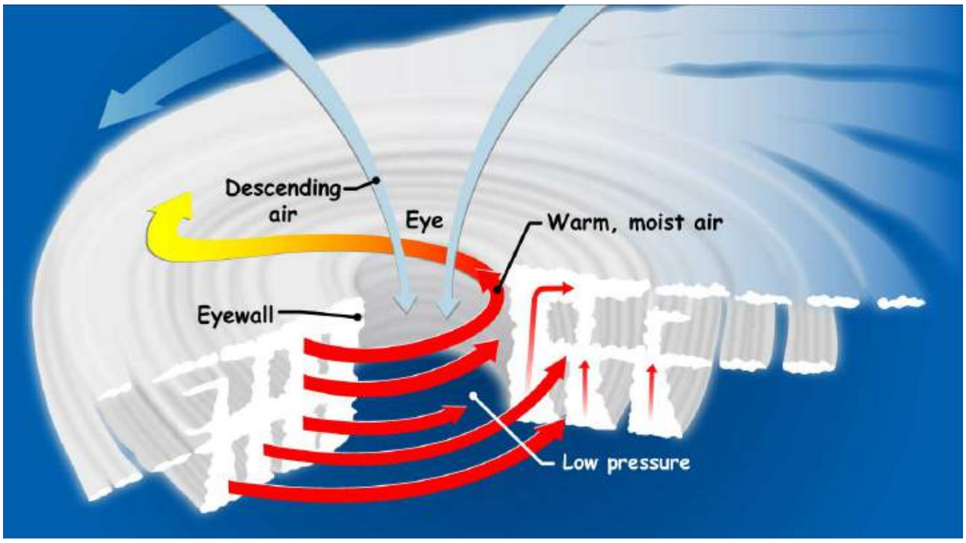


Figure 2.1. Formation of a tropical cyclone. (Courtesy of NASA)

In the Atlantic Ocean, the hurricane season begins on June 1st and lasts until November 30th. The number of storms varies significantly each season; however, the intensity and number of storms in the Gulf of Mexico typically peaks in August and September each year. NOAA estimates that in the Houston-Galveston region, the approximate return period of a tropical cyclone is once every 9 years and a major hurricane (Category 3 or higher) is once every 25-26 years (NHC, 2015). The last major hurricane to make landfall on the Texas coast was Hurricane Celia (Category 3) in 1970 and the most recent hurricane to affect the Houston Galveston region was Hurricane Ike (Category 2) on September 13, 2008.

The Saffir-Simpson Hurricane Wind Scale was originally developed in 1974 (and updated in 2010) as a tool to alert the public to a storm's probable impact (Table 1). The scale uses wind velocity to categorize a hurricane's potential damage on a scale from 1 to 5 – where a rating of five indicates that the storm will cause catastrophic damage to coastal infrastructure (Schott et al. 2012). In addition to damage from winds, tropical cyclones have the potential to cause devastating coastal flooding. Storm surge is generated when the low atmospheric pressure associated with a tropical cyclone causes sea levels to rise. In addition, along mildly sloped coasts and in coastal bays, local wind conditions can contribute to even higher set up. The highest storm surge are typically located in the northeast quadrant of the storm at the radius maximum winds, which is the location of the hurricane's eyewall and most destructive winds.

Table 2.1. Saffir-Simpson Hurricane Wind Scale (NHC n.d.)

Category	Sustained Winds[1] (km/h)	Anticipated Wind Damage
1	119-153	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	154-177	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Near-total power loss is expected with outages that could last from several days to weeks.
3 (major)	178-208	Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Electricity and water will be unavailable for several days to weeks after the storm passes.
4 (major)	209-251	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Most of the area will be uninhabitable for weeks or months.
5 (major)	>252	Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Most of the area will be uninhabitable for weeks or months.

2.2. Hurricane Harvey

Harvey first developed as a low pressure system just east of the Lesser Antilles on August 17, 2017. It briefly became a tropical cyclone as it crossed the Caribbean before degenerating into a tropical wave over the Yucatan Peninsula on August 18. By Wednesday, August 23, Harvey had regenerated into a tropical depression and hurricane and storm surge watches were initiated for parts of the Texas coast. Initial forecasts had Harvey heading for mid-Texas coast, somewhere near San Luis Pass, Texas, however with weakening wind shear in the Gulf of Mexico, Harvey intensified and shifted further south. On August 24, 2017 Harvey strengthened

[1] Sustained winds are the highest one minute surface wind occurring within the system (Powell et al. 1996).

into a Category 1 hurricane. As Hurricane Harvey approached the Texas coast, unusually warm water in the Gulf of Mexico further fueled the storm's development. Harvey intensified substantially in the final hours before landfall, strengthening into a Category 4 hurricane with maximum sustained winds around 209 km/h (130 mph).

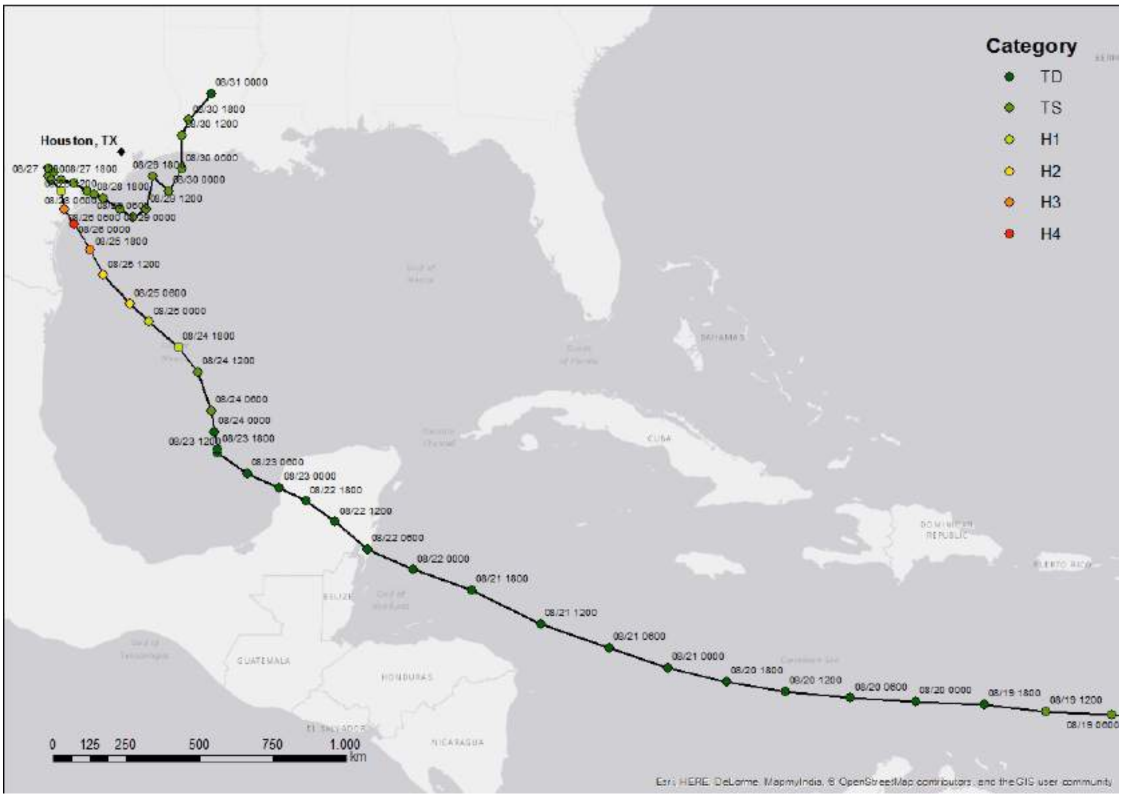


Figure 2.2. Hurricane Harvey's track

Harvey made landfall at approximately 10:00 PM CDT (0300 UTC) on Friday August 25, 2017 at the northern end of San Jose Island about 6 km (4 miles) east of Rockport (NHC). At landfall, hurricane force winds extended approximately 65 km (40 miles) and tropical storm force winds extended outward approximately 220 km (140 miles) (Figure 2.3). Peak wind gusts of up to 212 km/h (132 mph) were reported near Port Aransas, Texas (NWS 2017). The highest storm surge was recorded in the coastal bays to the east of Harvey's landfall location: Corpus Christi Bay, Copano Bay, and San Antonio Bay, where total water levels exceeded 2 meters. The highest total water level was recorded at the Aransas Wildlife Refuge, where storm tide reached 3.7 m (12 ft).

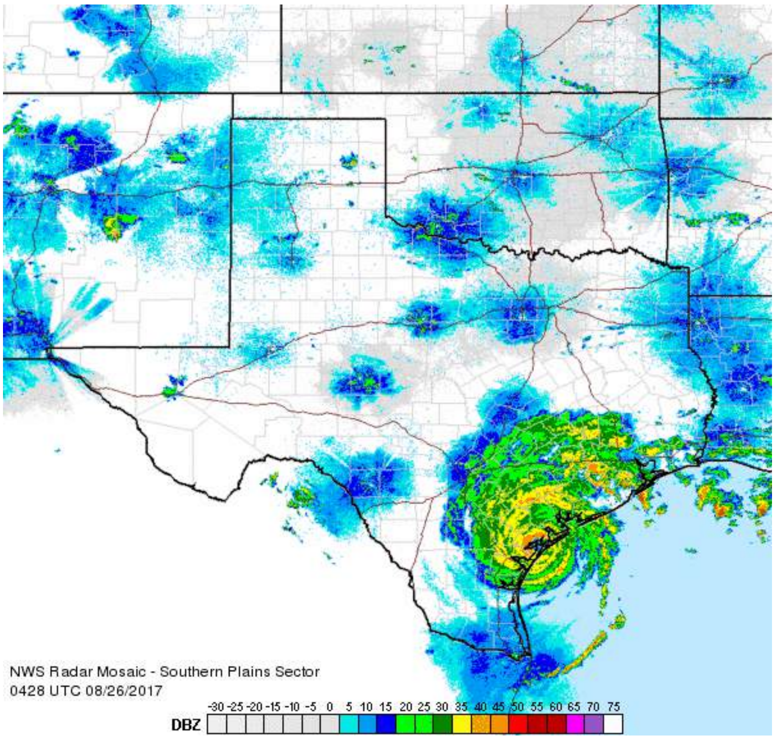


Figure 2.3. Hurricane Harvey making landfall near Rockport, Texas at approximately 1000 PM CDT on Friday August 25, 2017 as a Category 4 hurricane (NWS).

Upon landfall, Harvey's Category 4 winds passed right over the city of Rockport exposing the small town to the strongest winds inside the storms eyewall. Many structures and residences in Rockport and surrounding areas were damaged or destroyed, and tens of thousands of south Texans lost power for days with the most severely impacted areas losing power for weeks. In addition, many areas lost access to clean drinking water because the local water treatment plant was closed due to the power outage.

Figure 2.4. (a) Damages in Rockport, Texas were primarily wind and surge driven, whereas (b) damages in Houston were driven by extreme precipitation. (Images courtesy of (a) FEMA - Dominick Del Vecchio and (b) www.defense.gov)

Harvey continued to move inland at approximately 11 km/h (7 mph), and was expected to slow considerably in the coming days, hovering over southeastern Texas and bringing catastrophic rainfall and life-threatening flooding to Houston and surrounding areas. Heavy rainfall of 380 to 760 mm (15 to 30 in) was forecasted, with isolated rainfall totals as high as 1270 mm (50 in) through the following Thursday, August 31, 2017. By August 30, 2017, more than 635 mm (25 in.) of rain had fallen over southeast Texas with isolated observations of more than 1016 mm (40 in.) in 48 hours in the Houston Galveston area (Figure 2.5). The highest recorded rainfall totals in U.S. history occurred in Cedar Bayou in Southeast Texas where a total of 1318 mm (51.88 in) of rain fell during the storm (NWS 2017). The remainder of this report focuses on impacts to Houston and the surrounding areas. It is important to point out that significant flooding and damages due to heavy rainfall also occurred in other areas of Texas, e.g., Beaumont; however, this is not substantially covered in this report.

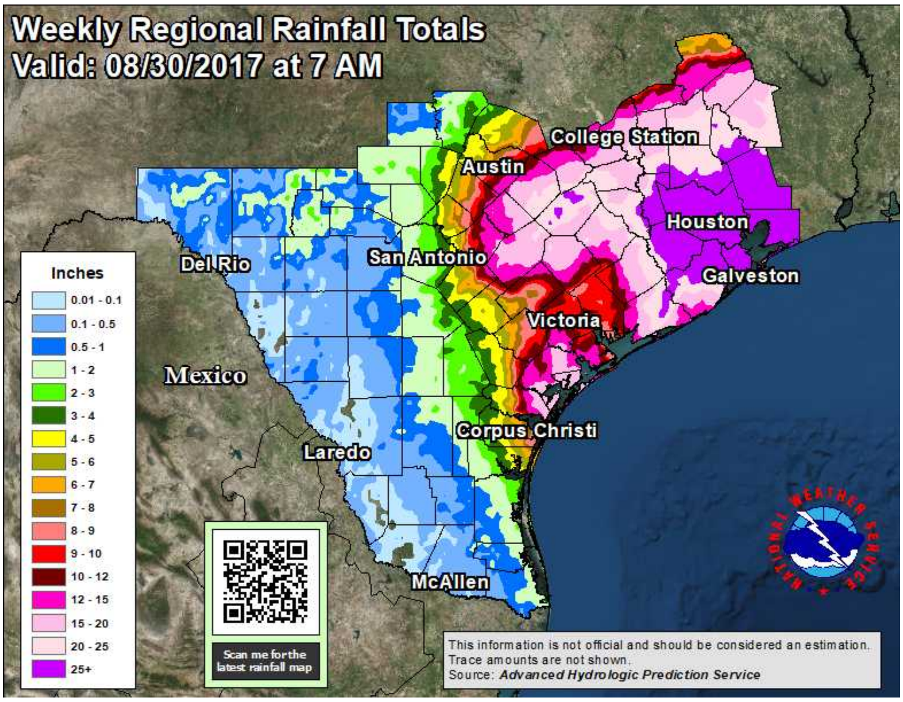


Figure 2.5. 7-day cumulative precipitation totals (in inches) for Hurricane Harvey as of August 30, 2017 (NWS 2017)

Flooded residential area, Woodland Heights, Houston, August 28, 2017 (Image courtesy Mike Burcham).

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Flood Management in Houston, Texas

3

3.1. Introduction

Houston is the 4th largest city in the United States with an estimated population of 2.3 million people. The City of Houston is located in Harris County and is part of a greater metropolitan region spanning eight counties (Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller) (Figure 3.1). The entire region is home to an estimated 6.4 million people and is expected to grow to 10 million people by 2040 (HGAC 2016).

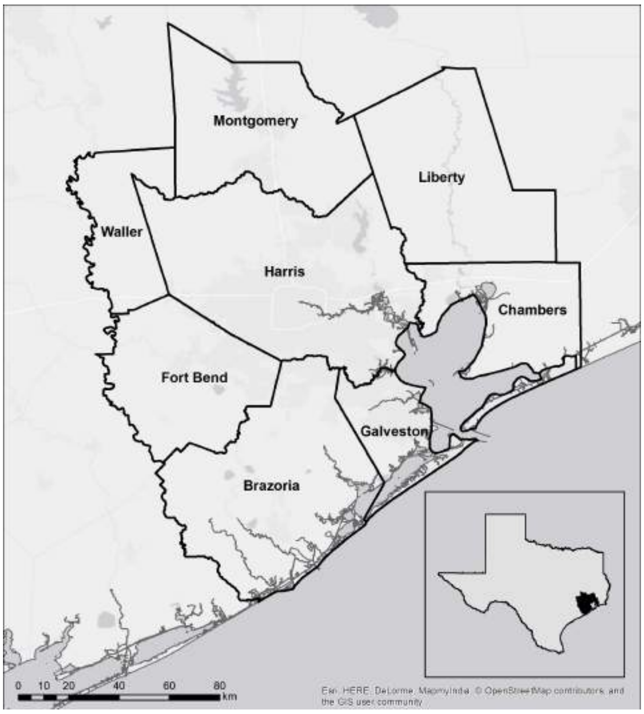


Figure 3.1. Greater metropolitan Houston spanning eight counties.

The regional economy is driven by the energy, healthcare, biomedical research, and aerospace sectors. The gross domestic product (GDP) of the Houston metropolitan region was $503 billion USD in 2015, which accounts for about 3% of the national GDP (Rodriguez et al. 2016). In addition, Houston lays claim to the largest medical center in the world – The Texas Medical Center – and the largest petrochemical complex and foreign port in the U.S. – The Port of Houston.

In Houston, flooding is never a matter of 'if', but only 'when'. Intense rainfalls, characteristic of the Gulf of Mexico and brought about by tropical cyclones or strong convective systems, have the potential to drop extreme rainfall over the region. The average annual rainfall in Houston is 1264 mm (49.77 in), and it is not uncommon to receive a significant percentage of this rainfall during a single event. Houston is characterized by clay soils and little topographic relief, creating wide and shallow floodplains. In its natural state, the region would be covered by wetlands and coastal prairie that have the ability to absorb and store floodwaters, slowly releasing them into small creeks and bayous: small, tidally influenced rivers, which are fed by rainfall-runoff and act as the primary drainage system for the region (Figure 3.2).

In addition, Houston's location on the edge of Galveston Bay also makes it vulnerable to inundation from storm surge during extreme wind events. To date, the Galveston Hurricane of 1900 remains the highest recorded storm surge in the region, with observed storm surge exceeding 4.5 meters on Galveston Island. A number of small protection systems have been built in the wake of historical events, including the Galveston Seawall (1902), the Texas City Dike (1915) and Levee (1962), and the Freeport Levee System (1962), but no regional system currently exists to protect Houston or surrounding areas from storm surge. Moreover, elevated water levels in the bay also have the potential to exacerbate inland flooding by preventing runoff from entering Galveston Bay. Previous research has indicated that backwater from storm surge could influence water levels as far inland as downtown Houston.

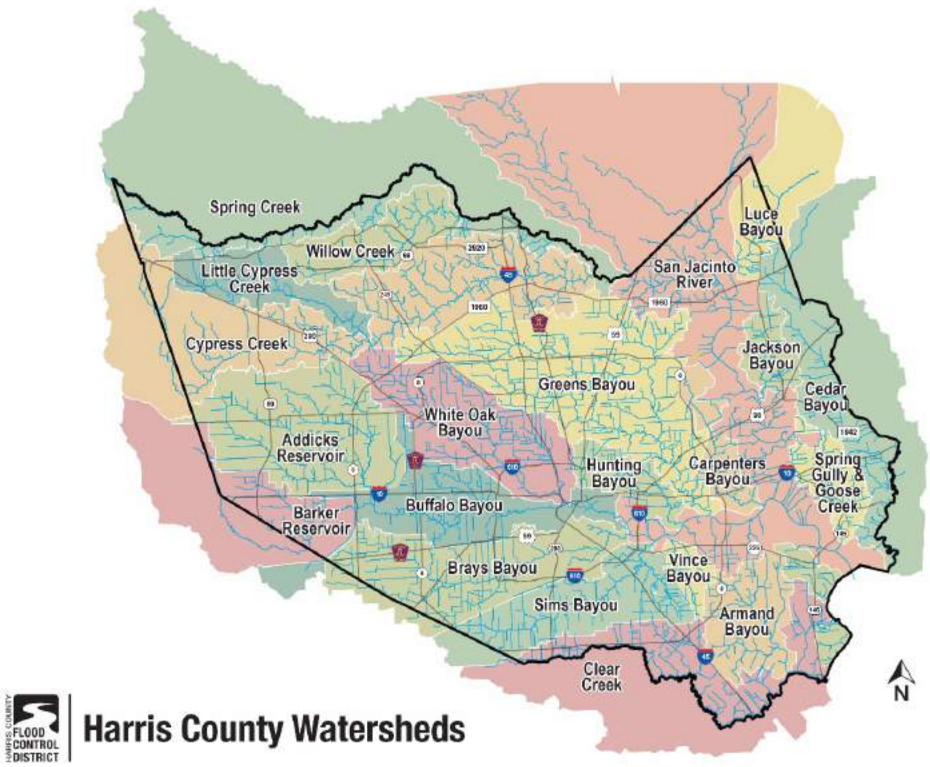


Figure 3.2. [Watershed map](#) by Harris County Flood Control District (HCFCD)

3.2. Riverine Flood Control

Houston was founded in 1836 at the confluence of Buffalo and White Oak Bayous and early settlers lived directly on the banks of the Houston Ship Channel. However, severe floods in 1929 and 1935 immediately highlighted the city's vulnerability to flooding (HCFCD n.d.). This prompted the creation of the Harris County Flood Control District (HCFCD), which later became the local cost-share partner and regional counterpart to the USACE, and charged it with evaluated the hydrologic response of the region and designing flood protection for the City of Houston. With more than 1,500 bayous and creeks within the county totaling approximately 4023 km (2500 mi) in length, the HCFCD is responsible for devising flood risk reduction plans, implementing them, and monitoring and maintaining infrastructure.

To alleviate flooding in downtown Houston, the HCFCD, together with the USACE, designed and built two flood control reservoirs in the upstream portion of the Buffalo Bayou watershed, west of downtown Houston. The two reservoirs, Addicks and Barker, were completed in 1945 and 1948, respectively. Several small creeks feed the reservoirs during normal events and Addicks also holds overflows from Cypress Creek during extreme events. The dams consist of earthen levees with a total height of 37 meters[2] (Addicks) and 34 meters (Barker) and are equipped with flow gates to release water into Buffalo Bayou. In addition, they have been retrofitted with concrete-armored auxiliary spillways at the upstream ends of the dams to prevent water from overtopping or eroding the earthen embankments (Figure 3.3). Other dams in the greater Houston area, such as the dam at Lake Conroe, serve similar purposes.

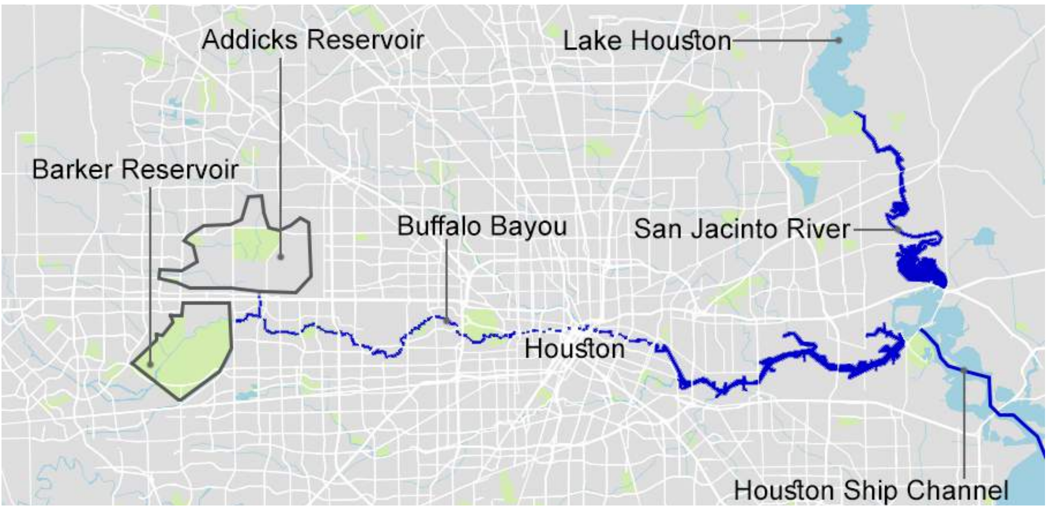


Figure 3.3. Diagram depicting Addicks and Barker reservoirs and their location relative to Houston.

At the time of construction, Addicks and Barker were built on government property. Since then, residential development has encroached into the storage areas within the reservoirs' footprints and previous floods have increased sedimentation in the reservoirs, reducing their total storage capacity. According to the USACE, the reservoirs can still hold a 100-year flood event within the boundaries of the government-owned land (Tang and Neil 2017). In addition to a reduction in storage capacity of the reservoirs, urban areas downstream of the dam were constructed along Buffalo Bayou increasing the potential risks if the dams were to fail or if significant releases were to occur.

In recent years, both Addicks and Barker have received considerable attention after the USACE announced that they are "extremely high risk." Inspections revealed cracks and voids in and

[2] All water levels are reported relative to NAVD88 unless otherwise noted.

under the dams and the USACE identified six critical failure modes. It was estimated that property damages downstream of the dams could reach $22.7 billion USD (19 billion euro) and an estimated 6,928 people would be affected by life-threatening flooding (Caruba 2016). The USACE allocated $72 million USD to repair and reinforce the reservoirs; renovations began in 2012 and are on-going.

With the expansion of urban areas into the upstream portions of Houston's watersheds also came the need for regional flood control strategies. Houston and surrounding areas experienced rapid urban growth during the 1960s and 70s. To offset its impact and to allow for development and economic growth in previously flood-prone areas, many of Houston's primary waterways were channelized, including Brays, White Oak, and Greens Bayous. These channelization projects involved widening, deepening, and straightening the bayous, and in some places adding a concrete-liner to increase flow velocities and more quickly evacuate flood waters (Figure 3.4). While this decreased the extent of the floodplain at the time, it has exacerbated flooding in these watersheds over the long term as urban development has increasingly led to higher runoff volumes and stages in downstream areas (Sebastian, 2016; Sebastian and Gori, 2018). Today, it is estimated that some of Houston's bayous can only accommodate a 10-year rainfall event (Schaper 2017).

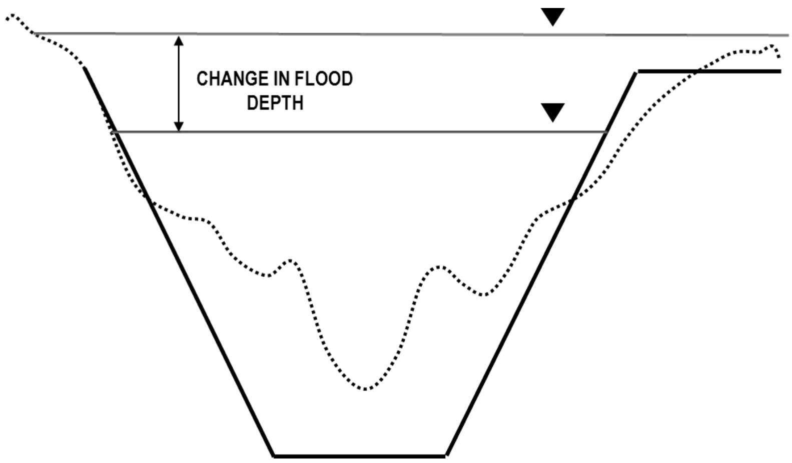


Figure 3.4. Typical cross-section of a modified channel in Houston

To manage overland flooding in urban areas, storm water systems consisting of concrete pipes and – in older neighborhoods – roadside ditches are used to route water into the creeks and bayous. At a minimum, these systems are designed to handle the 5- to 10-year 24-hour rainfall totals. For larger storm events, the street network acts as a secondary drainage system. In addition, there are several large on-going structural projects in Harris County, including Sims Bayou Federal Flood Damage Reduction Project, Greens Bayou Federal Flood Risk Management Project, and Brays Bayou Federal Flood Damage Reduction Project (Project Brays), aimed at reducing the impacts of flooding in the watersheds. There are also several examples of successful buyout programs in which flood prone neighborhoods have been converted into detention areas, including the Bretshire, Hall Park Stormwater, and Mud Gully Stormwater Detention Basins.

3.3. The Role of the National Flood Insurance Program

In 1968, the U.S. federal government enacted the National Flood Insurance Program (NFIP). The NFIP was intended to offset the need for federal disaster relief after major flood events and encourage floodplain management in participating communities. To participate, communities were required to identify the areas that can be reasonably expected to flood during a 1% event, i.e., the '100-year floodplain' or 'Special Flood Hazard Areas (SFHAs)' (Figure 3.5). Thus, the 100-year floodplain became the primary marker of flood risk in the United States, driving where development can take place and decisions regarding household and community flood mitigation (Brody et al. 2015). For example, under the NFIP, homeowners with federally-backed mortgages living within the SFHAs are required to buy federal flood insurance and those living outside can buy insurance on a voluntary basis. In addition, structures built in the floodplain are required to be elevated at or above the base flood elevation (BFE) associated with the 100-year flood; the amount of freeboard above the BFE is determined on a community-by-community basis.

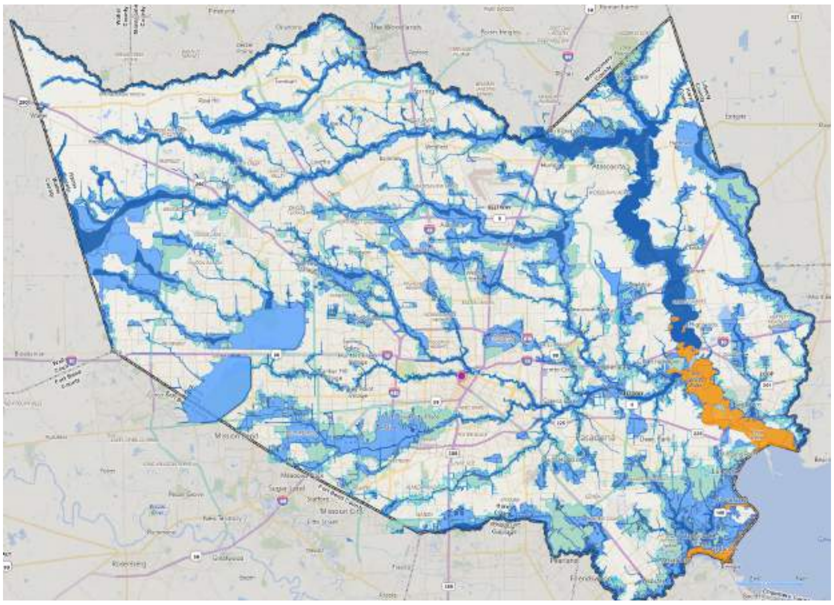


Figure 3.5. Current floodplains for Harris County, Houston; showing the 100-year (light blue), 500 year (light green), floodplains along the floodways (dark blue) and coastal floodplains (orange). Courtesy of HCFCD.

The City of Houston has been a member of the NFIP since 1974, with surrounding communities joining shortly thereafter. However, despite 43 years and millions of dollars of investments in flood risk reduction, Harris County still experiences the highest rate of repetitive flood losses in the country (Conrad et al. 1998; Highfield et al. 2013). As of June 30, 2017, the total insured damages in Harris County exceeded $3 billion USD (FEMA 2017a), a large percentage of which fell outside of the mapped floodplain areas. This has raised many questions as to the use of the 100-year floodplains as a marker of risk and the accuracy of the hydrologic and hydraulic models used to map them (Blessing et al. 2017; Brody et al. 2013; Highfield et al. 2013).

One potential reason for the inaccuracy of floodplain maps is that they are mapped at a single point in time, neglecting to account for the effects of changing land use/land cover on flood flows in urban watersheds (Sebastian 2016). This problem is especially prominent in the Houston region where a lack of comprehensive land use controls has encouraged and allowed for largely unrestrained development across the region. It is important to note that there are no significant geographic boundaries that limit Houston's growth to the west or northwest and development of these areas has been characterized by urban sprawl – low-density, mono-functional, car-dependent development – rapidly replacing the natural land cover with pavement. Between 1996 and 2010, the developed area in Harris County, alone, grew by more than 473 km^2 (183 mi^2), or 22.4%, greatly contributing to Houston's flood problem by increasing overland rainfall run-off volumes and flow rates (NOAA 2016).

3.4. Historic Tropical Cyclone Events

Houston has been referred to as 'America's Flood Capital' (Erdman 2016). Since the creation of the HCFCD in 1937, an estimated 30 damaging floods have occurred in the Houston area (HCFCD n.d.). Notable record-setting rainfall events include Tropical Storm Claudette (1979), Tropical Storm Allison (2001), and Hurricane Ike (2008). Tropical Storm Claudette made landfall on the Texas-Louisiana border on July 24, 1979. The storm stalled over Alvin, TX on the evening of July 25, dropping considerable rainfall. The highest one-day total in U.S. history was recorded in Alvin, TX where 1070 mm of rain fell in 24 hours and the total precipitation over the entire event was recorded to be 1143 mm. While Claudette's heaviest rainfall narrowly missed the developed areas near downtown Houston, it demonstrated the potential for extreme rainfall in the region.

Tropical Storm Allison made landfall on June 5, 2001. The storm stalled over Houston for four days. During Tropical Allison a large portion of Harris County received upwards of 800 mm of precipitation; the highest recorded total during the event was 985.5 mm. At one point during the event, more than 711.2 mm of rain fell in 12 hours near downtown Houston. Allison affected an estimated 2 million people, causing 22 fatalities, damaging 95,000 vehicles and 73,000 homes, and leaving over 30,000 people without homes (HCFCD n.d.). Substantial damage occurred at the Texas Medical Center and to businesses and infrastructure in downtown Houston. Insured losses totaled $5 billion USD and the total damages from Allison are estimated to have been around $9 billion USD, making it the costliest urban flood in U.S. history at the time (Blake and Gibney 2011).

During Allison, two-thirds of the flooded areas were located outside of the mapped floodplain areas (FEMA n.d.). In the wake of the storm, Harris County received substantial funding from FEMA to comprehensively re-analyze the region's flood risk. The Tropical Storm Allison Recovery Project (TSARP) aimed to revise the floodplain maps using more accurate data and latest models. As a result of this project, Houston became one of the first cities to utilize LiDAR to map the ground's topography for floodplain modeling. The models were also updated to include the latest land use/land cover information. The new maps were used to better assess locations of substantial flood risk and affected flood insurance premiums. In addition, substantial upgrades were made to the Texas Medical Center (TMC), including further development of the Rice University/TMC Flood Alert System (FAS), the installation of flood doors and gates, and improvements to the campus' emergency management strategy. A comprehensive list of upgrades and review of measures can be found in the paper by Fang et al. (2014).

Hurricane Ike made landfall near Galveston Island on September 13, 2008 as a Category 2 storm. While Ike was primarily a surge event, the interaction between storm surge and urban runoff in coastal areas highlighted the vulnerability of the region to compound flooding. In the wake of Hurricane Ike, several organizations have proposed structural solutions to mitigate storm surge flooding in the region including the coastal spine system, the Centennial Gate at the Houston Ship Channel, and, more recently, a mid-bay barrier (Blackburn et al. 2014; Merrell et al. 2016)

3.5. Recent Precipitation Events

In addition to tropical cyclones, two recent rainfall events resulted in severe flooding in Houston: the Memorial Day (May 26, 2015) and Tax Day (April 16-17, 2016) flood events. Properties in Brays Bayou, especially the Meyerland area, were flooded during both events. During both events, water in Brays Bayou overflowed the channel's banks, emphasizing what could happen if a larger, more severe event were to occur. In addition, during the Tax Day Flood, the area upstream of Addicks and Barker Reservoirs received over 330-430 mm of rain in 12 hours and the water behind the reservoirs reached record levels. Severe flooding occurred in the Cypress Creek watershed. In total, an estimated 9,800 homes and 40,000 cars were affected during the Tax Day Flood (Lindner 2016); insured damages approached $0.5 billion USD (FEMA 2017b).

After the Tax Day Flood, the HCFCD issued a statement encouraging Houstonians to purchase flood insurance to avoid dramatic out-of-pocket expenses during future events (HCFCD 2017a). In addition, public discussion about the limited capacity of the reservoirs took place and a number of proposals were put forward to reduce the vulnerability of Buffalo Bayou to flooding, including the constructing of a dam in Cypress Creek to prevent water for overflowing into the Addicks Reservoir (Caruba 2016). However, no flood risk reduction strategies were implemented prior to Hurricane Harvey.

3.6. Understanding Flood Risk Management in Texas

There are significant differences between the governance of flood risk reduction in the Netherlands and Texas. Whereas the responsibility for flood risk management in the Netherlands is largely shared between two authorities: Rijkswaterstaat at the national level and the Waterschappen (Water Boards) at the regional level (with some input from the Provinces and municipalities on land use issues), the responsibilities for managing flood risk in the U.S. are considerably more distributed. Flood risk management in the U.S. is often a shared responsibility between multiple federal, state, and local government agencies and organizations via a complex set of programs, responsibilities, and regulations (Figure 3.6).

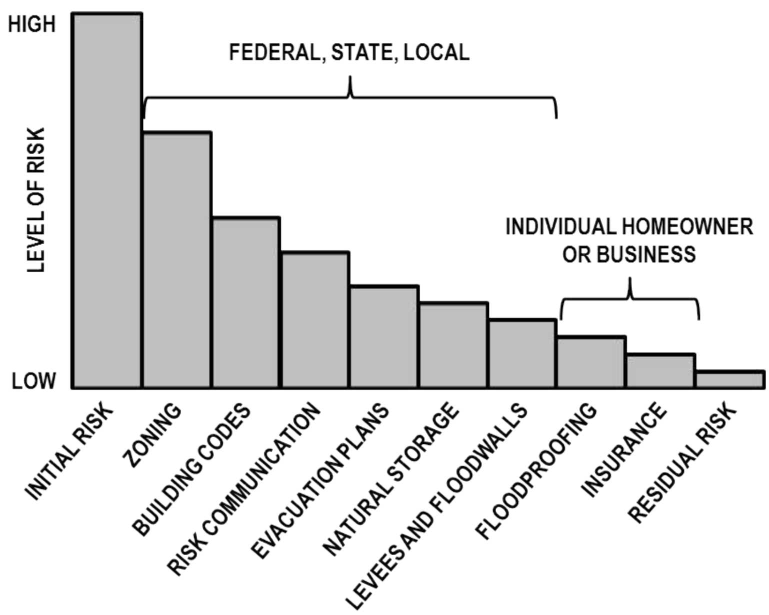


Figure 3.6. Distribution of flood risk management among federal, state, regional, and local authorities in the U.S. Modified from NRC (2013)*; Traver* (2014)*; USACE* (2006).

Similar to Rijkswaterstaat in the Netherlands, there is a federal agency – the U.S. Army Corps of Engineers (USACE) – responsible for the construction, maintenance, and operation of large civil works. However, there is also an additional federal agency – the Federal Emergency Management Agency (FEMA) within U.S. Department of Homeland Security (DHS) – that is responsible for coordinating government-wide disaster relief by 'preparing for, protecting against, responding to, recovering for, and mitigating all hazards' (FEMA n.d.). FEMA is also responsible for administering the National Flood Insurance Program (NFIP) and funding Hazard Mitigation Assistance (HMA) Grants to facilitate pre- and post-disaster mitigation (see Section 3.3).

At the regional and local levels, flood risk management becomes significantly more complex. Especially in the State of Texas, where, in general, an aversion to federal interference concerning land use and private property is prevalent, a scattered and increasingly localized organization of responsibility for flood risk management has developed over time. Several state-level organizations, including the Texas General Land Office (GLO), the Texas Commission on Environmental Quality (TCEQ), and the Texas Department of Transportation (TxDOT), are broadly involved in permitting and monitoring the state of urban infrastructure, including dams, storm water systems, and industrial facilities. In addition, there numerous local jurisdictions, including cities, levee improvement districts (LIDs)[3], and municipal utility districts (MUDs)[4], which set their own criteria for managing floods, designing urban infrastructure, and allocating resources for emergency response (Figure 3.7).

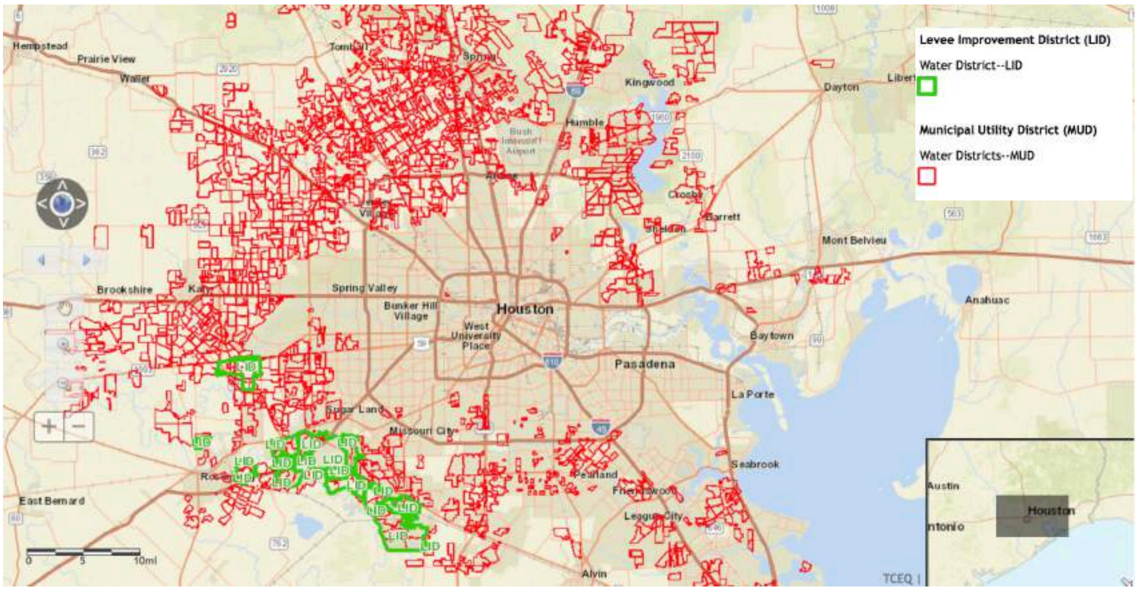


Figure 3.7. MUDs and LIDs locations in Greater Houston (Source: TCEQ Water districts map viewer)

[3] LIDs are created to manage and maintain public levees. They are not federally funded, so they rely on local ad valorem property taxes. The levee systems must meet and continue to meet minimum design, operation, and maintenance standards set forward by the USACE and FEMA to receive NFIP recognition.
[4] MUDs are political subdivisions of the State of Texas, authorized by the TCEQ, in areas where municipal services are not available (typically outside of city limits). They are independent, limited governments which are able to raise revenue via property taxes. They may be responsible for emergency services (e.g., fire, EMS, police); public works, engineering, and localized drainage systems; building permits for incorporated areas; and floodplain management.

Perhaps the most significant difference in flood risk management between the Netherlands and Texas is created by the fact that flooding in Texas occurs on a regular basis, and thus the public entities responsible for managing emergency response are not only strongly present, but also accompanied by multiple private and NGO organizations actively participating in reducing flood risk via Safety Layers III and in some extend in Safety Layer II (see Chapters 6 and 7). In the Netherlands, by contrast, a flood event is extremely rare and preferably prevented through structural measures (Safety Layer I) resulting in a lean emergency response system which relies on disaster and emergency response training rather than lessons learned through real-world experiences. Moreover, few Dutch citizens have experienced a flood event (Kothuis and Heems 2012).

3.7. Houston's urban fabric and land use policies

Empirical evidence exists that Houston's lay out (where it is built: in watersheds and wetlands that serve as storage areas for extreme rainfall events) and its urban fabric (how it is built: sprawling, low-density development with an abundance of paved-over surface) have contributed to repetitive losses over time(Blessing et al. 2017; Brody et al. 2008, 2014). In fact, Harris County and surrounding areas rank among the highest rates of repetitive loss in the country (FEMA 2007). The flooding caused by Harvey and other recent flood events, suggest that an expanded strategy is required to include the urban fabric's vulnerability to flooding, and policies and local cultural values behind it. To date, spatial research has identified two main obstacles that discourage spatial adaptation in the Galveston Bay area: fragmentation of discretionary powers (Brand, 2015; 2017) and inconsistency between existing urban planning documents (Berke et al., 2015; 2017).

The region's pro-development policy is a primary driver behind its extremely vulnerable land use pattern. Houston imposes minimal land use controls in favor of private initiative and economic growth (Lerup 2011). In the City of Houston, the municipality – the default government entity in charge of spatial planning tools throughout the world – does not have a zoning ordinance, the most basic tool of U.S. land use regulation. This does not mean that the metropolitan region's urban development is completely uncontrolled; however the tools for control, like the so-called deed restrictions and building codes, reside within a multitude of special districts at the local level (i.e., MUDs and LIDS) that pursue their own independent policies (ULI, 2015). The capacity for 'self-regulation' of these special districts are locally seen a means to satisfy a high demand for new homes (Basset and Malpass 2013), and to build and maintain their own levee-systems (like those in Fort Bend County). In 2015, policy makers at the city-level have succeeded to mobilize piecemeal policies of special districts into a shared spatial strategy geared towards economic growth ('Plan Houston').

Houston, Texas, August 31, 2017 (Image courtesy: FEMA - Dominick Del Vecchio)

Flooding during Hurricane Harvey

4

4.1. Introduction

Between August 25 and 30, 2017 Hurricane Harvey dropped substantial rainfall over the City of Houston and surrounding areas resulting in devastating urban flooding (Figure 4.1). The highest precipitation totals during the storm were registered in southeast Harris County where isolated rainfall gages recorded as much as 1224 mm over the five-day period with some areas receiving upwards of 531 mm of rain in 12 hours during the morning of August 27 (Figure 4.4). By Sunday afternoon August 27, 2017, the majority of the 22 watersheds in Harris County were experiencing flooding with about half reaching record levels. In addition, widespread street flooding occurred city-wide as the storm sewer network reached its capacity.

Figure 4.3. August 29, 2017 - A flooded bayou in Houston is carrying high amounts of rain water downstream (Image courtesy FEMA - Dominick Del Vecchio)

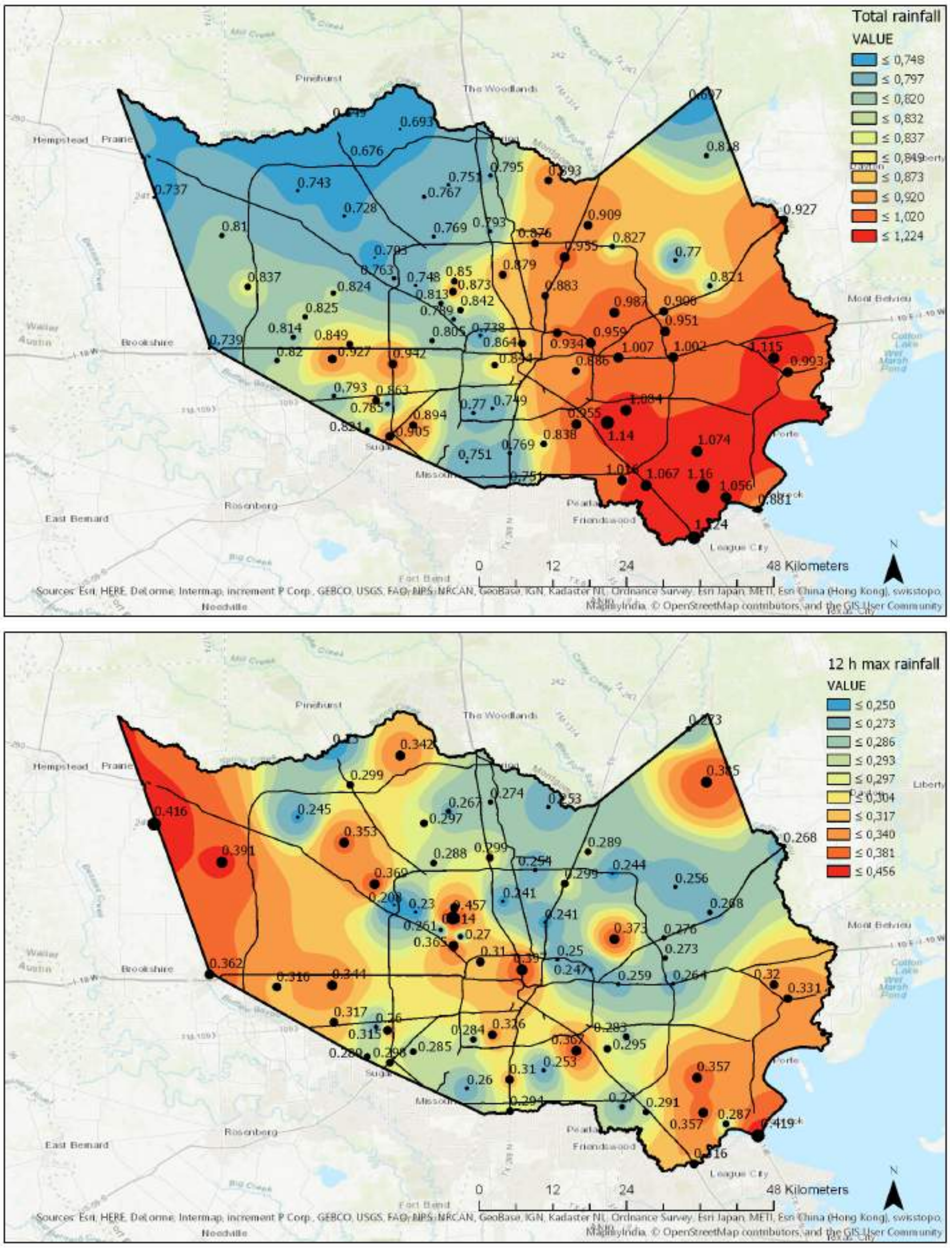


Figure 4.4 (a) Cumulative 5-day precipitation totals (m) and (b) maximum 12-hour rainfall (m) intensities in Harris County, Texas. Red areas indicate the highest precipitation totals whereas blue areas indicate the lowest. Black dots show the location of precipitation gages.

An overview of the HCFCD stream gage network is presented in Figure 4.5. The red markers illustrate locations where water levels exceeded the top of the channel at 12:00 AM (CDT) on August 28. By the morning of August 30, much of the water had receded from the neighborhoods and returned to within the confines of the channels with the exception of Cypress Creek, Buffalo Bayou, and Clear Creek, where local watershed conditions prevented the water from receding quickly.

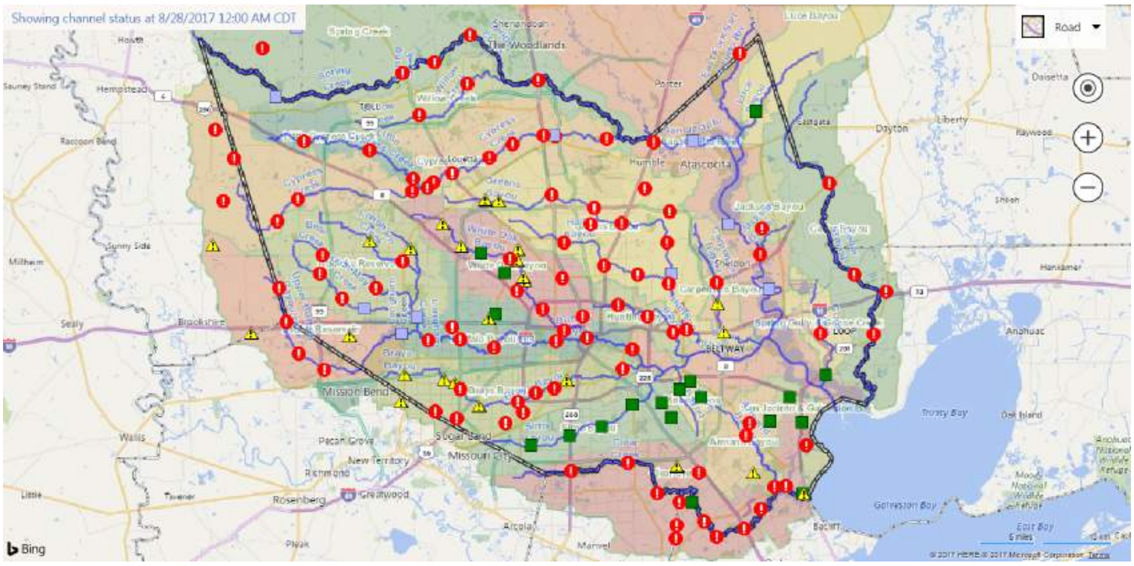


Figure 4.5. Status of the HCFCD stream gages as of August 28, 2017 12:00 AM (CDT). Locations marked in red are out of bank and locations in yellow are near the top of bank. Figure courtesy of https://www.harriscountyfws.org/.

Record-setting flooding during Hurricane Harvey occurred throughout the greater Houston region. To give the reader a sense of the extent and severity of flooding region-wide, the following sections focus on the hydrologic and hydraulic response in a few key watersheds: Buffalo Bayou and contributing areas; the San Jacinto River and Houston Ship Channel; and the Brazos River.

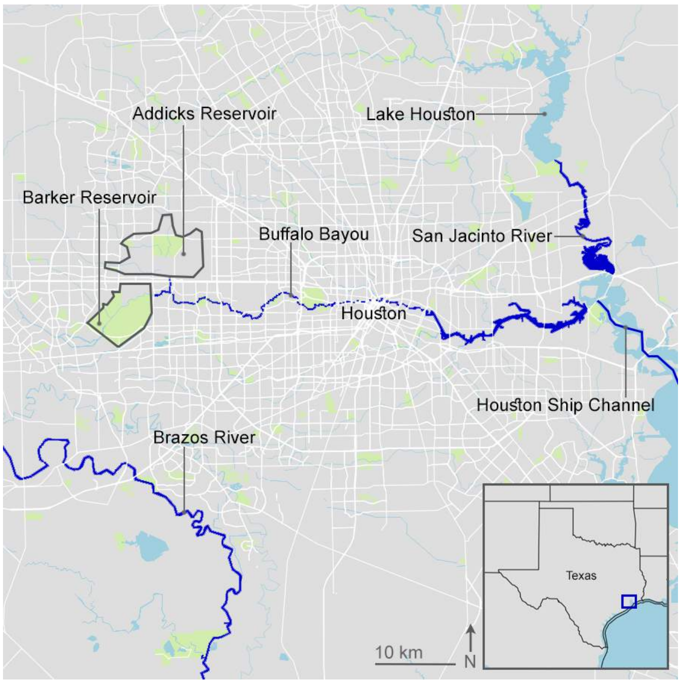


Figure 4.6. Map showing the locations of key areas discussed in the following sections: Buffalo Bayou; the San Jacinto River, Lake Houston, and lower portion of the Houston Ship Channel; and the Brazos River near Sugarland, Texas.

4.2. Buffalo Bayou – Addicks & Barker Reservoirs

During and after Hurricane Harvey, substantial flooding occurred both upstream and downstream of the Addicks and Barker reservoirs. On August 25, in preparation for Harvey, the USACE had closed flood gates ‘as a routine precaution’ prior to a predicted rainfall event. In part due to the large volumes of water flowing into the reservoirs, neighborhoods built within the footprint of the dam (i.e., those at levels lower than the maximum elevation of the dams) began to flood before the water levels in the reservoirs could be sufficiently reduced (i.e., the inflow exceeded the outflow). Downstream of the reservoirs, portions of Buffalo Bayou had already exceeded channel capacity prior to controlled releases that began on August 28. Other areas were at or near channel capacity and flooding was further exacerbated by reservoir releases. The chain of events leading to flooding along Buffalo Bayou is described in further detail below.

Addicks and Barker Reservoirs

Between August 25 and 28, approximately 254 and 457 mm of rain fell in the contributing areas upstream of the Addicks and Barker reservoirs, respectively (HCFCD 2017b). Water rose inside the reservoirs, reaching record levels. Around midnight on August 27, water began rising into neighborhoods on the western and northern sides of the reservoirs. At this point, the Army Corps of Engineers (USACE) announced that it would begin controlled releases from Addicks and Barker in the early morning hours on August 28 at ‘higher-than-normal’ rates (above 115m^3/s) to prevent uncontrolled and even catastrophic releases from the dams (i.e., due to overflowing of the emergency spillways or dam failure) and reduce additional flood risks.

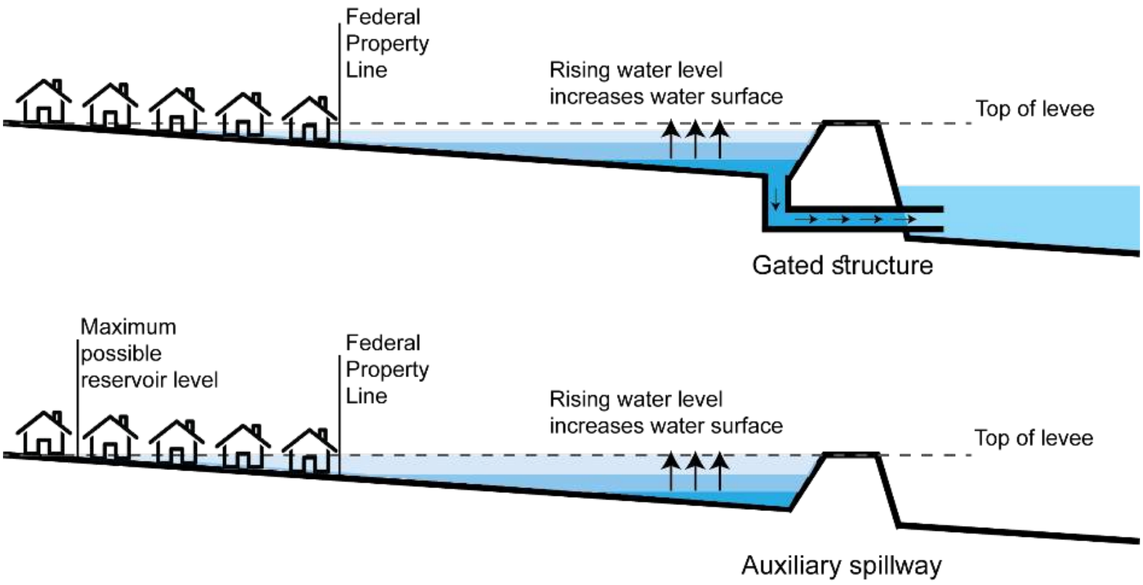


Figure 4.7. Longitudinal cross section of Addicks Dam and reservoir pool.

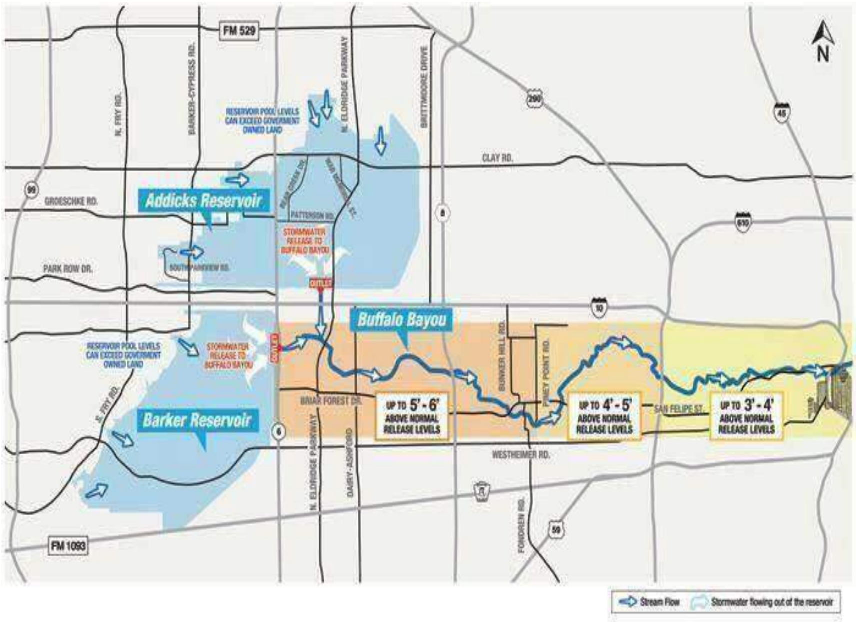


Figure 4.8. Expected water levels in areas downstream of Addicks and Barker reservoirs when release rates exceed 115 m^3/s. Depths in downstream areas can increase an additional 0.6 – 1.2 meters (in yellow) to 1.5 - 1.8 meters (in orange) above normal levels when releases occur. Courtesy of HCFCD.

The USACE began releasing water around 02:00 AM (CDT) at Addicks and 11:00 AM (CDT) at Barker on Monday, August 28 (Harden and Ellis 2017). The combined releases from the two reservoirs peaked on August 28 with Addicks releasing at about 200 m^3/s and Barker at about 170 m^3/s. The reservoirs continued to rise until August 30 due to continued rainfall and substantial runoff from areas upstream, including overflow from the Cypress Creek watershed. Despite controlled releases, the water flowed over and around the emergency spillways of the Addicks reservoir, peaking at 33.5 meters on August 30 (Figure 4.9a). The water levels in the Barker Reservoir remained below the level of the spillways, peaking at 31 meters on August 30 (Figure 4.9b). The USACE continuously monitored the dam during the event and has indicated that there was no risk of failure.

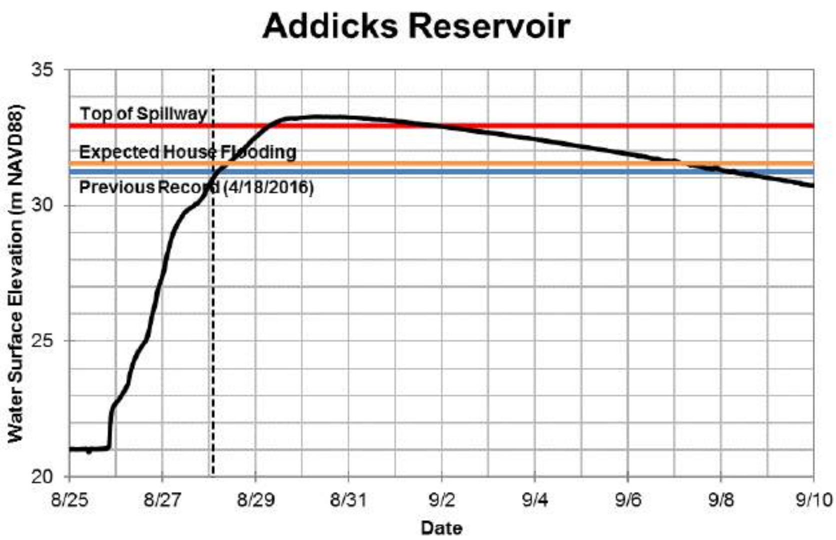


Figure 4.9.a (Full caption next page)

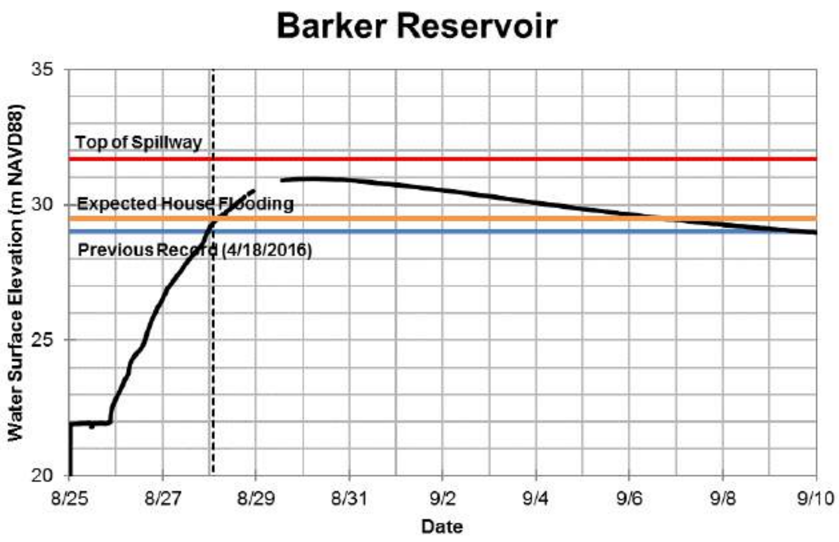


Figure 4.9b. Water levels (m NAVD88) in (a) Addicks (USGS 8073000) and (b) Barker (USGS 8072500) reservoirs between August 25 and September 10, 2017. The tops of the spillways are at 31.2 and 29.0 m, respectively. The previous record maximum water elevations reached during the Tax Day Flood (2016) are also shown.

To reduce the levels of water in the reservoirs behind the dams as quickly as possible, the USACE continued releasing water at higher than normal rates through the second week of September (for a period of approximately 15 days), after which the rates were lowered to 115 m^3/s.

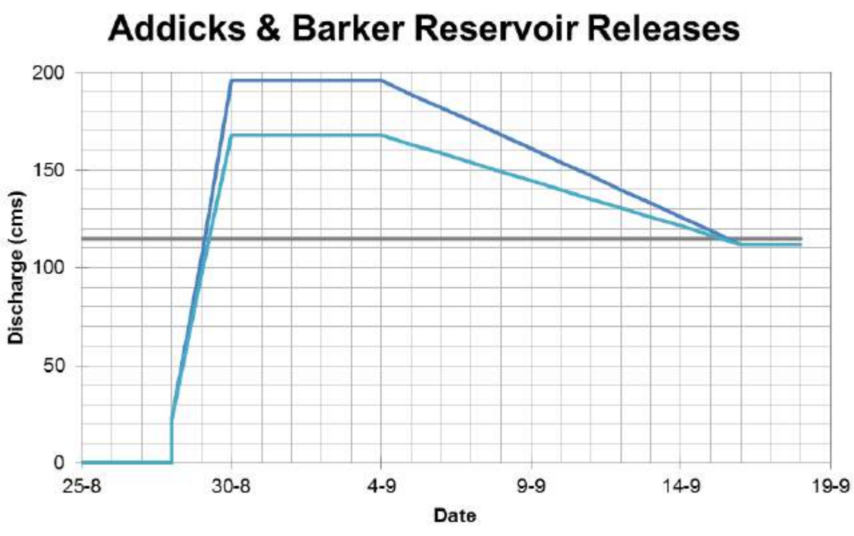


Figure 4.10. Approximate release rates (m^3/s) from Addicks and Barker Reservoirs as reported by USACE starting on August 28. Release rates are reported to have peaked at about 200m^3/s and 170 m^3/s, respectively. Reduction of releases were reported as of September 4, however, the rate of release during the period between September 4 and 17 is unknown. By September 17, releases had been reduced to 115m^3/s.

Flood levels in Buffalo Bayou

By mid-day on August 27, before the USACE is reported to have begun releasing water from the reservoirs, water levels in Buffalo Bayou had already exceeded its banks in the areas directly downstream of the dams (e.g., at Beltway 8). Water levels continued to rise after the releases began on August 28, eventually peaking at 23.4 meters on August 30 (Figure 4.11). This is the highest water level ever recorded at this location; considering that the 500-year water level is estimated by the HCFCD to be 22.8 meters, the water level likely exceeded the 500-year event (HCFCD 2017c). Moreover, considering that the majority of rain had already fallen prior to releases from the dam on August 28 (Figure 4.12), it is expected that much of the flooding in neighborhoods downstream of the dams was exacerbated by the release of water from the reservoirs, however, further investigation and a more detailed hydrological modeling study is recommended to assess the exact contribution of the reservoir releases to downstream flooding and flood impacts.

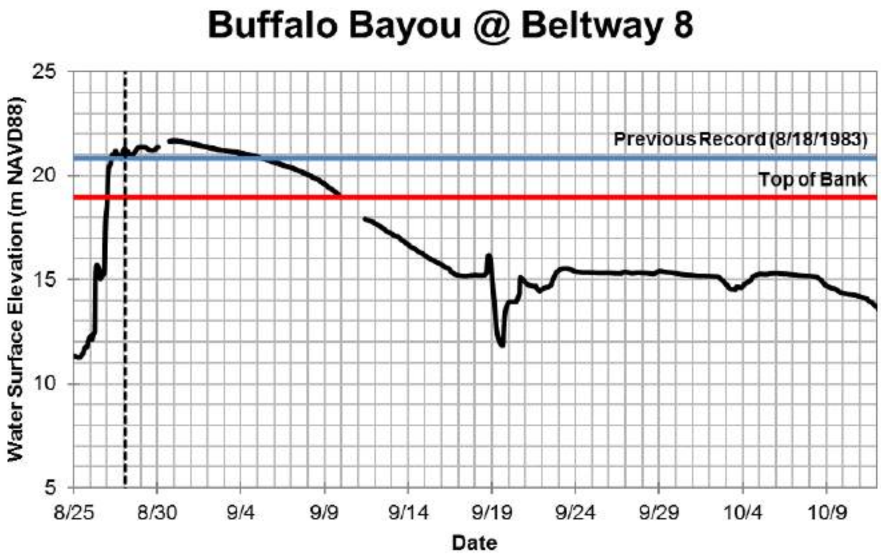


Figure 4.11. Water levels in Buffalo Bayou, at Beltway 8, between August 26 and September 9..

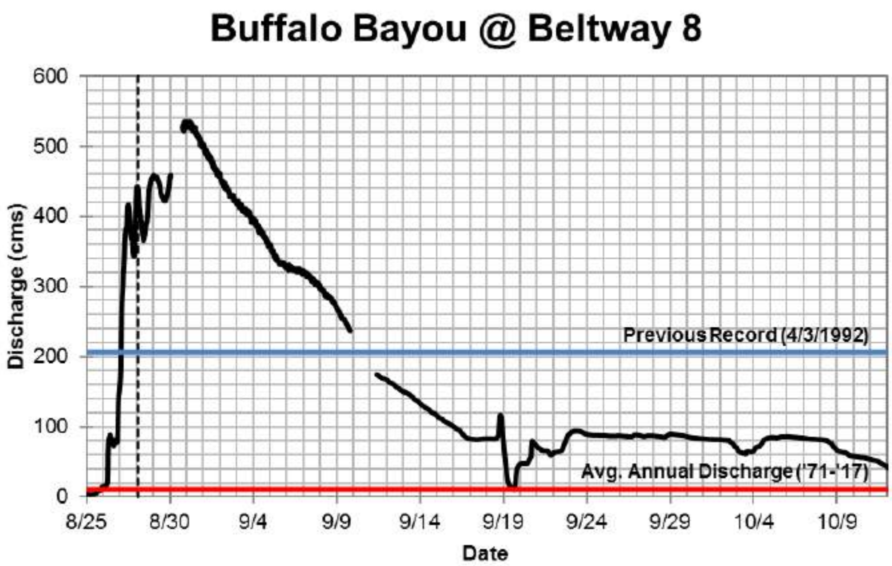


Figure 4.12: Discharge through Buffalo Bayou expressed in cubic meters per second (cms). Included is the average annual discharge rate (approx. 11 cms) based on records from 1971-2017.

As of September 1, 2017, it was estimated that approximately 4,000 homes had been affected by flooding downstream of the reservoirs. Anecdotal evidence from citizens living in the neighborhoods downstream of Addicks and Barker Reservoirs has suggested that insufficient information was provided prior to the releases of the reservoirs and that flooding occurred earlier than anticipated. Moreover, the speed with which water rose in these neighborhoods came as a surprise, forcing many residents to flee their homes with little preparation and necessitating a number of rescues. Conversations with residents suggest that the loss of personal property (e.g., cars, house contents) could have been avoided with additional warning. However, further investigation is required to determine whether there were mistakes in terms of emergency warning and public communication or whether water levels rose faster than expected by public officials, and if so, why.

4.3. San Jacinto River

Lake Houston is a reservoir on the San Jacinto River. The reservoir was built in 1953 and serves as the primary municipal water supply for the City of Houston. During Hurricane Harvey, water levels in the reservoir peaked at nearly 16.1 meters overtopping the top of the spillway by approximately 3.3 meters. This is the highest level ever recorded and considering that the 500-year water level at the spillway is estimated by the HCFCD to be 15.8 meters, the water level likely exceeded the 500-year event (HCFCD 2017c). Downstream of the dam, flood levels were so high that many stream gages along the river stopped recording or malfunctioned. Moreover, the combined flows from other watersheds in Harris County (e.g., Buffalo Bayou) and the San Jacinto River caused the water in the Houston Ship Channel to rise to unprecedented levels. It is also possible that high water surface elevations in Galveston Bay due to Harvey's storm surge further exacerbated flooding in the Houston Ship Channel.

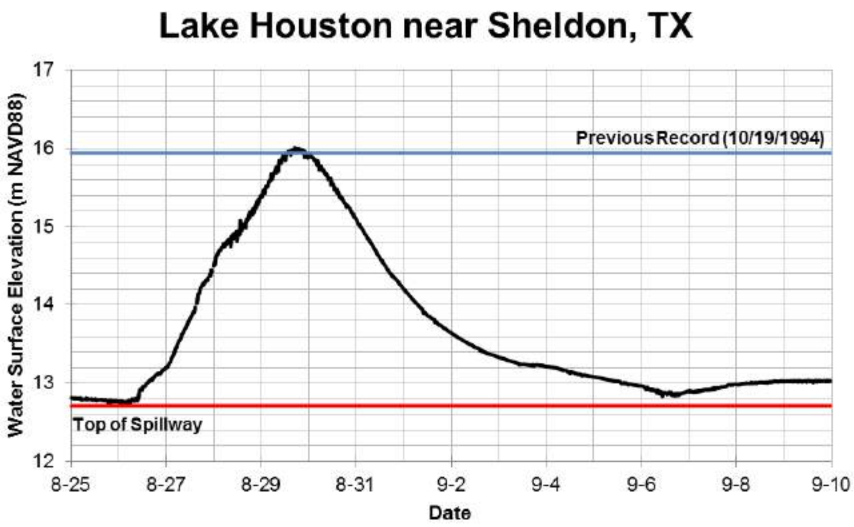


Figure 4.13. Water levels at the Lake Houston Dam near Sheldon, Texas (USGS 08072000).

4.4. Brazos River

In addition to flooding in Harris County, the Brazos River in Fort Bend and Brazoria Counties (Figure 4.13) southwest of Houston also reached record levels. In Fort Bend County, several levee systems were built to protect neighborhoods adjacent to the Brazos River from flooding. These levees are designed to withstand the 100-year flood event and have an approximate height of 18 meters. Initial predictions forecasted water levels in that area to reach as high as 18 meters suggesting that the river would overflow much of the levee systems in the area. Fortunately, the river crested at 16.8 meters on Thursday, August 31 (Figure 4.14).

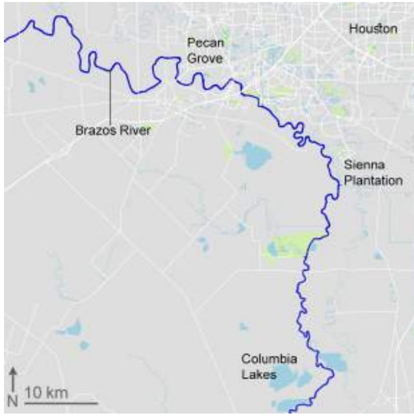


Figure 4.14. Map of Brazos River

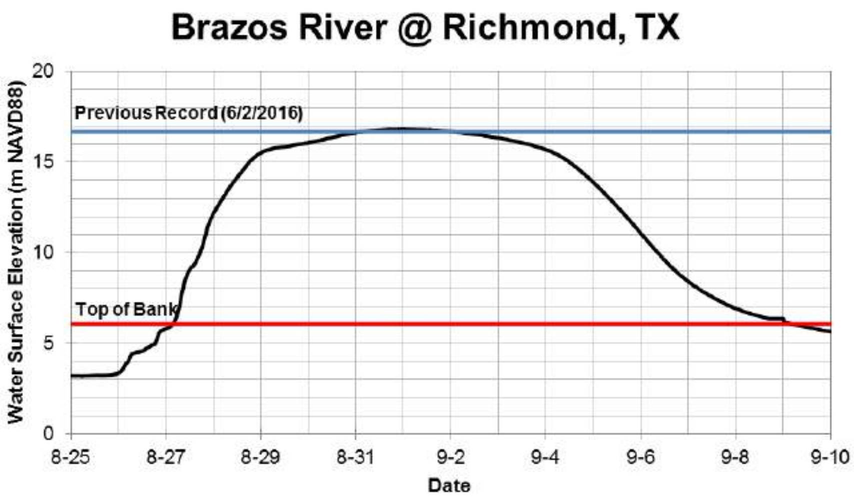


Figure 4.15. Water levels in the Brazos River near Richmond, Texas (USGS 8114000).

Although no levees overtopped, at least two complications with levees were reported. Near Pecan Grove, an open valve beneath the levee was leaking water through the levee, which required an emergency fix. A heavy crane operator and a dive team were able to close the valve. Further downstream, near Sienna Plantation, the interior rim of the levee system required reinforcements to prevent overtopping. Volunteers and the National Guard increased the crest of the levee with plywood and two-by-fours. Because the river water levels were not forecasted to decrease, they ran temporary pumps forcing seepage water back in to the river, and placed sand bags on top to increase the height (Carpenter and Foxhall 2017). According to the Fort Bend County Office of Emergency Management, the problems were not believed to be a cause for major concern (Foxhall 2017). Nevertheless, news about levees breaching near Columbia Lakes had spread (Figure 4.15).

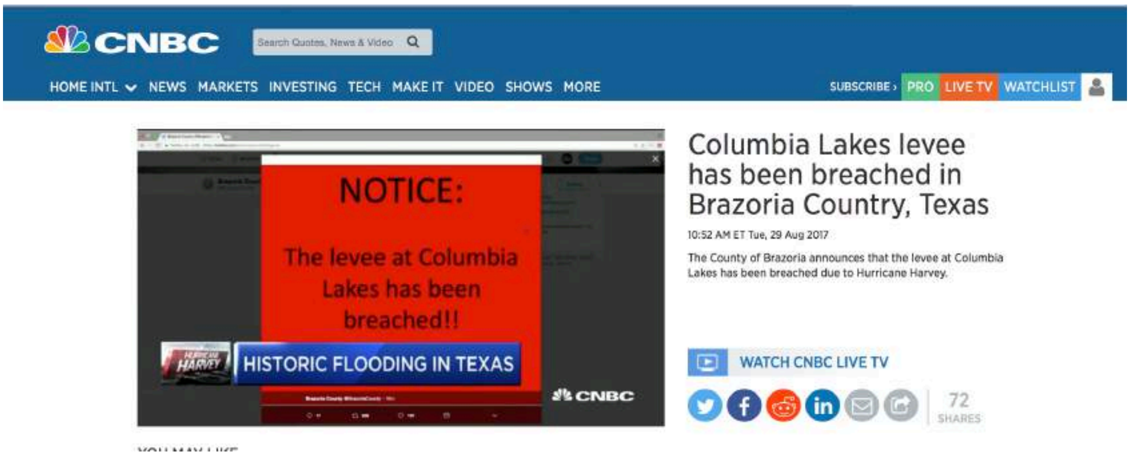


Figure 4.15. Wrongfully issued warning by Brazoria County about levees breaching (Retrieved from CNBC/ County of Brazoria)

4.5. How does Harvey compare to previous floods?

Many reports have stated that Harvey was unprecedented and various return periods have been mentioned in combination with precipitation and flood levels during Hurricane Harvey, ranging from 100 years to over 1000 years (Meyer 2017; Samenow 2017). In this section we attempt to substantiate some of these claims by comparing Harvey against previous floods and available information regarding return period rainfall and water levels.

The precipitation rates observed during Harvey for Harris County were compared to the depth-duration frequency (DDF) values calculated by USGS for sub-regions in Texas which can be found in Asquith (1998). Figure 4.16 shows a comparison between the peak rainfall totals at two gage locations: gage 1730 in Cedar Bayou and gage 110 in Clear Creek, and the curves for five duration periods: 1-, 2-, 3-, 5-, and 7-days, in Harris County Region III. The results indicate that Harvey was, indeed, an extreme event with respect to rainfall. None of the observed maxima correspond to a predicted return period shorter than 5,000 years according to existing frequency estimates[5].

[5] It is important to note that the return periods are based upon historical observations and are statistically extrapolated from point estimates. Results for very low probabilities should thus be interpretated with the greatest care. This is illustrated by the observed maximum for 3-day rainfall, which coincides with a return period of more than 6 million years. This does not seem to be a realistic return period, suggesting that the distributions and parameters for the derivation of the return periods from the USGS should be re-evaluated – leading to changes in the curves.

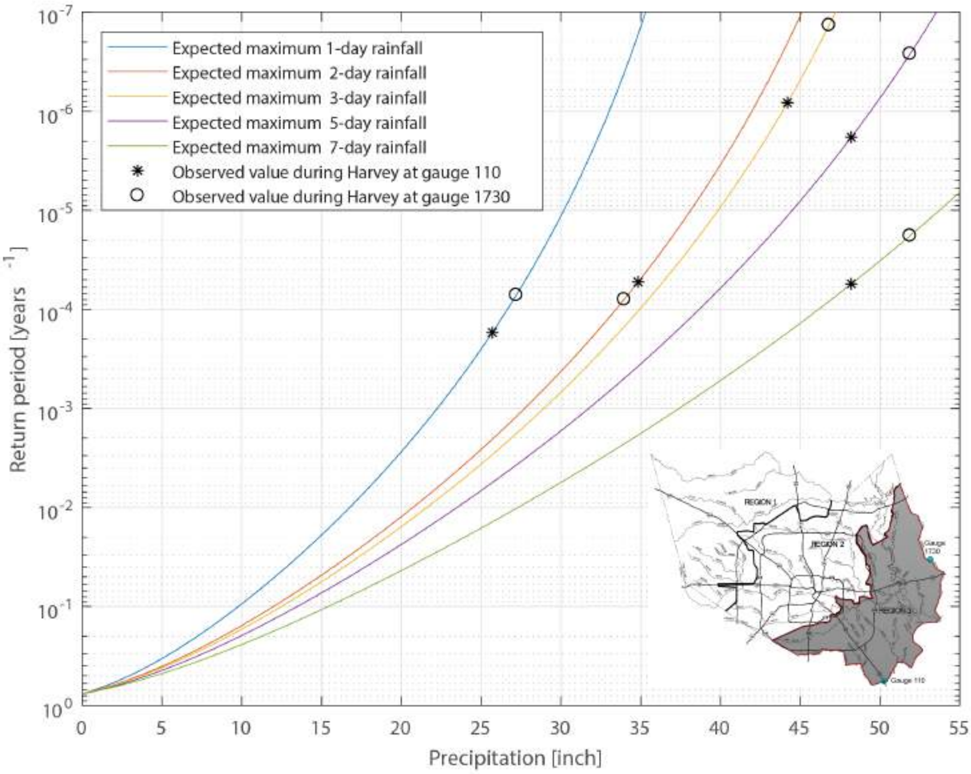


Figure 4.17 Observed precipitation in Cedar Bayou (Gage 1730) and Clear Creek (Gage 110) in inches for five different periods during Harvey compared with the existing curves for the expected maximum rainfall. The precipitation curves are fitted with the Generalized Extreme Value distribution.

Also, water levels for some locations have been compared with existing estimates of return periods. For example, in the Brays Bayou, the level of flooding is similar to what was observed during the Memorial Day Flood in 2015, which according to HCFCD estimates corresponds to a return period between the 100-year and the 500-year event. For example, water levels at Almeda Road peaked at 12.3 meters while the 100-year water level is estimated at 11.9 meters and the 500-year water level 12.8 meters. In Clear Creek and Dickinson Bayou, the water levels during Harvey exceeded those during TS Claudette, the previous storm of record (and have exceeded water levels during Hurricane Ike). The water level in Clear Creek at I-45 reaching a level of 5.1 meters. This exceeds the 500-year event that was estimated at 4.6 meters. Similarly, in Cypress Creek watershed, some stage gages recorded water surface elevations over 3 meters above the channel banks. The catastrophic flooding levels in Cypress Creek watershed during Hurricane Harvey surpassed levels observed during the Tax Day flood of April 2016 (SSPEED report).

The comparison of Harvey against previous events has raised questions as to whether the strength of the hurricane was affected by climate change. The IPCC suggests that in the future, a warmer climate will lead to more intense hurricanes, pointing to the possibility that Harvey's outsized rainfall could be attributed to climate change. While higher-than-average temperatures in the Gulf of Mexico likely fueled Harvey's development into a Category 4 hurricane just before landfall, the upper atmospheric weather phenomena that contributed to Hurricane Harvey's track and subsequently the immense amount of rain that fell have not yet been studied.

It is important to point out that storms that stall over Harris County have occurred in the past. Both Tropical Storm Claudette (1979) and Allison (2001) behaved similarly to Harvey in that they remained over the region for multiple days, but the notable difference in these events were that they were substantially smaller in spatial scale. The cumulative totals from both of these events fell across and much smaller area, and while they caused devastating flooding in certain watersheds, their impacts at a regional scale are dwarfed by Hurricane Harvey. In addition, while significant measures were taken to reduce flood risk in Harris County after Allison, the number of people and structures in the region has grown substantially, increasing exposure to floods.

Finally, substantial evidence suggests that rapid growth in Houston and decisions regarding the management of and flood control in Houston's watersheds have likely contributed to the substantial losses that were observed during Hurricane Harvey. While the cumulative precipitation and intensity of rainfall during Harvey was beyond typical engineering design criteria, measures can be taken to help reduce risk of rainfall-induced flooding in the future.
Recommendations regarding directions for research on flood risk reduction and mitigation in the Houston region are discussed in Chapter 8.

Damages and Fatalities

5

5.1 Introduction

In this report, we describe economic damages and the number of fatalities for which the data was available at the time of writing. Total damage estimates due to Harvey still vary. According to the NY Times, total damage estimates ranged from 70 to 108 billion USD as of September 1st, while Texas Governor Greg Abbott suggested that the damage could reach between 150 and 180 billion USD. This puts Harvey as the second costliest event in U.S. History, with Hurricane Katrina being the first. Among the top ten most costly events in the US, at this point three will have occurred in Houston: Allison (2001), Ike (2008) and Harvey (2017).

Flood damages are typically categorized as economic damages, expressed in monetary terms (e.g., houses and cars), and non-economic damages, not expressed in monetary terms (e.g., injuries and fatalities). Among the economic damages, a distinction is made between direct and indirect damages:

- Direct damages constitute damages caused by flooding in the affected areas. Examples include water damage to houses, cars, buildings, agriculture, infrastructure, evacuation and shelter costs and business losses within the flooded area.
- Indirect damages constitute damages and costs outside of the flooded area. Examples include business losses from business located outside the affected area, temporary housing outside the flooded area, social disruption and governmental costs.

The following sections describe impacts to residential structures (section 5.2), industry (section 5.3), the environment (section 5.4), airports (section 5.5), and critical infrastructure (section 5.6), as well as the reported fatalities (section 5.7).

5.2. Damage to residential structures

Many of the Bayous flow through populated residential areas which were flooded when the Bayous reached full capacity and overtopped. Here, roadways turned into entire rivers. Damage to houses range from mild to severe, depending on the height, velocity and duration of flood levels inside the structure. After having overtopped, the water levels in many of the Bayous (e.g., White Oak, Brays) receded quickly leaving the surrounding neighborhoods dry after having been flooded for several hours. However, also with short durations of flooding, as of August 27 FEMA predicted that more than 90,000 residential structures in Harris, Galveston and Fort Bend counties could have been damage from the storm. Predictions were based on a comparison against the 500-year floodplain (given that the flood levels were expected to have exceeded the 500 year flood level).

Especially near Addicks and Barker dams, where the controlled releases through the dam have resulted in high velocities and flood depths, a lot of residential structures would have suffered major damages. The duration of flooding in these areas is significant due to the long period of controlled releases required to drain the reservoirs. Fleetwood and Briar Hills neighborhoods, for example, situated directly downstream of both dams, experienced flooding well over the 500 year floodplain as shown in Figure 3.5, Chapter 3.

Final damage estimates still vary. As of August 29th, FEMA estimated that 115,412 houses would have suffered some form of damage. By September 6th, the Houston Chronicle estimated a total of 119,000 houses damaged by Harvey of which 800 are destroyed completely. Texans filed more than 87,000 flood insurance claims after Hurricane Harvey as of 28 September 2017, and the National Flood Insurance Program (NFIP) has made $608 million in expedited claims payments. NFIP implemented temporary changes to the claims process to help policyholders get started rebuilding as soon as possible.

Besides damage to houses, flooding left 300,000 people without power. In addition, initial estimates suggest that about 500,000 cars are damages due to Harvey. The full extent of damages to infrastructure is still unknown, although there are several reports of bridges collapsing due to scouring of the foundations. Some of the earlier-mentioned sites or neighborhoods have suffered repetitive losses over the last two decades (since Allison), and/or have developed a reputation for being vulnerable to flood losses. Such sites include the community of Meyerland in southeast Houston, and Turkey Creek, near Addicks reservoir.

5.3. Damage to industry

Industrial damages triggered by floods are among the most frequent technological disasters triggered by natural-hazard, i.e., ‘natech’ disasters. These damages can be divided in direct damages (e.g., to structures and equipment) and business losses suffered due to downtime.

- Direct damages: The hydrostatic and hydrodynamic forces of floods can cause structural damage to chemical- and process facilities (Figure 5.4). Structural damage can be in the form of displacement, floating, overturning, and shell buckling of vessels along with shell rupture due to the impact of waterborne debris. The displacement of process vessels (due to sliding, flotation, overturning, and even excessive shell buckling) may lead to the damage of connected pipelines. Roof collapse occurs regularly as well.
- Indirect damages: Floods can cause cascading effect in industry, where floodwaters can cause electrical or cooling equipment to shut down due to power outages, ultimately resulting in entire plants to shut down, which may lead to significant business disruption and loss of revenue.

Direct damages

Structural damages may result in disastrous release of hazardous chemicals, which, aside from the danger of subsequent fires and explosions, can cause very severe environmental pollutions. The damage to chemical and process facilities due to the Hurricanes Katrina and Rita in 2005 led to the second largest environmental pollution in the U.S. after the Deep Horizon disaster in the Gulf of Mexico in 2010.

Figure 5.1. A massive oil spill that threatens this town in St. Bernard Parish resulted when an oil tank was forced from its foundation by Hurricane Katrina's massive storm surge. (Courtesy of Bob McMillan/ FEMA)

The following table includes a list of industrial plants that suffered direct damages during Hurricane Harvey, while the following section describes the environmental damages resulting from direct damages to industrial facilities.

Table 5.1. Type of industrial plants damaged during the Hurricane Harvey

Company Name	Type of Industry	Type of toxic chemicals
Invista	Plastic Manufacturer	Polytetramethylene ether glycol, Tetrahydrofuran, and 1,4 Butane Diol
LyondellBasell	Plastic Manufacturer	Polymers
LyondellBasell	Refinery	Gasoline, diesel, benzene, paraxylene, orthoxylene
Celanese Chemical	Chemicals Manufacturer	Methanol
Dow	Plastic Manufacturer	Polyurethanes
Eastman	Plastic Manufacturer	non-phthalate plasticizers
Indorama Ventures	Chemicals Manufacturer	Ethylene Oxide
Indorama Ventures	Plastics Manufacturer	Glycols
Arkema	Chemicals Manufacturer	Sulfuric substances
ExxonMobil	Refinery	Acrylic Acid
Enterprise	Refinery	Hydrocarbon fuels
Chevron Phillips	Petrochemical	Hydrocarbon fuels
Shell	Refinery	NGL fractionators

Indirect damages
As a large portion of the nation's refining capacity is situated along Texas Gulf Coast, the impact on the oil and gas industry is significant. Cascading effects due to Harvey include several refineries along the coast to shut down, due to power outages caused by flooding. As of September 1st, an estimated 3 million barrels per day of refining capacity have been still down due to flooding caused by Harvey, which represents 16% of the nation's refining capacity. As a result, gas prices in Texas have increased with $0.50 per gallon. Also in New York, gas prices increased by $0.20 per gallon, because the Texas-to-Jersey gas pipeline is not delivering any gas to the city. The direct (material) damage to refining facilities is still unknown. Other indirect damages due to Harvey industry include damages to the car industry, where estimates suggest that a total of 366,000 new vehicles suffered damages due to Harvey.

Arkema facility
At Arkema facility in Crosby, Texas (Figures 5.2 and 5.3), approximately 1016 mm (40 in.) of rain caused flooding of the majority of the chemical plant which caused power outages in the entire plant. The back-up generators were also quickly flooded causing the entire facility to shut down on Sunday (August 27th). At the facility are refrigerators containing organic peroxide; the low-temperature in un-refrigerated trailers can catch fire and degrade. This caused at least two explosions at the facility in the days after.

Figure 5.2. Arkema facility in Crosby, Texas; August 31, 2017 (Photo: Arkema Facebook page).

5.4. Environmental damage

Water dispersion and reaction with released toxic chemicals due to flooding are the main causes of environmental damage (e.g., soil contamination, wildlife damage, etc.) as well as water resource pollution (leakage of toxic substances to groundwater and surface waters). Ignition of flammable – and explosive chemical substances (e.g. hydrocarbons) - floating on the floodwaters can also be a potential source of hazard and environmental damage. As of September 12, Hurricane Harvey was estimated to have caused 2.000 tons of chemicals to be released.

At refineries, damages to storage tanks can cause considerable environmental damages. For example, during Hurricane Katrina, ruptured storage tanks released several millions of gallons of oil causing huge oil spills in the surrounding areas. Also during Harvey, more than two dozen storage tanks ruptured spilling large amounts of crude oil and gasoline (about 550 cubic meters) into surrounding areas and releasing toxic pollutants into the air. ExxonMobil for example, had to shut down two facilities, with one damaged plant in Baytown releasing more than 5,6 tons of chemicals including benzene and xylene.In addition, due to the large amount of rainfall that fell during Harvey, the "floating roofs" (i.e., roofs on tanks that float on the chemicals that are stored inside them) of 400 storage tanks experienced problems causing at least 14 roofs to sink. These also caused pollutants to be released into the air. Refineries and chemical plants in the Houston Ship Channel region have reported more than 2,700 tons, or 5.4m pounds, of extra air pollution due to direct damage from the hurricane as well as the preventive shutting down of facilities

Days after Hurricane Harvey hit the Houston area, toxic substances have reportedly been spreading miles from a damaged chemical plant. Tests detected the substances in soil, water and ash samples taken miles from Arkema plant that flooded during Harvey (1.8 m of water flooded the plant), caught fire and partially exploded.

Figure 5.3. The EPA states on their Response to Hurricane Harvey: "Arkema Facility, Crosby TX. At the Arkema chemical plant in Crosby, emergency responders undertook a 24-hour operation to monitor the facility due to fires that erupted on August 31 and September 1, 2017." (Text and image retrieved from epa.gov.arcgis.com ; October 17, 2017).

Superfund sites are sites where toxic wastes have been dumped and the Environmental Protection Agency (EPA) has designated them to be cleaned up. By September 22, 2017, EPA had assessed all 43 Superfund sites located in the hurricane-affected area (Figure 5.2). and on the National Priority List (NPL). Of these, 42 sites have been cleared from contaminations. The San Jacinto Waste Pits site requires additional follow up. These waste pits are currently protected by an "armored cap" which is a fabric layered with large rocks designed to prevent contaminated soils from being released, while the courts determine what to do with them. This cap has required extensive repairs six times since it was placed in 2011. Harvey's floodwaters damaged parts of the cap resulting in sediments containing dioxin being released from the waste pits in to the bay system. As of October 6, the Responsible Parties are continuing cap repairs and maintenance activities under EPA oversight. The repair includes manual placement of the armor rock that is placed on a pontoon and positioned over the deficient areas.

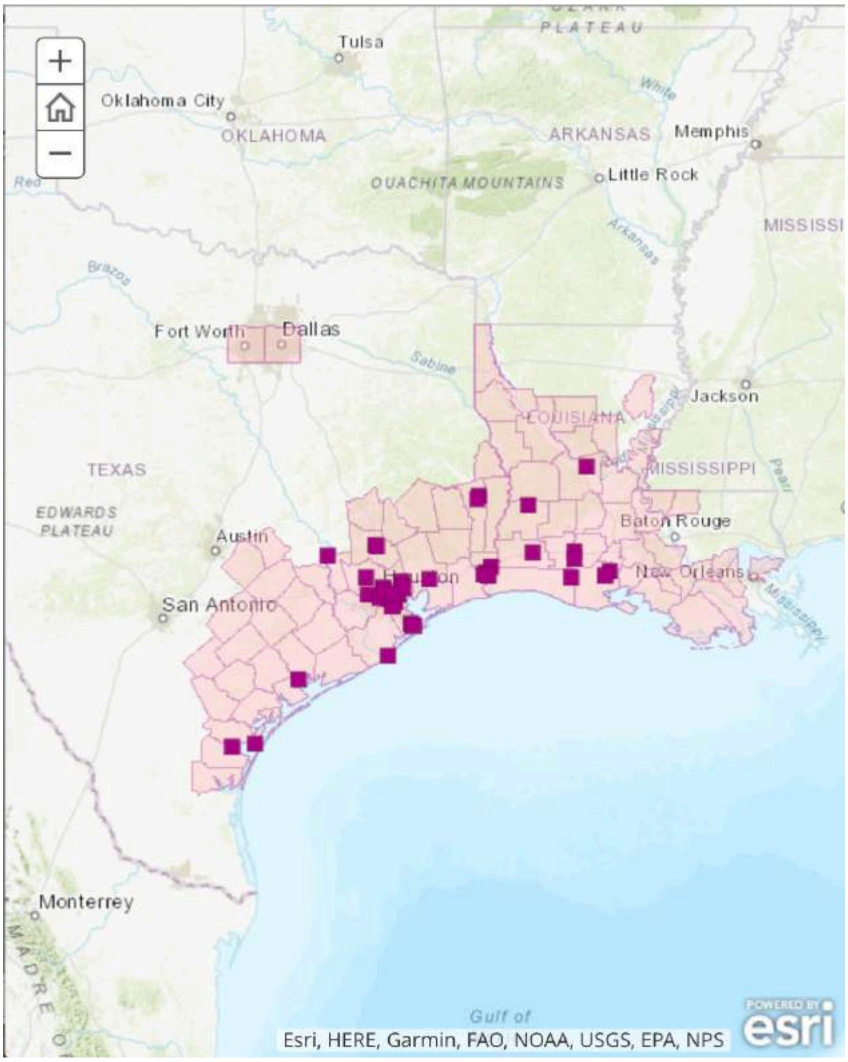


Figure 5.2. Superfund sites located in Hurricane Harvey affected area (Map courtesy EPA, retrieved from epa.maps.arcis.com October 17, 2017)

5.5. Airports affected

Confronted with the threat and passing of Harvey, the airports in the wider Houston area served different functions. Prior to the arrival of the hurricane, airports are mainly used as a getaway for people in the region to escape from the possible hurricane impact, or serve to pre-position essential relief items. After the hurricane has passed airports serve as hubs for delivering any needed relief, such as water, food or temporary shelter, in addition to their role of getting stranded passengers on their way out or getting evacuated inhabitants back home.

Before, during and after the hurricane, airports face many challenges such as the prioritization of landing slots, import regulations, cargo handling, passenger handling (PAX), storage capacities, etc. These functions are often affected by damaged infrastructures once the hurricane hits, precisely at a time when the incoming relief presents an increased load on the airport systems and operations in terms of aviation, in-and out-bound logistics or protective measures (safety, security and medical).

Commercial flights at the two busiest Houston airports – George Bush Intercontinental Airport Houston (IAH) and William P. Hobby Airport (HOU) – remained grounded for five days in a row (Friday August 25 – Tuesday August 29), resuming limited operations by Wednesday August 30 at 4 pm. Harvey caused over 10.000 flights nationwide to be cancelled during the hurricane and in the days after.

By Thursday morning, August 31, 2017, the Federal Aviation had issued 43 unmanned aircraft system authorizations to drone operators supporting the response and recovery for Hurricane Harvey or covering it as part of the media. The authorizations cover a broad range of activities by local, state and federal officials who are conducting damage assessments of critical infrastructure, homes and businesses to help target, prioritize and expedite recovery activities.

Figure 5.8. Tweets on the use and accessibility of IAH

With the Harvey Hackathon (Chapter 8), we analysed the activities of 24 large and regional airports in the wider Houston area, ranging from the immediately affected George Bush IAH to Austin-Bergstrom international airport where the U.S. President landed a few days after the hurricane for his visit to the Houston area. Not all airports were directly affected by Harvey, yet most of those felt the indirect consequences as flights had to be rerouted or cancelled due to closure by the other, affected, airports.

The information gathered during the hackathon pointed mostly at the direct consequences for the airport, ranging from destroyed weather reporting services (Corpus Christi airport), flight cancellations to unusable runways (102 flights cancelled at Houston William P. Hobby airport, runways closed). Passenger care was another important theme: providing clean drinking water, cots and food to stranded passengers, simply counting the number of people still in the terminals, allowing people to pick up their cars from parking lots that had been flooded, or offering waivers to passengers whose flight was cancelled. Indirect effects were also identified: supply roads were flooded and impassable, so employees could not reach the airport for work.

5.6. Critical Infrastructure

Critical infrastructures are lifeline systems, on which societies depend. Without communication communities are not able to connect and ask for help (see Section 6.4), and without transportation professional responders are unable to reach those in need or to organize evacuation. Damage to critical infrastructures therefore directly impacts the response operation.

During the Harvey Hackathon (Chapter 8), students were looking for reports of critical infrastructure disruptions. More than 100 reports and news items related to disruptions of infrastructures were identified. Over 80% of the data sources retrieved were media sources (newspaper sites such as Guardian or NY times as well as local news agencies). Second, about 10 % of the reports stemmed from official reports including FEMA or EPA. And finally, about 8% of the sources were social media (Twitter and Facebook). Note that sometimes, initial social media findings were verified through official media outlets and then categorized under the latter.

The distribution of disruptions that were retrieved during the Hackathon show a focus on transportation, oil and chemical industry (Figure 5.9). The first, because of the frequent reports of roadblocks or disrupted air traffic (see § 5.5) that were part of the warnings and instructions to citizens.

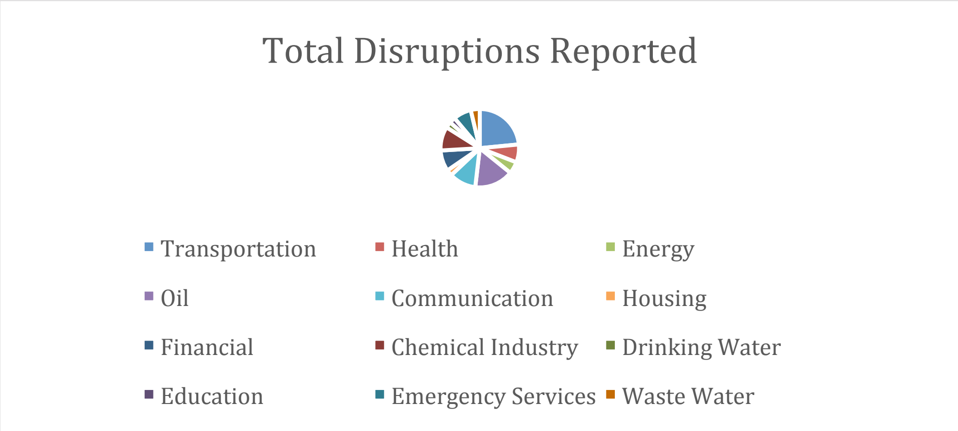


Figure 5.9: Share of information items reporting disruptions per sector, as retrieved during the Harvey Hackathon, in total 81 disruptions were reported.

Disruptions of the transportation network were also important for their impact on industry. Major disruptions occurred the because of halted traffic due to flooded roadways and damaged infrastructure, suspended rail service, closures of regional shipping terminals and ports in Houston, Galveston, Texas City and Freeport and chaotic supply chains due to extra shipments and lower productivity. Many companies including Valero Energy, ExxonMobil, Motiva and Royal Dutch Shell shut down operations in southern Texas, and almost one-third of U.S. refineries have been affected by Harvey. In a Forbes survey, supply chain managers particularly expect impacts on fuel and petrochemical products with potentially important impacts for other industries such as automotive.

Figure 5.10 also highlights that initially the focus was on immediate warnings and reports that directly related to the safety and well-being of affected citizens, including transportation, healthcare, communication, energy and housing. Later on, also more longer-term impact in terms of education or financial implications became more prominent. In total, 45 of the 350 schools suffered from water damages, but even if schools and sports centers were not affected by the hurricane directly, many of them were used as shelters.

In case of Harvey, not surprisingly the chemical and oil industry received special attention. The prominent role of Houston's oil and chemical industry has been discussed before, but also for the pollution they caused (see § 5.2 and § 5.3). The NY times listed a wide range of damages: "*escaping gasoline from a submerged roof at a Phillips 66 storage tank; a sinking tank roof at ExxonMobil's vast refinery in Baytown, which resulted in the release of hazardous gases including volatile organic compounds and benzene above permitted levels; and a lightning strike that disrupted operations and led to toxic-gas releases at a Dow Chemical plant in Freeport.*"

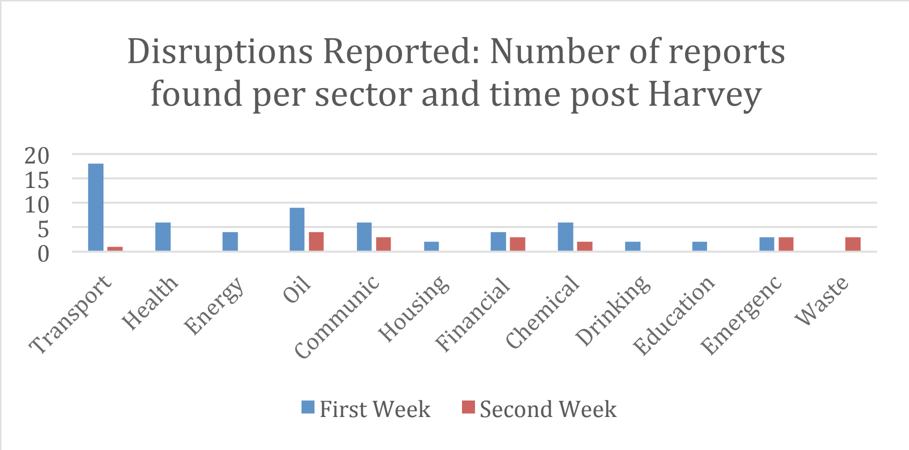


Figure 5.10. Evolution of disruption reports over time, data as retrieved during Harvey Hackathon

Perhaps most prominently figure the fires that broke out a chemical plant in Crosby, TX. Because of power blackouts and failures of generators, the cooling systems needed to keep the chemicals (organic peroxides) safe were failing. Because of the disrupted road infrastructures, fire fighters could not access the site, and eventually decided to let the chemicals burn out and keep evacuation plans in-place in case further containers would explode.

Further examples of so-called secondary or indirect effects include failures of 911 systems (and access to emergency services) as a consequence of outages in the communication network. Combined with the typical overload of the phone network in disasters, population then reverted to using social media hashtags instead of official communication lines.

In total, about one third of the reports the students retrieved related to indirect effects of Harvey, underlining the importance of cascades and rippling effects. Figure 5.11 maps the interdependencies that were identified during the Hackathon. It shows the different critical infrastructures and highlights specifically the important role of energy and power supply, as well as the severe consequences (in red) of disruptions of the communication, drinking water and emergency services.

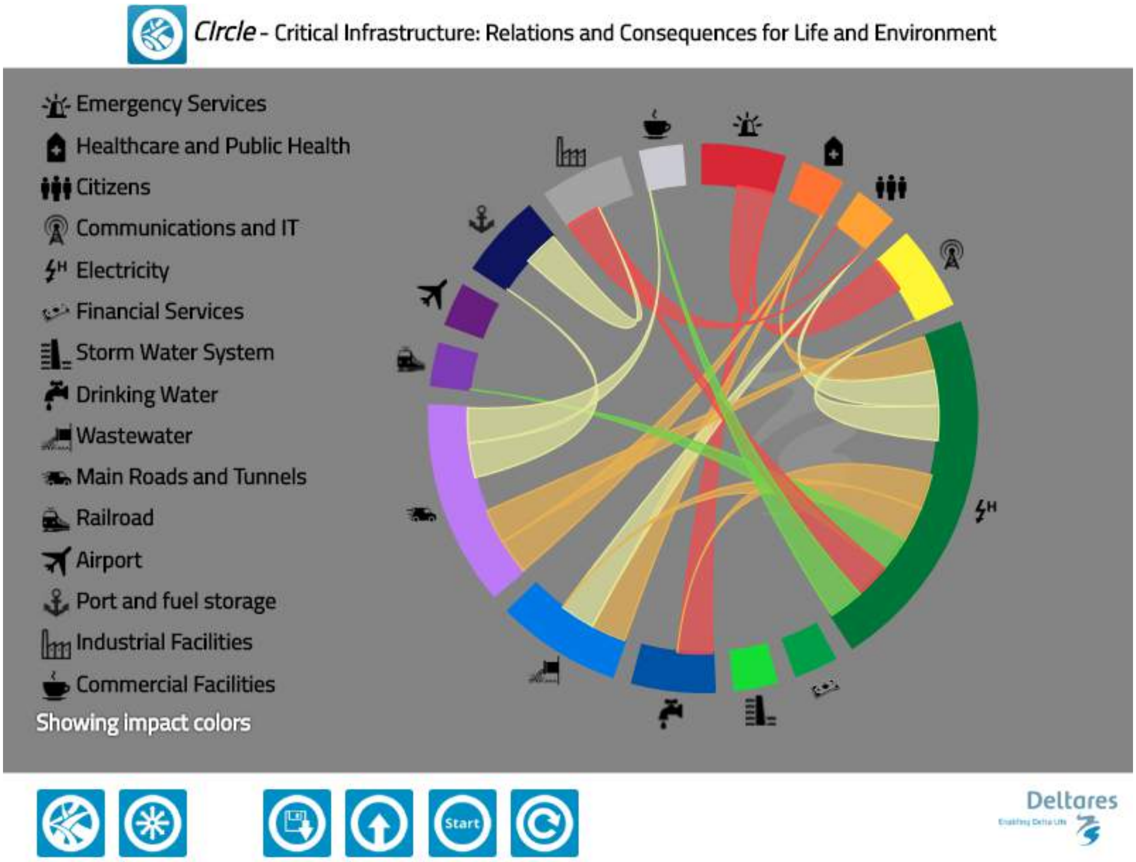


Figure 5.11 Circle analysis of critical infrastructure dependencies that were collected during the Harvey Hackathon showing the impact colors - red is most severe. (Image courtesy of Micheline Hounjet, Deltares).

This initial exploration of critical infrastructure failures and their interdependencies will serve as a basis for a deeper analysis of critical infrastructure resilience.

5.7. Fatalities

As part of the fact finding, information on fatalities due to Harvey has been assessed. Determination of a death toll due to hurricanes and large-scale floods has proven to be complicated in the past. During past events, most fatalities have occurred due to water related incidents (Rappaport, 2014). Substantial additional mortality occurs outside the flood zone, and due to indirect causes, such as incidents during recovery. This analysis focussed on fatalities in the greater Houston area, directly due to the hurricane and flooding, and those that died within the first days after the disaster.

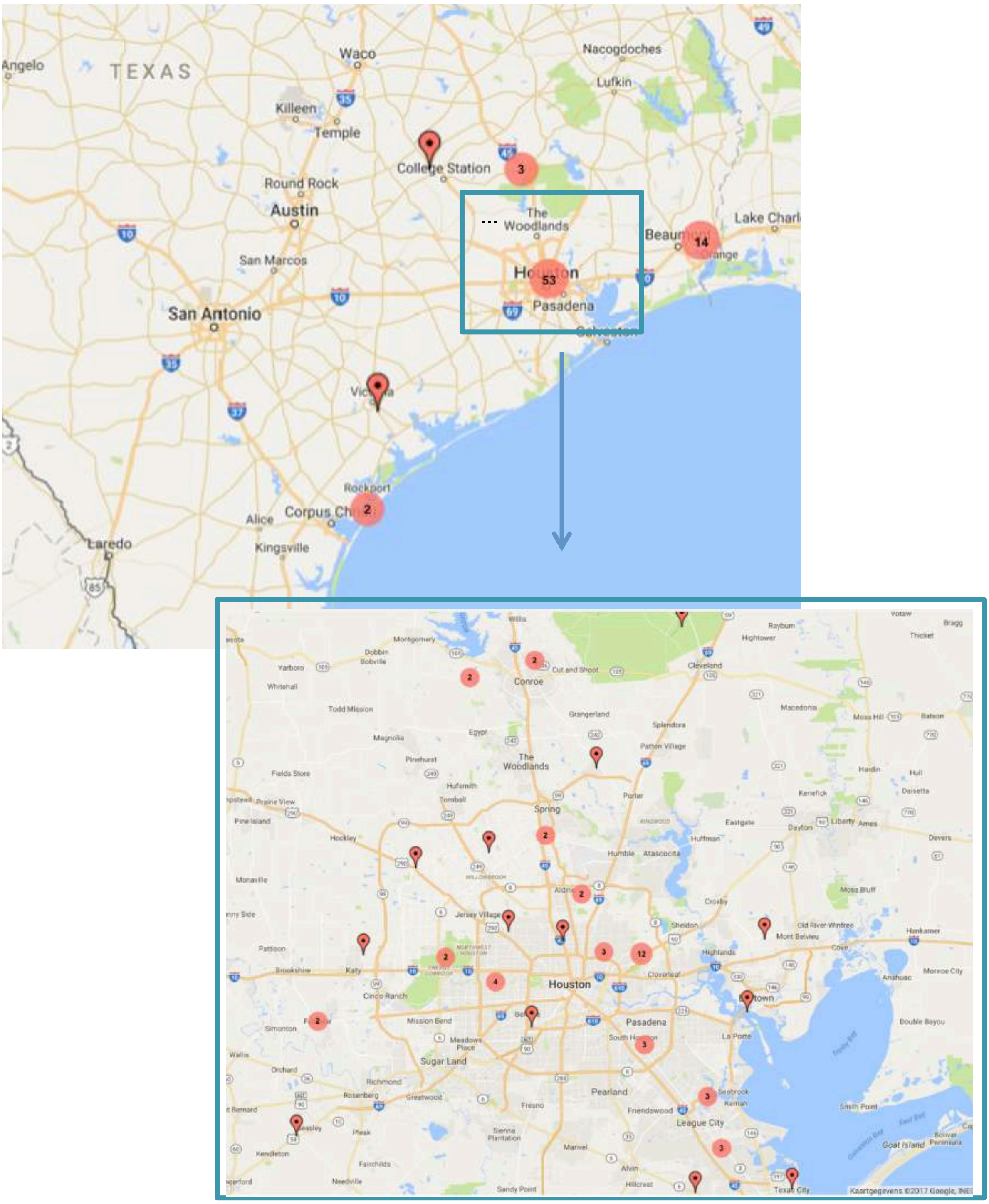


Figure 5.12 Location and number of fatalities following Hurricane Harvey along the southern Texas Coast (upper image) and in the Houston metropolitan area (lower image) as of September 21, 2017. For four of the victims, no details about the location were available.

In the days after Hurricane Harvey, information about casualties appeared mostly on local news websites. Although the larger part of the casualties fell during or directly after Harvey made landfall, even four weeks later, newly discovered casualties were mentioned in the media. Data sources included various media reports and data from the county[6]. Official reporting on casualties and the level of detail varied greatly between counties. Harris County, where most of the victims fell, is the only county so far that has published an official and public list of casualties.

Data analysis

In order to analyse the Harvey related casualties, a database has been compiled. Information about the victim (age, gender) and the circumstances of death (location, time, cause of death) were listed. Additional details on the circumstances, if available, were collected as well. These details can contribute to further analysis (e.g. correlation with flood levels, direct/indirect casualties, possible lack of judgement).

At least 78 people have died as a result of Harvey. This number includes both direct and indirect casualties. Approximately half of the victims were found in Harris County (38 out of 78). Casualties stretch so far over 14 counties with a large spatial scattering (maximum distance of over 200 miles). The recovery locations of the victims are shown in Figure 5.12.

The number of casualties increased over time: 38 deaths were reported until August 30th, 50 deaths were reported until September 3rd and 78 deaths were reported as of September 21.
The direct casualties during Harvey appeared to be mostly caused by drowning accidents (54 out of 78). Many of them were found after floodwaters receded. A significant part of the victims drowned as a result of driving a vehicle into floodwaters or getting swept away by the current while getting out of a car (confirmed for 18 of 54 drowning victims). A tragic example is a case were six individuals of one family, including four children, drowned when their van ended up in high water in east Houston. An overview of causes of death is shown in Figure 5.13. Besides drowning, lack of medical treatment is the second biggest death cause and consists mostly of (very) ill people who did not get proper treatment in time (i.e. dialysis, asthma, heart failure). A smaller number of fatalities occurred due to other causes such as car accidents (n=4) and electrocution (n=4).

[6] Selection of consulted sources (in total over 30 sources have been consulted):
- https://ifs.harriscountytx.gov/Pages/default.aspx
- http://www.chron.com/news/houston-weather/hurricaneharvey/article/Harvey-Aftermath-Houston-police-officer-dies-19-12159139.php#photo-14023358
- https://www.nytimes.com/2017/09/01/us/harvey-texas-flooding.html
- http://www.beaumontenterprise.com/news/article/Profiles-Those-we-lost-to-Harvey-12206036.php#photo-14151715
- https://www.washingtonpost.com/news/post-nation/wp/2017/08/30/a-toddler-clung-to-her-mother-in-harvey-floodwaters-only-one-survived/?utm_term=.8e7234db8f5a
- http://www.galvnews.com/news/free/article_a2aefdbf-1e2d-5af4-9cf6-9eafff89a748.html
- https://www.buzzfeed.com/briannasacks/at-least-16-people-have-died-in-tropical-storm-harvey-as?utm_term=.fh3Ken3Y7#.pne42kXxM

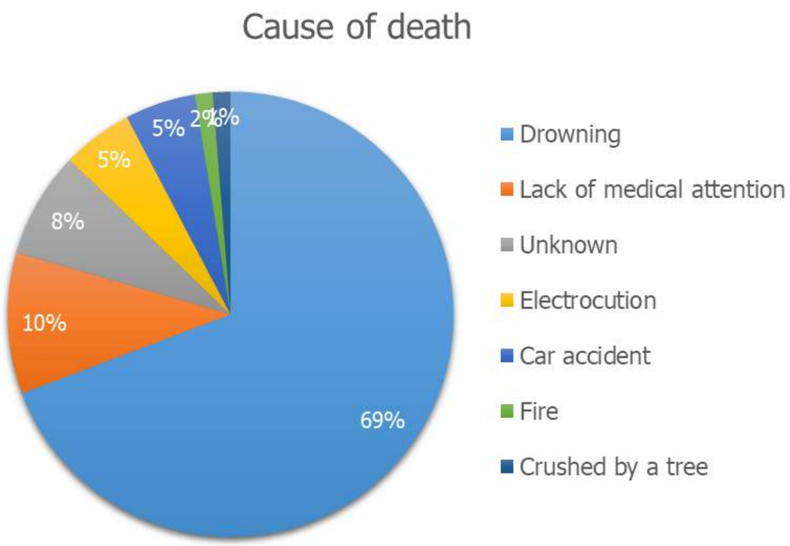


Figure 5.13 Causes of death due to Hurricane Harvey, both direct and indirect.

Of the victims, 59% was male and 28% was female. For 13%, the gender is unknown. The majority of male fatalities are in line with findings for previous floods (Jonkman & Kelman, 2005). Males tend to be involved more in risky activities, such as driving and rescue.

Table 5.2 shows a classification based on age, a relative large part of the victims were over 50 years old. This suggests an increased vulnerability for elderly people as was also found for the flooding of New Orleans due to hurricane Katrina.

Table 5.2. Classification of victims based on age.

Age	*Number*	*Percentage*
0-18	6	8%
19-50	22	28%
51-65	19	24%
>65	19	24%
Unknown	12	15%

Apart from the deadly victims, many more were injured. Also, longer-term health effects are expected associated with the experience of the flood event, and possibly due to pollution and increased moisture levels in flooded homes. Furthermore, dozens of people are currently still missing. As there is no central institution that keeps track of missing persons, most communication is via social media. Many times, people are found but their status is never updated.

(Top) Marines hand over supplies, Orange, TX (Courtesy: Marine Corps, Photo by Lance Cpl. Niles Lee).

(Mid) Hurricane survivors seek assistance at a nearby FEMA Disaster Recovery Center at the Colorado County Services Facility in Columbus, Texas (Courtesy FEMA News Photo).

(Bottom) Debris on the side of a road in Houston, TX (Courtesy: FEMA News Photo).

Emergency Response & Decision Making

6

6.1. Introduction

Hurricane Harvey created significant impact on both the physical environment and the lives of people in the greater Houston area as illustrated in the previous chapters. In this chapter we introduce another aspect of Hurricane Harvey: the emergency response and related decision-making processes to reduce its impact. Impact reduction includes prevention of injuries and casualties, reducing damage to property and infrastructure, and preventing further escalation of a crisis situation.

The emergency response stage differs from the prevention and preparation stages. Often the measures in the latter stages take place without being triggered by a specific and imminent threat, although often mitigation measures *follow* catastrophic events. In the emergency response stage, decisions and actions are taken and implemented in a much shorter timeframe. At the same time, decision makers and rescue workers are dealing with information shortage, uncertainty (Comes et al. 2011), and coordination between different agencies, organizations and not in the least the affected population (Van den Homberg et al. 2014).

The following sections describe the decisions and actions made immediately prior to the impact of Hurricane Harvey and those taken after it reached the Houston region. Section 6.2 (Evacuation) describes the complex interplay between formal evacuation decisions by the emergency management authorities and adoption of these instructions by local population and organizations. Sections 6.3 and 6.4 describe the formal response by federal organizations, e.g., FEMA, and the community-driven response, respectively. The latter concerns emergency response activities organized by groups without a formal mandate, such as community organizations, or ad-hoc volunteer initiatives. Finally, Section 6.5 describes the detrimental effect of viral hoaxes, often referred to as ‘Fake-news’, potentially stressing those affected by the hurricane and misleading emergency response.

An interesting and recurring element throughout the emergency response stages and decision-making processes is the coordination between different stakeholders and actors. Emergency operations involve more (both government mandated and community-driven) organizations, citizens become more empowered through information access, and the overall complexity and connectivity is increasing. This signals a paradigm shift for this multi-actor system: emergency response is shifting from a ‘command-and-control’ approach towards a ‘coordinated network’.

6.2. Evacuation

In this paragraph we look at the decisions made for evacuation in greater Houston. A call for evacuation can be made in advance of the exposure based on forecasts, as well as after the exposure to save human life. Houston experienced an evacuation before. In 2005, a large scale, partly autonomous, evacuation took place in anticipation of hurricane Rita. This evacuation caused many people to loose their life -mainly due to accidents and health effects of a mass evacuation- although no flooding did occur after Rita. To get a better understanding about evacuation, we focus on the moment on which the decisions are made related to the threat, the information used for this decision as well as the costs and benefits

Types of evacuation in greater Houston

We distinguish different types of evacuation. Evacuation is defined as the process of alerting, warning, deciding, preparing, departing and (temporarily) holding people, animals, personal belongings and corporate stock and supplies from an unsafe location at a relatively safer location given the actual circumstances. Different types of evacuation are related to the moment of the onset of the evacuation and the flood, the destination (inside or outside the flood zone), and the relation with first responders.

An evacuation can be advised (voluntary) or mandated (i.e. ordered). People can evacuate to multiple destinations such as dry floors in their own residences, public shelters or leave the threatened areas prior to a flood. People can also be informed about risk without an advice and start to act on their own, as was the case after Hurricane Rita. Houston then experienced a spontaneous evacuation. People outside the threatened area also evacuated and used road capacity, which therefore was not available for others (this is called a shadow evacuation). All decisions related to movement of people are considered as evacuation decisions. Also a decision not to evacuate, or to postpone an evacuation is considered as a decision.

Although the data gathered during the Harvey Hackathon are not yet complete, it already showed that all abovementioned types of evacuation occurred during Harvey. Although preventive evacuation was not mandated or advised (voluntary), some people evacuated spontaneously as preventively. It is also clear that the evacuation decisions vary geographically based on the local circumstances. Based on current data, it is not possible to define a complete timeline of all evacuation decisions, more research is needed. However, several key moments in the decision making process for evacuation in greater Houston during Harvey can be stated.

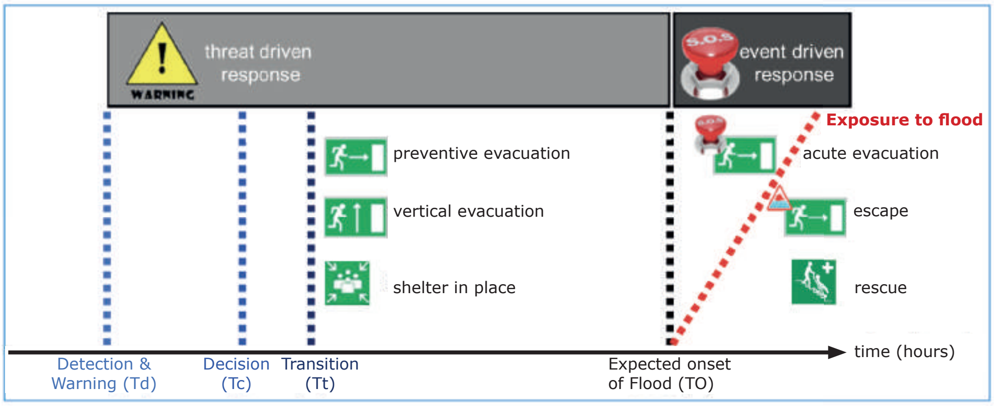


Figure 6.3. Different types of evacuation (Kolen, 2013) (Image courtesy of Bas Kolen)

Key moments for evacuation in Greater Houston during Harvey

Based on the hackathon a first analysis of the evacuation decisions during the Harvey event show that they were both were threat driven (based on forecasts prior to the onset of exposure to the wind and rainfall) and event driven (based on rainfall and use spillways to relief dams) related to multiple hazard layers (see also Figure 6.3).

- Threat-driven response: The first hazard was the hurricane itself and its forecasted impact on greater Houston area (the strength of the wind, expected rainfall and storm surge).
- Event-driven response: Further hazards were related to possible dam failure because of extreme rainfall filling up Addicks and Barker Reservoirs, and the release of water from the dams' spillways.

Threat driven response

The first decision about evacuation of the great Houston Area was to *not evacuate* preventively (because of the hurricane itself). Houston mayor Sylvester Turner decided instead to inform people about the threats and advised them to shelter at home and prepare themselves. These decisions were based on the forecasted path of Harvey and the potential impact. At the time of the decision to advise sheltering at home and not to evacuate preventively, the expected rainfall was 400-800 mm of rain. There were no estimations about the possible impact for loss of life given this amount of rainfall found yet. The mayor stated that the consequences of preventive evacuation of 6,5 million people would be enormous and would put people at higher risk than when they would remain at home (and prepare themselves). He referred to the evacuation of 3 million people prior to hurricane Rita in 2005, which resulted in about 100 fatalities.
However, some smaller cities still decided to call mandatory evacuations (e.g.; Missouri City, Bay City, Sugarland, Rosenberg, Simonton).

Event driven response

However, during the event some parts of Houston were still ordered to evacuate. These second order decisions for evacuation were based on the actual precipitation and the release of water of reservoirs by spillways to reduce the probability of dam failure. For example McDade Estates was under mandatory evacuation after officials made the decision to release water from Lake Conroe. Also for other areas evacuation was mandatory or recommended. During the Harvey Hackathon, no information was found about the costs (of the evacuation decision) and benefits (possible reduction of damage and loss of life in case of a flood) and the prior probability of flooding of the flood prone area, prior to the arrival of Hurricane Harvey. More detailed analyses about these variables can offer a better understanding about decision-making and how evacuation decisions can be related to the risk based approach.

The people who were exposed to the floods had to be rescued (by emergency workers), to escape (by themselves or with help from other citizens), or to wait until the water was gone. A first review of the acquired data shows examples of all of these. More data are needed to get an overview of the number of people rescued by emergency services or by other citizens as the required means (as the amount of boats, firemen etc.) to save them. Also in multiple areas the water level declined so quickly that people did not have to escape or be rescued.

Figure 6.4. Texas National Guardsmen rescue a resident by boat during flooding caused by Hurricane Harvey in Houston, Aug. 27, 2017. (Courtesy of Army National Guard; photo by Lt. Zachary West).

Evacuation response and individual choices

Evacuation decisions can also be considered as symbols. The decisions made by authorities are not always fully responded to, as even in case of a mandatory evacuation some people will not evacuate. This was also the case in Houston. In case of large-scale events like Harvey, it is impossible for authorities to check all houses and force people to evacuate. Evacuation decisions by authorities therefore have a strong symbolic value to encourage people to act (and most people will do so). However, each individual makes their own decision how to prepare depending on their own values, circumstances and information at hand.

Parts of this information can also come from unexpected or unconventional sources. For example from The Waffle House, a fast food company that tries to be open during storms as long as possible. When they close (code red), the situation is considered really bad. In general, other businesses, organizations and people act sooner. Figure 6.5 shows the ‘storm’s severity index’ used by the Waffle House and their locations that were closed during Hurricane Harvey; seemingly even for FEMA an indication of the gravity of the event.

During Harvey, a wide variety of response measures by the government, people and businesses could be seen in the timeline of the event we compiled in the Harvey Hackathon. People were not only rescued by rescue workers, but in many cases by fellow-citizens as well.

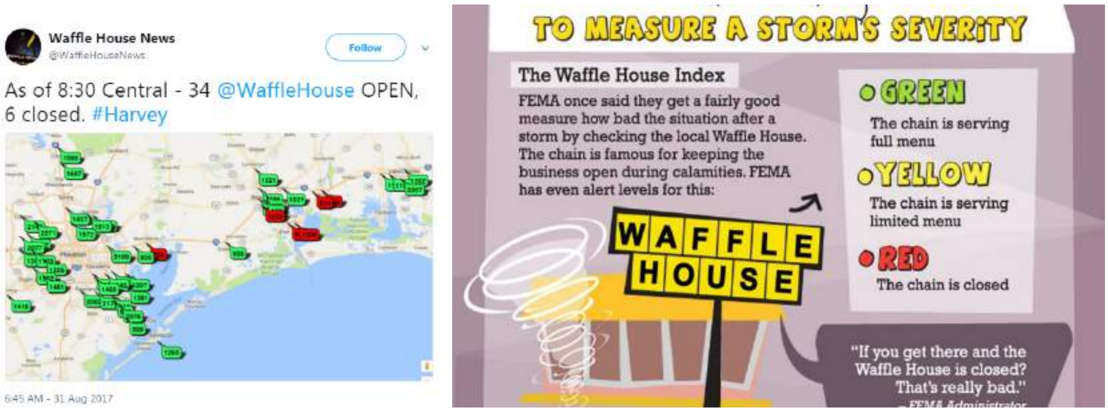


Figure 6.5. Example of twitter message by 'The Waffle House' and the index (Image courtesy of Twitter source)

Future research needs

The forecasts and response to Harvey can contribute to a better understanding of evacuation, and to improve the preparation for evacuation. More fact finding has to be done about the timeline of decisions and geographical distribution. Also a better understanding of the official information about probabilities, costs and benefits of evacuation is needed.

Future lines of research can be defined to define optimal evacuation strategies based on a risk based approach and taking uncertainties of forecast and consequences into account. Using the risk based approach, cost benefit analyses decision support instruments can be used to support the call for evacuation. These lines of research makes the assumptions made by the Mayor of Houston explicit and reduces the meaning making in the aftermath. This line of research also puts the risk as the cornerstone of emergency planning which gives the opportunity to define the effectiveness of better planning, exercises, information systems etc.

Also for the Netherlands a better understanding of the call for evacuation is important, as well as the way the decision are communicated and result in response of the public and emergency services. Although experiences in the U.S. cannot directly be copied to the Netherlands because of different cultures, still many lessons can be learned from research on cases like Harvey.

6.3. Emergency Response

In the Daily Flash of August 18, 2017, the European Response and Coordination Center (ERCC) managed by Directorate General for European Civil Protection and Humanitarian Aid (DG ECHO), identifies Tropical Cyclone Harvey as one of the weather events that are being monitored, mentioning the storm warnings for the Windward Island and eastern Caribbean Sea. While the storm had been tracked by several meteorological institutes (including the NOAA), the storm then also appeared on the radar of emergency response organizations, including the CDEMA (Caribbean Disaster Emergency Management Agency). These emergency management authorities start implementing various emergency protocols, and issuing severe storm warnings. Different actions were undertaken, such as pre-emptive evacuations, pre-positioning of emergency response resources, and activating civil protection measures. In the Daily Flash of 28 August 2017 (see Figure 6.7), the ERCC reports that Harvey had made landfall in the United States the day before and mentions the disaster proclamation for the state of Texas and the activation of the FEMA response. The ERCC continued tracking Hurricane Harvey and updated the situation in their Daily Flash, including maps of the hurricane's path.

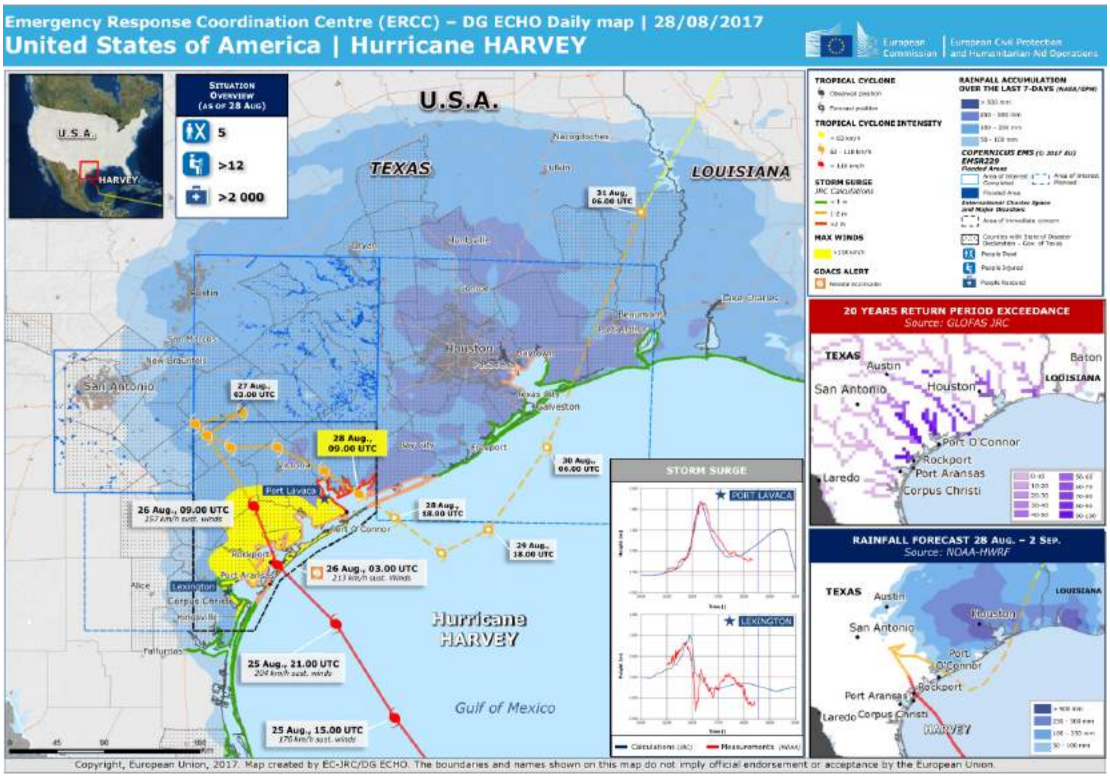


Figure 6.7. ERCC Daily Flash August 28, 2017 (Retrieved 1-10-2017)

Following the disaster declaration for the state of Texas by President Trump, the U.S. Department of Homeland Security and the Federal Emergency Management Agency (FEMA) started to act as the federal coordinating body for emergency response. FEMA in turn activated several other mechanisms at both the national level (National Response Coordination Center in Washington D.C.) and in the affected region (Regional Response Coordination Center in Denton). These coordinating mechanisms supported individual states in implementing a range of emergency preparedness measures. The measures included information to the population through weather alerts, information on evacuation shelters, and safety tips in multiple languages.

Aside from communicating to the public, the emergency response organizations also prepositioned teams and resources, including Incident Management Assistance Teams (IMAT) at the emergency operations centers. Throughout the response to Hurricane Harvey over 15 other government (federal or state) agencies have been involved, detailed list of these organizations and their involvement in the response is included below. In addition to these formal, governmental organizations, the American Red Cross and another 300 voluntary organizations were mobilized. The amount and size of these organizations, each with their own mandates, expertise, resources, procedures and structures contributed to the complexity of the response and challenges in coordination (Table 6.1) and (Howitt & Leonard, 30 August 2017). As of September 22, 2017, over 30,000 Federal employees had been active in response and over 122,000 rescues were conducted (Figure 6.8).

Table 6.1. Historic Disaster Response to Hurricane Harvey in Texas FEMA News release HQ-17-133 (d.d. 22 September 2017)	
Response organization	**Response activities**
Federal Emergency Management Agency (FEMA)	FEMA assigned 28 Urban Search and Rescue (USAR) teams from across the nation to deploy to Texas to assist state and local agencies with the lifesaving mission. The teams rescued 6,453 people and 237 animals, using boats and high-water trucks. Search and rescue efforts involved USAR, National Parks Service, U.S. Fish and Wildlife Service, Customs and Border Patrol and the Department of Defense. FEMA supplied 3 million meals, 3 million liters of water, 9,900 blankets, 8,840 cots and 10,300 hygiene kits to the state for distribution to survivors. FEMA quickly provided $186 million in Public Assistance funding to reimburse local and state agencies for the cost of emergency protective measures and debris removal. FEMA deployed teams of specialists to neighborhoods and disaster recovery centers to help Texans with registration and questions about disaster assistance. FEMA coordinated National Business Emergency Operations Center calls among 150 private sector partners working on disaster response, worked with social media companies to share disaster information and assisted cell service companies in providing charging stations for disaster survivors.
Coast Guard	The Coast Guard deployed 2,060 personnel, 50 aircraft, 75 boats and 29 cutters, rescuing 11,022 people and 1,384 pets
The Department of Health and Human Services (HHS)	HHS deployed more than 1,110 personnel with medical equipment and supplies. Personnel provided medical care to 5,359 patients and conducted 60 shelter assessments. The department established medical shelter and helped move Port Arthur residents who had been living in floodwater-contaminated houses and apartments to temporary housing at the Bob Bowers Civic Center.
U.S. Geological Survey (USGS) and National Weather Service (NWS)	USGS scientists deployed to the coast to help the NWS forecast storm surge and beach erosion, then worked through Harvey's landfall to keep the NWS informed of real-time flooding. After the floodwaters receded, USGS scientists collected more than 1,500 high-water marks to help develop future flood maps
Department of Housing and Urban Development (HUD)	HUD contacted all 61 public housing authorities in the disaster area to assess damage and to identify unoccupied units that could be made available to HUD-assisted and other survivors. Those authorities manage 91 public housing developments that serve 200,000 families. HUD did the same assessment with its 454 FHA-insured apartment complexes, comprising 50,000 units, of which 20,000 had direct HUD rental assistance. HUD also canvassed the four-state area surrounding the disaster for available public housing and multifamily housing units.
U.S. Army Corps of Engineers (USACE)	USACE, deploying 390 personnel, worked with local and state agencies and the Coast Guard to clear navigation channels, allowing critical ports to resume operations. Engineers performed generator inspections and installations to provide temporary emergency power at critical locations and provided technical assistance for debris, temporary housing and commodities missions.
Environmental Protection Agency (EPA) and Texas Commission on Environmental Quality (TCEQ)	EPA, working with TECQ, completed 625 drinking water assessments and 441 waste water assessments. The agency conducted assessments of 43 Superfund sites and recovered 517 containers of unidentified, potentially hazardous material.
Department of Energy (DoE)	DOE supported the Texas Division of Emergency Management and utility companies in efforts to restore power to more than 300,000 customers. Utility companies responded in a coordinated effort, activating their mutual support networks and assigning more than 10,000 workers from at least 21 states to the response and recovery effort, including crews, line workers and support personnel. DOE worked with the EPA to issue waivers that allowed more fuel to go into the supply pipeline. Secretary Perry authorized release of 5.3 million barrels of crude oil from the Strategic Petroleum Reserve as a resource if needed.

Department of Defense (DoD)	DoD supported more than 30 mission assignments from FEMA that included search and rescue, strategic airlift, transportation, evacuation, installations support, patient movement and logistics. As part of the search and rescue mission, U.S. Northern Command rescued nearly 3,000 people.
U.S. Small Business Administration (SBA)	SBA, working with the Texas Gulf Coast Small Business Development Center, opened five business recovery centers to provide a wide range of services to businesses impacted by the disaster. SBA extended the deferment for first payment from the standard five months to 11 months from the date the borrower signs the loan closing documents. SBA provided an automatic 12-month deferment of principal and interest payments for SBA-serviced business and disaster loans that were in regular servicing status on August 25 in the counties designated as federal disaster areas.
Civil Air Patrol	The Civil Air Patrol conducted 270 flights with 32 aircraft to assist with emergency response.
Department of Agriculture (USDA)	USDA activated the Disaster Supplemental Nutrition Assistance Program to provide food benefits to households that wouldn't normally qualify, if they meet disaster income limits and have disaster-related expenses. Schools in hurricane-stricken areas were allowed to provide meals through the National School Lunch Program to all students free of charge through Sept. 30. Animal and Plant Health Inspection Service deployed 25 tons of pet food to affected areas and used helicopters to identify stranded livestock, assisting the Texas National Guard in dropping 210,000 pounds of hay to 10,000 head of livestock.
General Services Administration (GSA)	GSA leased facilities to provide work sites for several thousand federal employees deployed to Texas, including a joint state/federal field office, area field offices and call centers.
Centers for Medicare and Medicaid Services (CMS)	CMS temporarily modified the Medicare, Medicaid and Children's Health Insurance Program to provide immediate relief to Texas disaster survivors. Specific attention is given to care for renal patients to ensure there are enough facilities to serve beneficiaries in need of dialysis. The agency is accepting requests from end stage renal disease suppliers to become a temporary Special Purpose Renal Dialysis Facility (SPRDF).
Department of Transportation (DoT)	DoT provided technical assistance, training and on-site damage assessments for state and local partners to begin returning transportation infrastructure to pre-storm conditions. The Federal Highway Administration activated or deployed 36 employees in the response effort. Staff provided assistance for emergency repairs under the Emergency Relief Program with an initial $25 million in quick-release funds. All major airports returned to normal operations by Sept. 6. Ports in Corpus Christi, Houston, Beaumont and Port Arthur were open with restrictions. Metropolitan Transit Authority of Harris County returned to limited service. As of Sept. 20, 191 damage inspection reports documented emergency repairs completed and permanent repairs to be completed.
Texas Workforce Commission (TWC)	TWC began taking unemployment insurance claims the day Hurricane Harvey made landfall. FEMA activated Disaster Unemployment Assistance (DUA) for Texans whose employment was lost because of the disaster. The program is administered by the State of Texas. As of September 19, the commission processed 136,576 unemployment insurance claims, of which 17,714 were under the DUA program. DUA call centers are operating seven days a week.
American Red Cross (ARC)	The ARC provided $45 million to more than 100,000 disaster survivors to help them with immediate needs. The Red Cross deployed more than 3,000 staff and volunteers, 171 emergency response vehicles, served 965,000 meals and 1 million snacks and operated shelters throughout the impacted counties.

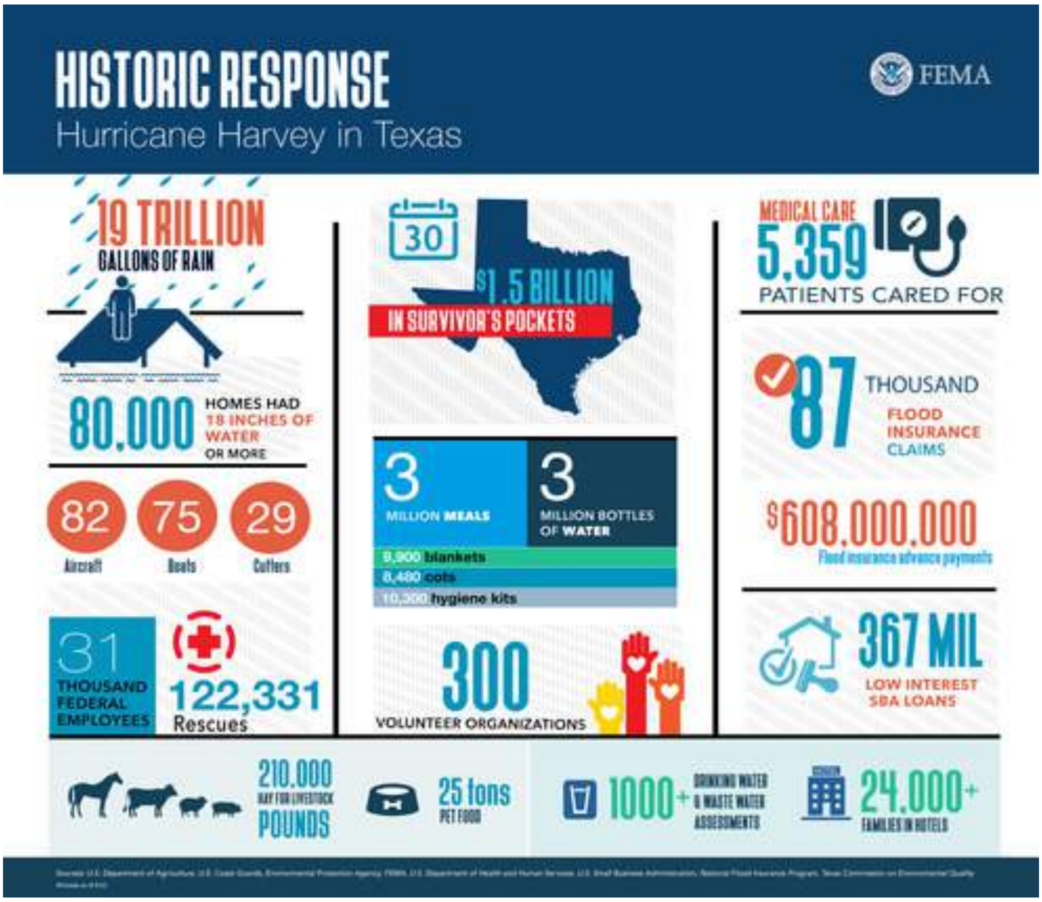


Figure 6.8. Historic Disaster Response to Hurricane Harvey in Texas. FEMA News release HQ17-133 (22 September 2017)

These organizations jointly organized the emergency response for the affected areas. This response comprised of operational activities such as search and rescue, evacuations, and medical care. Furthermore, the response also covered the provisioning of relief items to the affected population such as food and water, emergency shelter equipment, and financial compensation. Figure 6.8 provides a brief overview of the provided aid by these organizations. It can be noted that the figure mentions over 300 volunteer organizations that supported the emergency operations. These non-governmental organizations contributed a large portion of the resources, both manpower and items, in the aftermath of Hurricane Harvey. Not only their resources contributed to the emergency response; their local presence, familiarity with the region and access also ensured a more effective operation for the government mandated organizations. The coordination, integration and collaboration with formal response organizations are key factors in ensuring that these organizations jointly effectively deliver aid and emergency response, as illustrated by the remarks by Gail McGovern, CEO of the American Red Cross.

Comparing Harvey emergency response to Katrina and Irma

Harvey is not the first major hurricane to strike the United States, and over time the United States and its emergency response mechanisms have evolved. Partly through lessons learned from previous crisis response operations but also due to innovations (technological and otherwise) in the emergency response domain. However, integrating lessons learned often proves difficult for emergency response organizations for a variety of reasons including high staff turnover and disconnect between operational emergency response staff and those responsible for adapting policy (Donahue et al 2006, Birkland et al 2009).

To find comparable events, we have to consider the context. Hurricane Harvey and Hurricane Irma, making landfall in Florida a few days after Hurricane Harvey, are expected to be amongst the most costly natural disasters in U.S. history. We could compare Harvey and Irma with Katrina 2005, which was the most devastating hurricane in U.S. history. Moody's Analytics estimated economic cost of Hurricane Irma will be $64 billion to $92 billion; damage from Harvey is estimated $108 billion. Hurricane Katrina caused $160 billion damage in today`s dollars according to the National Oceanic and Atmospheric Administration. These statistics help us to understand impacts of hurricanes in approximately the same context but in different timelines.
They also tell us something about risk preparedness. FEMA director William Long noted that U.S. residents still are not prepared for disasters, which can also be concluded when comparing the immense damage costs of Harvey and Irma to those of Katrina. Long stated that there is ‘a long way to go’ in the U.S. overall disaster readiness.

When looking at the response, it seems that FEMA has had better performance in Harvey response compared to Katrina. More than 1800 FEMA staff deployed two days after the landfall (August 27) increased to more than 32000 in nearly a week (September 4). On September 6, FEMA started officially to prepare for the Irma. However, when Irma made land fall on September 10, logistic problems emerged. The challenges mainly happened due to the size of Irma, spanning the entirety of Florida’s southern peninsula, not its strength nor lack of staff. Several of pre-positioned items could not be mobilized due to access constraints: Staff was ready but could not reach places where they were needed. 2650 FEMA staff was in Florida by September 14. Overall, comparing Harvey to Katrina, responders were mobilized more efficient and effective mainly because plans were in place before the hurricane struck. The main criticism for Katrina response was that U.S. officials did not have plans regarding how to respond, how to coordinate, and how to use skilled responders. Hence, several problems were experienced with respect to search and rescue, logistics, relief delivery, and also recovery. Furthermore, during Katrina, FEMA seemed almost unwilling to accept help from non-government organizations. For example, the American Red Cross was not allowed into New Orleans following the disaster and was unable to supplement the government’s response. Several articles can be found that criticized Katrina response for lack of efficiency, effectiveness, and coordination which apparently improved a lot in Harvey and Irma response. For instance, number of rescued people in the aftermath of Harvey was more than 72000 while it was about 34000 in Katrina.

Overall, one of the main differences between in the emergency response organizations between hurricane Katrina and Harvey is the approach towards the inclusion other organizations. As one of the key lessons from the Katrina response, the resulting policies emphasized the need to strengthen the network (Moynihan 2009). Throughout the response to Hurricane Harvey, both before and after the impact, the coordinating emergency management authorities (most notably FEMA) worked closely with other agencies, including state and local organizations as well as non-governmental, community or volunteer organizations. The shared information, close coordination and collaboration not only ensure more resources were available, but also used in a more coordination and effective manner. The Harvey response illustrates the importance for emergency management authorities to use an ‘open’ and networked approach in coordinating the emergency response efforts.

6.4. Community Response

Before, during and after a response, emergency management authorities are working closely with other government agencies as well as other organizations, including community initiatives as illustrated above. The added benefit of working closely with different organizations is not only the enlarged pool of resources that can be deployed for the response, but also the access to local knowledge and expertise. Combined with the technological development that provide new communication options and support the self-organization of groups, communities are playing an increasingly important role in disaster response (Baharmand et al 2016).

Communities play an important role in crises and disasters, because they are on-scene and very often the first to respond. According to the Red Cross World Disaster Report 2013 about 90% of rescued victims are saved by the local community. Community members provide life-saving support, have access to resources and provide local knowledge. As such, they are a key to effective disaster response, particularly if access restrictions delay professional responders or if resources are scarce. While communities have important capacities and capabilities, they also represent the most vulnerable among the actors involved in emergency response.

While ad-hoc community efforts have always played a key role in disaster response, today more ‘tools’ are available to not only facilitate easier connections but also enable a wider reach. Twitter and Facebook allow people to connect, form groups and plan, forming ad-hoc initiatives comprised by spontaneous, unbound (not affiliated to a formal organization) volunteers. However, this is a double-edged sword. While volunteers can complement the resources of professional responders with local resources and knowledge, they do not have the training, experience, tools or methods of professional responders (Meesters et al. 2016). For example, unsolicited donations can cause bottlenecks and hinder vital aid to reach its recipients. Spontaneous efforts usually will not follow any guidance or ethical standards, potentially leading to safety concerns (for both the affected population as those offering aid), privacy violations and inviting misuse. Additionally, due to their ad-hoc and unbound nature, integrating and aligning these community efforts with the formal response can be challenging.

In order to improve the alignment and coordination, it is important to understand the motivations, modus operandi and (self-) organization of these community responses. Since there are many different initiatives, platforms, and groups it is difficult to get an overview of what has been initiated, by whom, when, where and why. To gather and analyze the various community initiatives, a task specifically on the community driven relief has been introduced at the Harvey hackathon (see Appendix A). The data gathered during the Harvey hackathon illustrates the scope, variety, and importance of the various community efforts. This community response is provided by a wide variety of stakeholders, ranging from private (commercial) sectors to local ad-hoc grassroots initiatives and from international volunteer groups to in-country assistance. Equally, the aid provided covers a wide span ranging from financial contributions to physical relief items and from offering places to stay to remote mapping of the affected area.

In the following paragraphs we introduce several of these researched initiatives to illustrate the scope, variety, and impact of the community efforts. Moreover, these examples serve to illustrate the important contribution these initiatives make to the overall emergency response, not only in the immediate rescue states, but throughout the relief and recovery stages. The section concludes by outlining the key challenges for emergency responders and the overall response to fully leverage the potential of community response while reducing the risks. Future research directions our outlined as well, that would support further improving the impact of community response, considering the ad-hoc, spontaneous nature of these efforts.

Private sector contributions

Several companies supported communities through in-cash or in-kind contributions. Most of these initiatives are directly linked to customers or employees, and as such they do not explicitly follow the humanitarian principles of impartiality and neutrality (Stewart et al 2009). A common characteristic of the collected data is that information on contributions by important companies is often clearly provided by their marketing and communication offices. Because they are thus much easier to find and identify than more hidden local initiatives that are not linked to marketing, the data collection effort during the Harvey Hackathon may have been biased to over-emphasize private sector contributions. However while the aid from the private sector may not be fully altruistic, the private sector has made an important contribution to the emergency response and disaster relief efforts including in-kind assistance and donations.

Relief aid

Home Deport (a DYI chain) activated their Hurricane Command Center to support coastal communities in the path of the storm. The company ensured additional supplies were redirected towards the affected area. As far as food production firms are concerned, the yogurt company **Chobani** provided 300.000 food supply items for affected families. The products were transported from North Idaho and New York to Texas.

Telecommunication

The Telecommunication industry made important contributions. For example, on August 25th **AT & T** was on the ground to restore the service in order to support both professional emergency responders and communities. Several solutions were deployed, including vehicles able to recover cell services in a specific area. On August 26th (in Texas) and 28th (in Louisiana), the company started providing unlimited data, voice and text to prepaid customers in the affected areas. This service was kept until September 15th. Eventually, on August 29th a total amount of $ 350.000 were donated by the company for community aid. Similarly, on August 29th **Verizon** pledged 10 million US$ to fund the Harvey relief effort. More specifically, they relieved customers in the affected areas from prepaid data and talk charges. They also deployed cells on wheels to help the communication for the response effort and offered mobile chargers in shelters.

Automotive industry

Many automotive companies offered cash assistance to their clients. For instance, on August 21st the **Nissan** Group of North America pledged support to Hurricane Harvey Relief and Recovery Efforts. The assistance included donations of $ 150.000, plus $ 100.000 matched employee contributions, truck donations, and payment extension programs for Nissan and Infiniti customers. In a similar way, on August 28th **Toyota** offered financial relief to customers affected by the Hurricane. Also **Ford** provided $ 3.5 million to fund, the so-called 'Texas is Family Program package'.

Other financial Donations

On August 26th **United Airlines** granted up to 1000 extra miles to Mileage Plus members who decided to donate. The donations had to be provided through the United Airlines fundraising webpage. The financed organizations were the American Red Cross, AmeriCares, Airlink, and Operation USA. There were contributions also from the film and entertainment industry. As an example, the Day of Giving Telethon was an initiative organized by **Disney** to encourage people to donate to the American Red Cross.

Sharing of resources and assistance

In addition to the aid and relief provided by commercial and private organizations, many other organizations also supported the relief efforts. These organizations are not traditionally (purely) focused on emergency response but do leverage their network, resources, and expertise to support communities in need during and after disasters. Often these initiatives look to people and groups that are part of their organizations' mandate and focal area. While these organizations do not have a specific emergency management focus, to often do have pre-existing structures, processes and trained or experienced volunteers, making it easier for both them and formal emergency response organizations to align their efforts and coordinate with each other. Examples of these non-profit organizations responding to Hurricane Harvey include:

- The Veterans of Foreign Wars (VFW) offered support to the affected veterans, their families and other members of their organization.
- Texas Muslims communities turned Mosques into shelters, where they offered food to evacuees, distributed hygiene items, and also helped in rescuing stranded Houston residents by boat.
- The Houston Food Bank, a well-established food distribution charity, contributed by collecting donations from community members and distributing them.

Additionally, new community initiatives and groups were formed in the wake of Hurricane Harvey. Volunteer and community 'activist' formed groups either based on their capacities, resources and abilities to support the emergency response and/or on identified gaps and needs in the emergency response operations. While these groups didn't exist as non-profit or community initiatives prior to the hurricane, they quickly transformed their mandate to support the ongoing operations and the affected population.

- A group of volunteers used five monster trucks to rescue victims of the floods in Houston. The group was formed by Josh James; he contacted people in his social network from the Dallas racetrack. The trucks helped emergency services staff to reach areas with severe flooding. The vehicles also pulled an army truck from the flood in the city of Houston (Copperfield).
- The Houston Relief Hub, recruited volunteers and helped by collecting donations and providing victims with clothes, food and cleaning supplies. The Hub was located at a specific address within the city and volunteers could sign up for shifts or just go the office to help during the day. The organization also started helping communities affected by Hurricane Maria in Puerto Rico, thanks to collaboration with the city of Houston.
- The Adopt a family in Need: Hurricane Harvey Facebook group was set up in order to connect people who wanted to help (or 'Angels') with those in need. The goal was to coordinate a community-based relief effort.

Grassroots Community Initiatives and Technology

At the local community level, different groups spontaneously initiated response activities as illustrated by the last examples above. The formation and organizations of these groups are for a larger facilitated by modern information and communication technologies. For example, the Cajun Navy is an ad-hoc volunteering organization, which was started in Louisiana after Hurricane Katrina. The organization recruited volunteers who owned a boat or wanted to help logistically and coordinated the search and rescue of flooded residents in Houston. This effort was supported by a walkie-talkie mobile and web application called Zello (Figure 6.9). Zello enables the creation of publicly available radio-like channels. These were used to recruit volunteers, train them, and ultimately try to connect those willing to help with those in need. Several of these channels were established. The app gained around 6 million new users in a week after Harvey had hit and Hurricane Irma was approaching. However, this is not the first time that the app has been used during crises with a consequent spike in the number of users.

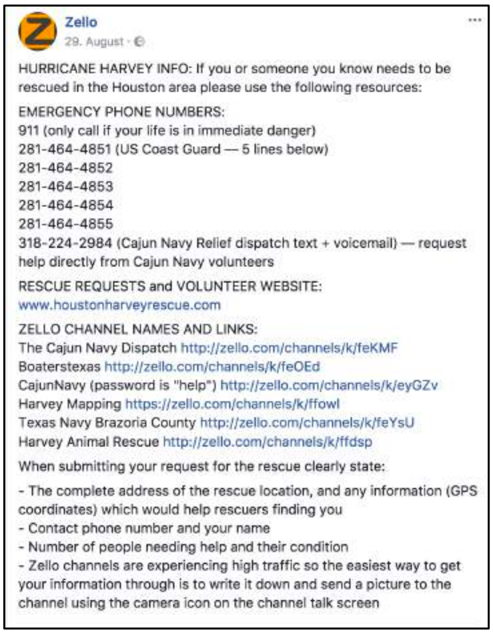

Zello
29. August
HURRICANE HARVEY INFO: If you or someone you know needs to be rescued in the Houston area please use the following resources:
EMERGENCY PHONE NUMBERS:
911 (only call if your life is in immediate danger)
281-464-4851 (US Coast Guard — 5 lines below)
281-464-4852
281-464-4853
281-464-4854
281-464-4855
318-224-2984 (Cajun Navy Relief dispatch text + voicemail) — request help directly from Cajun Navy volunteers
RESCUE REQUESTS and VOLUNTEER WEBSITE:
www.houstonharveyrescue.com
ZELLO CHANNEL NAMES AND LINKS:
The Cajun Navy Dispatch http://zello.com/channels/k/feKMF
Boaterstexas http://zello.com/channels/k/feOEd
CajunNavy (password is "help") http://zello.com/channels/k/eyGZv
Harvey Mapping https://zello.com/channels/k/ffowl
Texas Navy Brazoria County http://zello.com/channels/k/feYsU
Harvey Animal Rescue http://zello.com/channels/k/ffdsp
When submitting your request for the rescue clearly state:
- The complete address of the rescue location, and any information (GPS coordinates) which would help rescuers finding you
- Contact phone number and your name
- Number of people needing help and their condition
- Zello channels are experiencing high traffic so the easiest way to get your information through is to write it down and send a picture to the channel using the camera icon on the channel talk screen

Figure 6.9. New communication channels for community relief coordination: the Zello App. From Zello's Facebook page (https://www.facebook.com/ZelloMe/posts/1119029224863699)

Additionally, the Nextdoor app was used for the same purpose as Zello. This app creates a private social network in the neighborhood. Whether a new user actually belongs to a neighborhood is checked with by verifying the address e.g. with a credit card. While usually, the app is used to seek recommendations for a babysitter, sell items, or report suspicious activity. However, during Harvey, tens of thousands of new users signed up, and the app had a more than 500 per cent increase in posts, replies, and alerts.

This turn to technology is also linked to a failure of 911 communications lines (see §5.6). The need to communicate and the surge of requests were overwhelming the official authority's capacity to manage and cope with individual requests. As such, an institutional void was created that stimulated self-organization and bottom-up efforts, and people turned to their neighbors instead of waiting for authorities to respond.

Digital Response

Even further leveraging the potential of modern information and communication technologies, is the so-called digital response. These digital responses remotely and digitally support the ongoing emergency response for example by providing information or technologies to facilitate the response, whether formal or community driven. Given the role of social media and ICT, it is not surprising that there was a multitude of crisis mapping efforts that aimed to support coordination through providing an overview of the situation. Including support from the European Union through providing satellite mapping

Among these the Standby Task Force (SBTF) was activated to collect information by the U.S. Coast Guard to support the information gathering for Search and Rescue (e.g. location of victims) operations and pollution data from all available sources online. The Standby Task Force is a global organization of volunteers who operate online. It is also part of a wider network called Digital Humanitarian Network (DHN) which includes many other volunteering organizations. The DHN can be activated by formal Emergency management organization (such as FEMA) and its role consists in assigning specific tasks to competent volunteering organization under its umbrella. Volunteering organizations can subscribe to the DHN in order to be involved when something connected to their skills is required.

While the SBTF is maybe most prominent in crisis mapping, there is a broad range of initiatives that were mapping different aspects of needs or the response: Harvey Relief was a crowd-sourced initiative to map needs as well as shelter locations. The Houston Chronicle provided a crowd-sourced map of road closures. Houston Shelters offered a functionality to find the closest shelter. Overall, at least 10 different initiatives have been identified to support emergency response operations and facilitate the provision disaster relief to the affected communities.

All these services do provide valuable information that can guide people that urgently need to find assistance. However, the information presented is often of unclear origin, or validity, and there is no clear mechanism for information verification, updating, or monitoring (Streefkerk et al 2014). Moreover, the increasing number of platforms, website and other digital communication methods make it increasingly difficult to maintain a comprehensive overview not only of the platform themselves but also maintain overall situational awareness based information being offered. While the platforms, and the services and information they offer make a valuable contribution to the formal response and to the affected population, the diversity and their disconnected nature make increases the risk of information and coordination fragmentation, actually reducing their own value.

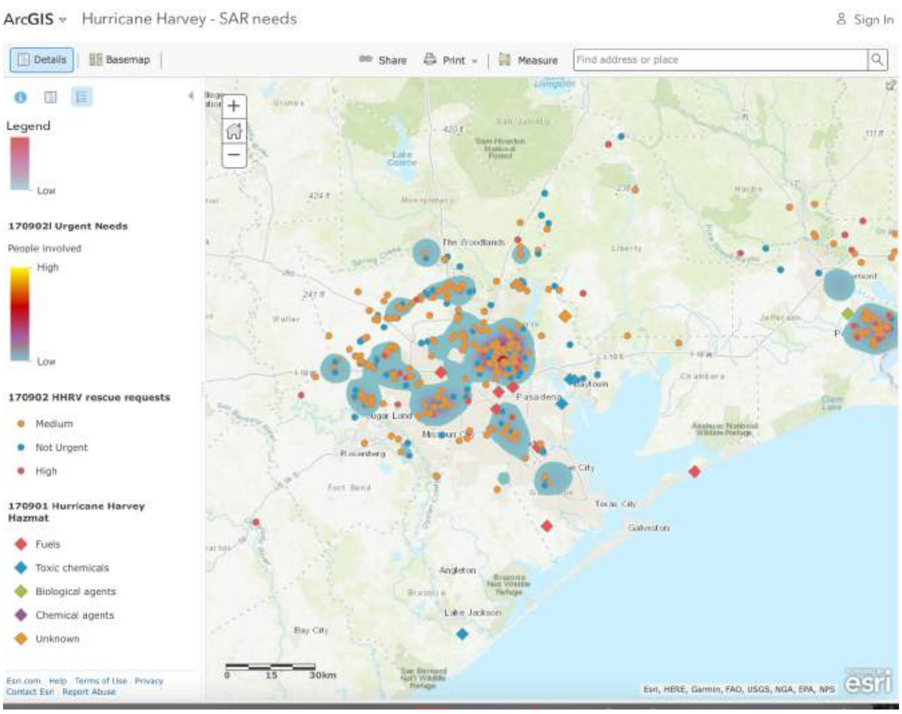


Figure 6.10. SBTF heat map for Hurricane Harvey.

Conclusions

Through the Harvey Hackathon we were able to explore the informal Emergency Response efforts. These were initiated by the private sector, affected citizens, and volunteer and technical communities that engaged in the digital response. In part, the degree of self-organization can be explained by the institutional void: when 911 lines broke down, communities had no choice but turning to their neighbors. At the same time, the use of social media or private and public chat groups on Zello or Nextdoor also bears risks, such as privacy violations, safety issues or fake news (see §6.5). Private sector engagement is often leaning towards supporting specific population groups, typically customers or employees. Relying on the private sector and community response thus cannot ensure that the most vulnerable groups and minorities receive the impartial help they need.

Despite these objections, community response and spontaneous initiatives are a fundamental part of the modern-day disaster response. Communities bring a large amount of resources (in-kind and relief items), capacities and capabilities (equipment and people) and expertise (local knowledge and skills) to the disaster response. Further supported by modern information and communication technologies, disaster response is no longer the sole responsibility of the government mandated emergency management agencies, nor are they able to apply a command and control approach. Rather collaboration needs to be formed between to emergency agencies and the community response. To fully leverage the potential of the community, a coordinated approach requires not only agility and flexibility from the emergency management authorities but most of all a paradigm shift from a command and control to a facilitating role.

6.5. Communication: the effects of 'Fake News'

Fake-news is defined as a type of yellow journalism or propaganda that consists of deliberate misinformation or hoaxes spread via traditional print and broadcast news media or online social media. Due to the political incidents in recent U.S election, the term 'fake-news' gained lots of attentions. However, it is neither a new phenomenon nor necessarily related to political concepts.

Harvey hurricane's fake-news didn't have fatal consequences as far as we have been able to assess; yet it did stress out several social network users. Whereas an image of a shark in the streets of Houston going viral might be not directly harmful, other viral hoaxes during a crisis can lead to catastrophic results (Washington Post, 29 August 2017). Besides creating unnecessary stress to people in an already stressful situation, this kind of news can degrade the value of social networks, shake financial markets, and even disrupt aid operations. Therefore, it is necessary to come up with a solution to overcome this malicious phenomenon.

Figure 6.11. (left) a Facebook post about fake-news of "flooding in Houston airport" and (right) a Facebook post about fake phone number of National Guard.

At the Harvey Hackathon (see Appendix A), we looked at the social media, to acquire data on how people reacted to the fake-news in this crisis. More precisely, what we pursued in three, two-hour sessions, was collecting Facebook posts relevant to some pre-determined fake-news at the time of Harvey hurricane, and trying to detect hidden patterns among the collected data-points. For collecting the data, an instruction sheet had been prepared and handed over to the participants. In this sheet very detailed procedure of data collection was explained.

In our sessions in Harvey Hackathon, we collected 127 data points. Each data point has the following structure:

		Date			Time				Emotion													
#	Category	Day	Month	Year	Hour	Minute	Location	Msg	Like	Love	Haha	Wow	Sad	Angry	Attitude	Account	Type	Goal	Share	Comments	Link	URL

Because each data point has several properties, it can be represented in very different ways. For example, our data can be ranked based on the time of appearance on Facebook, or it can be placed on a map based on its location.

For three reasons Facebook was chosen as the medium of studying fake-news. First of all, in Facebook users can react to the posts with six different emotions, while in other social networks "like" is the only way of showing emotion. Second, Facebook does not let the users to have access to the content of the posts through the regular API.

After the hackathon, we started to analyze the collected data to look for hidden patterns and to shape hypotheses for further research. In a first preliminary evaluation, three patterns can be indicated:

- Geographical boundaries

The first thing that we found out was about the importance of geographical boundary in the spreading of rumours during the crisis. We saw most of the posts about determined fake-news coming from Texas itself. So, we developed the hypothesis "*Crisis related fake-news propagate, mostly in the region of crisis*'.

- User's reactions

Our second insight was about the reaction of the users after revelation of a fake-news. We saw that users who react to these posts with extreme emotion (Love and Anger) are more interested in sharing the revelation news. So, we came up with the hypothesis of '*Users in highly emotional conditions have more potential for fake-news correction'*. If we can prove this hypothesis, a strategy for correcting the fake-news might have been discovered.

- Network structure

The third insight we got was about then structure of fake-news network. We observed only few number of fake-news items are shared by a significant number of people, and the rest are shared just a couple of times. In network science, this is exactly what we call it scale-free network. So, our hypothesis in this observation is '*Rumour networks are scale-free*'.

The data from Harvey Hackathon created a useful first impression of fake-news behavior in social media. For further research, currently, we are collecting more labeled data to be able to study the accuracy of the first two proposed hypotheses. A short first Phyton script shows that around 5000 tweets focusing on Harvey's fake-news were spread between August 17 and September 03, 2017. By a rough estimation based on earlier research experiences on this topic, we estimate that about half or two-thirds of these tweets appeared on Facebook. After finishing the data collection phase, we will form the network of fake-news to study the accuracy of the third hypothesis. Also, we are going to do some statistical analyses to see whether we can find other patterns in our dataset, such as cluster analyses of Twitter messages along the following axes:

- Type of message (warning, amusement, etc.)
- Level of fear (sentiment analysis)
- Popularity (number of retweets)

Ultimately this can become a base to develop insight in and strategies for handling fake-news consequences during a flood disaster The Netherlands.

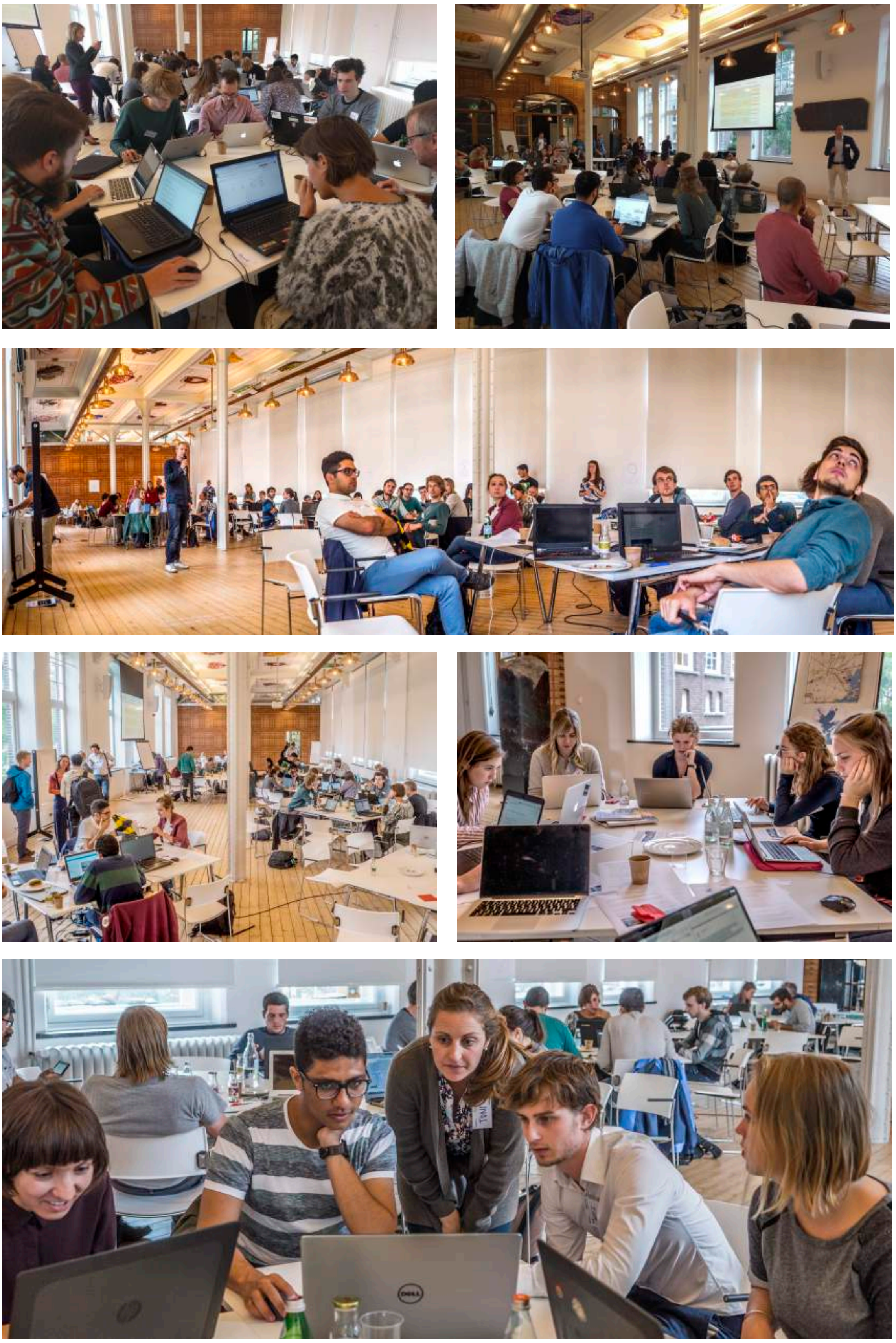


Figure 7.1. Students and researchers collecting data at Harvey Hackathon, TU Delft Science Center, 13 September 2017.

Harvey Hackathon Data Collection Event

7

7.1 Introduction

September 13, 2017, the Harvey Team and an interdisciplinary group of professors and researchers from TU Delft, Vrije Universiteit Amsterdam, Hogeschool Zeeland, Hogeschool Rotterdam, and IFV Institute for Physical Safety co-organized the *Hurricane Harvey Hackathon*. The aim was no to execute a 'competitive' hackathon as is usual, but rather to collectively and collaboratively work on various tasks that are centered around data regarding Hurricane Harvey. Throughout the day there were different data tasks participants could join; for example, collecting (searching) data, analyzing specific events or tracing satellite imagery across different topics related to Hurricane Harvey such as critical infrastructure, community response, flood defenses, etc.

Figure 7.2. Harvey Hackathon at TU Delft Science Center, 13 September 2017

Over 100 participants and topic-leaders from different institutes and studies collaborated during the day (Figure 7.3). The hackathon took place in the TU Delft Science Center from 9AM to 5PM. By working in blocks, students could choose to work on a new subject every 2 hours; or stay put at a subject if they were very interested (for topics, goals, and student tasks, see Appendix A). During each 2-hour block, staff from the various participating institutes provided two 10-minute presentations; either about the topic at hand in the hackathon or on related relevant topics. These short breaks were highly appreciated by students and colleagues alike, by providing a wide multidisciplinary overview. Moreover, they resulted in several new networks for future collaboration, which often overarched disciplines and institutes.

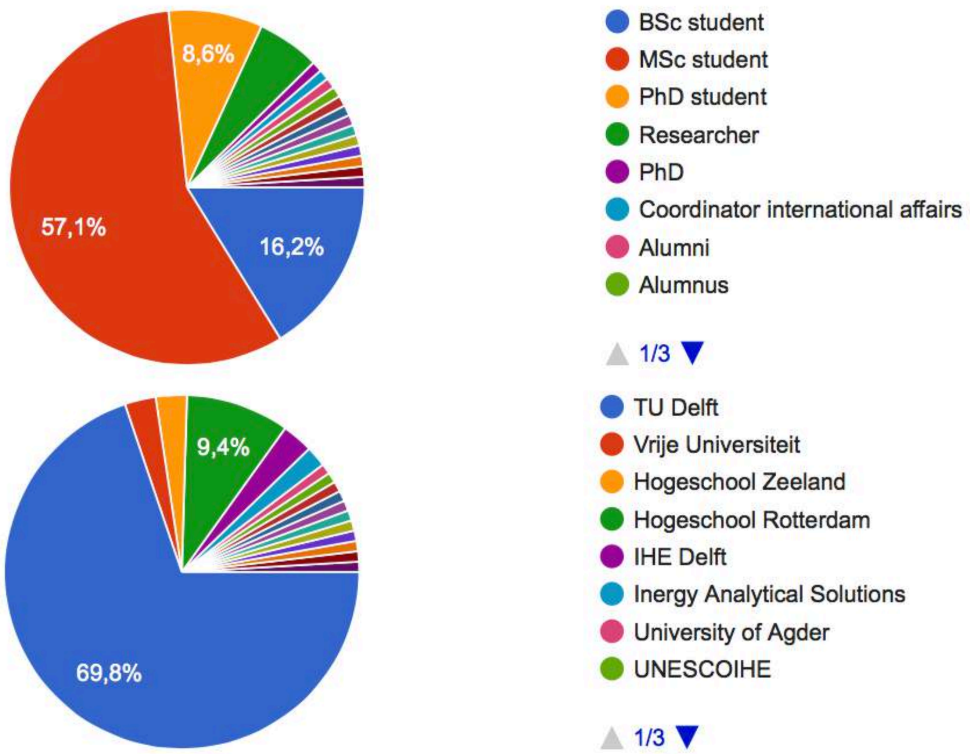


Figure 7.3. Participant's backgrounds (top) and affiliations (bottom)

7.2 Why Hurricane Harvey?

At the time, several other natural disasters were happening, amongst others massive flooding in Asia and hurricane Irma in the Caribbean and Florida. The choice to collect data on Hurricane Harvey was made for multiple reasons. First the Harvey and the Houston area provided a lot of data that could be searched. Since Harvey struck a highly developed region, where already a lot information was available, from either the government or research institutes, the choice for Harvey ensured there was enough 'material' (data) to work with.

Secondly, the data collected from Harvey in this context can be generalized and applied to analyze other hurricane disasters. Harvey is a good case to get an idea of impact, initial response and risks. From this we can draw lessons for future scenarios. This is in part due to the high availability of information and pre-existing knowledge about the region and analytical possibilities, but also because the Houston has certain characteristics that are also found in other (potential) flooding scenario's including dense urban environments, chemical industry and an extensive delta.

Thirdly, the hurricane had passed Houston at the time of the hackathon, which enabled to include the impact of the hurricane, the effect of the emergency response and the consequences for relief and reconstruction.

Finally, Hurricane Harvey and the Houston area served as a common ground of interest across different faculties and studies. As well as outside the university through the long-standing collaboration of TU Delft with Texas' universities – Rice University, Houston and Texas A&M University, Galveston (see Textbox 1.1 in Chapter 1)– offers a base for immediate and relevant follow-up research projects, relevant for both the Netherlands and Texas.

7.3 Structure & organization of hackathon

A structure with several time-slots for the various topics allowed spreading the topics throughout the day and gives participants various options to choose from. Added benefit is that this structure allows ad hoc changes, for example if a topic runs out of work, or turns out to be less or overly popular. Even more, if topic-leaders plan a 'break' for their topic, it gives them an opportunity to evaluate the first round and make changes for the next.

Participants only had to bring was their laptop. It was easy for them to switch between tasks and find links to different spreadsheets, because most topic-leaders used one shared Google Drive for their topic. During the Hackathon we gave access to the drive to all students who joined during the day. The advantage is that there is only one link needed to share initially and one can link to other documents, files, instructions from there if needed. It is easier then every topic-leader setting up their own collaboration environment. Also, Google Drive is an online environment, so no specific software needed for students. One issues to be aware of is the available storage space on the shared Google drive, especially if topic-leaders need to upload exceptionally large data in advance. However, a business account was used to ensure enough storage was available. Furthermore, throughout the day, regular backups to other media were made to ensure no data would be lost.

Task design
As there was a broad range of topics, each topic-leader was asked to design their own tasks that the participants could contribute to, and that would be engaging and 'fun' for the participants. We specifically asked for tasks that would not only require retrieving data, but also require participants to do some analytical work on the retrieved data. This also ensures that participants 'learn' more about the topics and gain new insights and understanding.

Next, topic leaders were asked to design so called 'micro-tasks' (derived from the crowd-sourcing approach). These tasks should be small, easily repeatable tasks with clear instructions, for example following a 'recipe' or 'how-to' manual. Thus participants could work independently on their tasks and still contribute to overall topic. These micro-tasks need to be designed in a way that they do not require too much prior knowledge, experience or expertise.

Finally, the topic-leaders were asked to support the communication of the hackathon by helping to spread the word and recruit participants. During the event, the topic leaders were encouraged to engage with the participants, not only discussing the tasks at hand, but also their relation to ongoing research; and ask about the interests of the participants, contributing to the overall inclusive ambiance of the event. Topic-leaders were also invited to give short presentations to enable interested participants 'deeper dives' in their respective topics. After the event we have asked topic-leaders to share their experience with the organizing team and others, and continue the collaboration with fellow researchers and students as well as contribute (some of) their finding to this report.

Combining data and visualizing results
In the preparations leading up to the hackathon the organizing team offered the topic-leaders three solutions for structuring the data collection / analysis in the task they provided to students. By employing one of these options it would become easier for participants to switch between tasks since there was only a limited amount of data structures and formats in use. It also enabled a direct feedback to the participants as they can see the result of their work immediate visualized. For the topic-leader making use of these systems, reduced the difficulties in setting up and maintaining a data-structure and tools since this was facilitated. It also enables an easier collation and combination of the data in later stages. Finally, the provided systems were setup in

a way that backups were to be made automatically reducing the risks for system failures and loss of data. It was up to the topic-leader to choose which one they wanted to use (or a combination) and how to integrate them in their task and instructions. However we encouraged all topic leaders to include spatial (lat/long) and temporal (date/time) information, so the data from the different topics could later be more easily combined.

Option 1: Own Google Sheet
The first and easiest option is to setup your own Google Spreadsheet. Using the shared Google Drive topic leaders could create one or more spreadsheets in their (topic) folder. The advantage of using Google Spreadsheet is that you multiple people could people work in the same document at the same time. And data-validation, formatting etc., could be used to make the spreadsheet look a certain way and 'force' participants to follow certain conventions. Optionally a Google Form could be used to enter data (although working together in a spreadsheet gives more a 'community feeling'). When using the Google Spreadsheet option, topic leaders were encouraged to add a time (date/time) and/or spatial (lat/long) element (column) so it could later be combined with other data.

Option 2: Timeline
For topics that had a stronger temporal element, the option to create timelines was offered e.g.; http://www.earthmapps.io/harvey.html. These timelines are filled from a Google Spreadsheet using a certain template. This template could be adapted to match the specific data needs of the task at hand and later be visualized in a timeline (Figure 7.4). The visualization is done through a web service developed by Knightlab: https://timeline.knightlab.com/. Since this timeline relies on a Google Spreadsheet the same advantages apply as in the previous option, although specific care has to be taken to follow the template and ensure data is entered in the correct format. The added advantage is the direct visualization of the results on a site that can be shared publicly.

Option 3: Mapping
The third option offered is best suited for tasks with a strong spatial component. This option offers a mapping solution, enabling participants to 'draw' point or polygons on maps and add data to them (Figure 7.5). This solution for example allows participants to trace buildings on satellite imagery and describe certain attributes (such as damage). This option uses Github as a data-store, providing backups and a version-history. The frontend (used by the participants) can be found here: http://geojson.io/. The advantage of this solution is the direct and (fairly) easy mapping and tracing on satellite imagery, providing direct visualizations and output. However, more instructions guidance is needed.

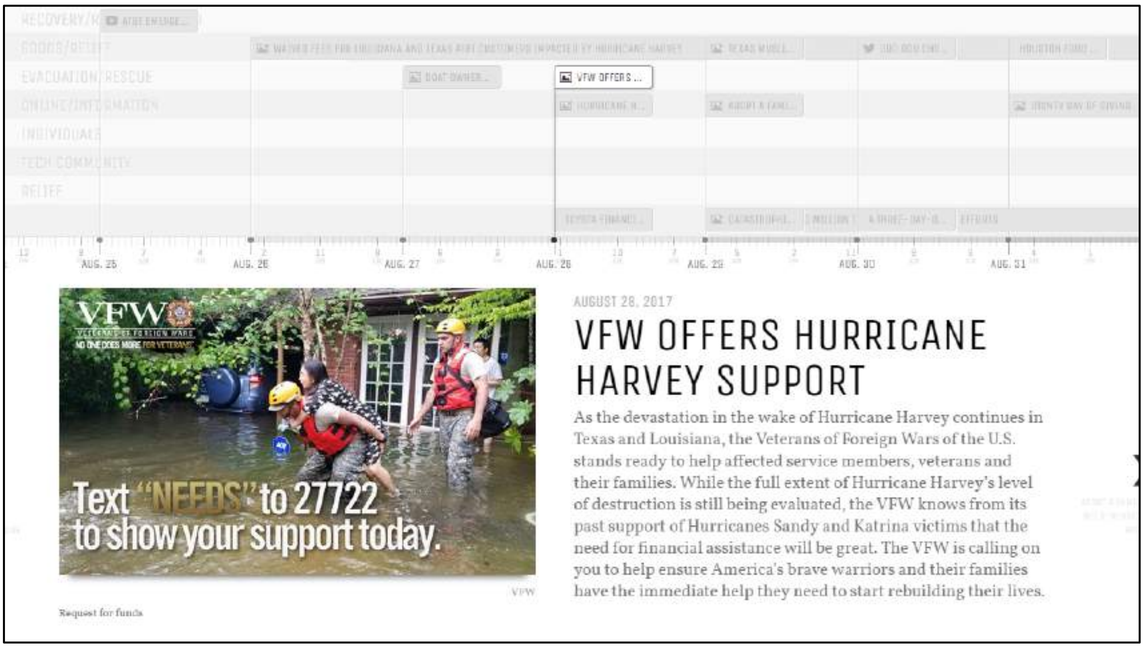


Figure 7.4. Example output of a Timeline (provided by Knightlab)

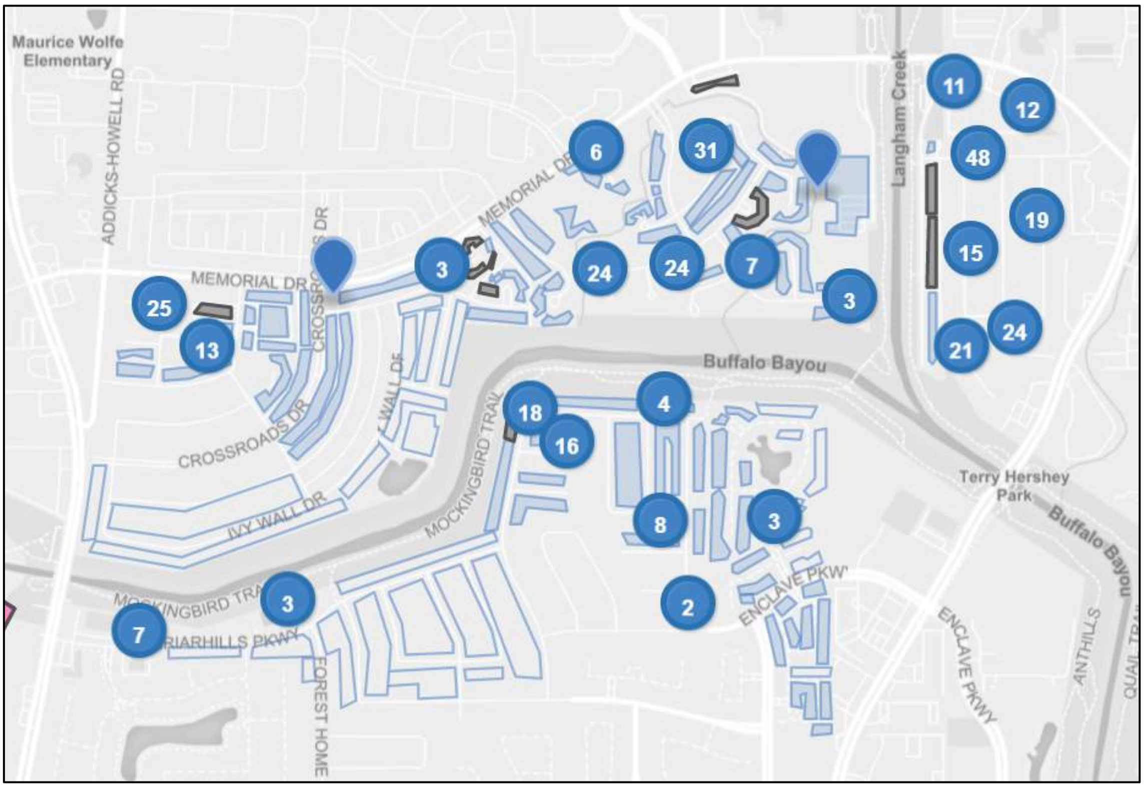


Figure 7.5. Example of Mapping Output (geojson displayed on GitHub)

7.4 Conclusions

Although the data gathered in the Hackathon are a promising base for further research, most of the data could be used only partly for this fact-finding report, as the set is still scattered and could not yet be collated. Nevertheless, all the data, materials, instructions and tools remain available to all participants and topic leaders to be freely used in their own work, projects and research.

For future hackathon events, faster direct use of data can be achieved when (initially) a narrower scope for investigations is chosen. For example, focusing on a specific area of interest or more concise research-area (e.g.; in the Hurricane Harvey case a specific scope could have been the Barker & Addicks Dam area). Multiple topics can thus be clustered around this area, which will ensure more in-depth and connected results in faster manner, rather than more scattered points. It will also contribute to participants' sense of significance from their effort and to be able to communicate some results to interested parties soon after the hackathon.

Related, live feedback to the participants is critical to maintain interest, motivation and momentum. This feedback can be for example from the topic leaders providing personal encouragement. But screens showing live-updated maps and timelines would further support the engagement of the participants. Additionally, those could be shared publicly right after.

From an educational perspective, the hackathon was successful. Experiences and feedback from students were very positive; e.g.; it gave them 'a feeling I could do something valuable with what I study' and they 'loved the experience of working in multidisciplinary teams'. Students have indicated in the follow-up survey that they would like to be informed about future events as well as stay involved in some of the research topics, for example for their own thesis or continue to be involved in one of the ongoing research projects. The hackathon -as a 'form of education'- provides a unique value to students. It provides direct interaction between research, practice and education in an open and hands-on manner. By participating, students learn to use various tools, gain knowledge and find new approaches themselves to leverage their skills to support and implement social relevant research.

From a networking perspective, the hackathon was also successful. Experiences and feedback from participants on this issue were very positive; Researchers mentioned they met colleagues they 'would've otherwise never met' and even 'made plans to co-write a journal article' combining the topics they hosted at the hackathon.

The event also proved interesting for the wider community in the Netherlands as the hackathon was covered by multiple media. Both Dutch national radio (NPO1 Nieuws & Co), regional television (Omroep West) have covered the hackathon. Additionally, websites of the participating organization also provided articles on the event on their websites: TUDelft, IFV and Delta (TUDelft magazine) and an interview on the TU Delft Facebook page. According to the TU Delft social media team the reach on twitter was 5124 impressions and a potential reach of 415050 impressions (Figure 7.6).

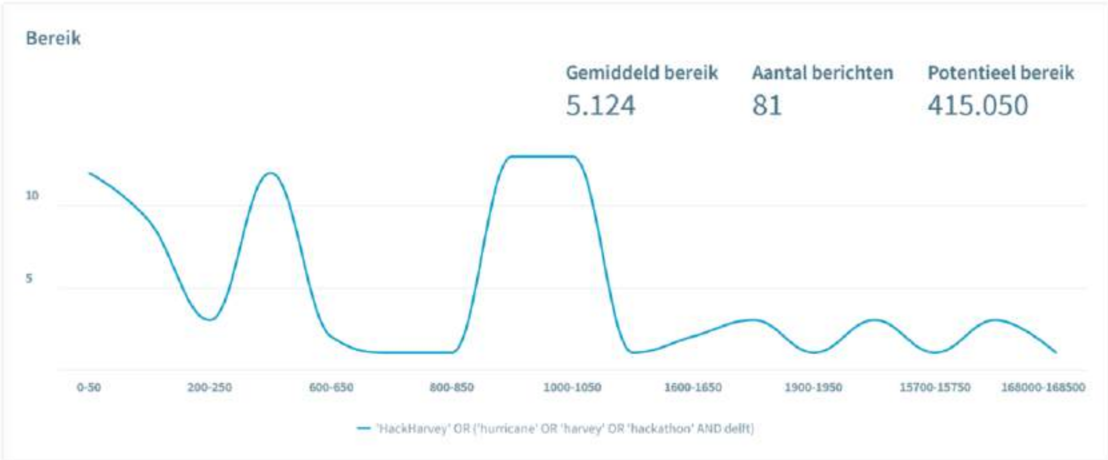
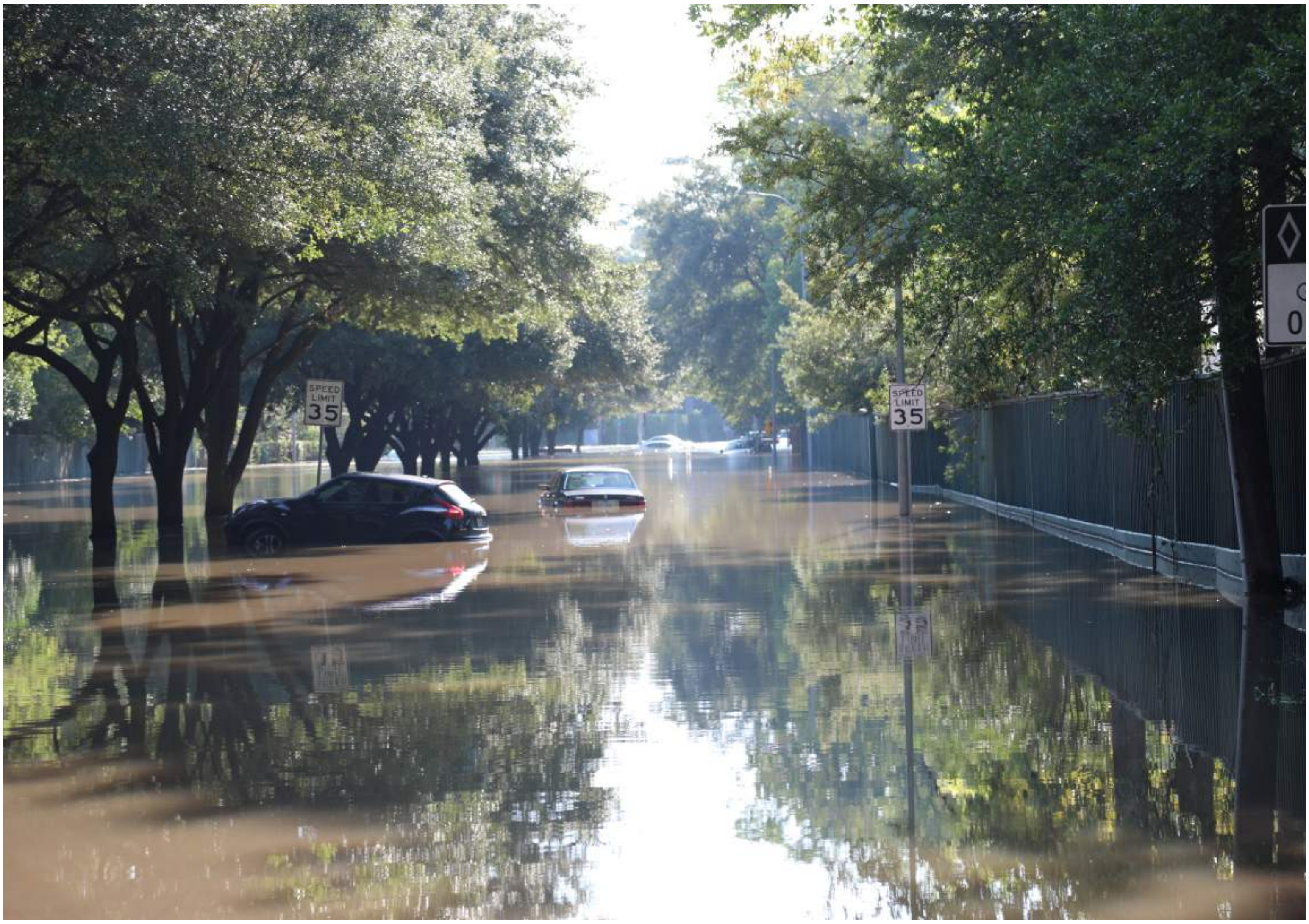


Figure 7.6. Social media reach (Bereik = impressions; Gemiddeld bereik = Average impression; Aantal berichten = Number of messages; Potentieel bereik = Potential impression).

In short, an event like this is worth repeating; it brings together students and researchers from different disciplines and methods in hands-on, open and motivating setting. While some improvements can be made to ensure a higher quality output of data, the approach of a collaborative hackathon seems to have struck a chord with many of the participants and topic leaders. Nevertheless, as there is unfortunately no shortage of disasters, a strategy is needed to determine when it is effective and meaningful to organize a hackathon. Organizing and participating in a hackathon requires a significant amount of effort and commitment, to be provided in a short time. Additionally, the interest enthusiasm for a hackathon may be lost when organized too often, as it very probably only works if it is not an ‘everyday’ activity.



Flooded street Houston, Texas, August 31, 2017 (Image courtesy: U.S. Marine Corps - Lance Cpl. Niles Lee)

Conclusions 8

8.1. Main findings

The following section describes the main findings of the fact-finding phase of the research conducted in response to Hurricane Harvey and its impacts in Houston and surrounding areas. The findings presented here are preliminary and are based on an analysis of the information available in the first weeks after the disaster.

1. Harvey made landfall near Rockport, Texas on August 25, 2017 as a Category 4 hurricane with maximum sustained winds of approximately 200 km/hour. After landfall, Harvey moved slowly inland before moving back out over the Gulf of Mexico and ultimately making a second landfall near the Texas-Louisiana boarder. Harvey caused severe damages in coastal Texas due to extreme winds and storm surge, but will be go down in history for unprecedented rainfall totals and flood-related damages in southeast Texas.
2. Harvey dropped substantial rainfall over the Houston a period of 6 days (August 25-31, 2017). During this period, upwards of 760 mm with a maximum of 1244 mm of rain was recorded in Harris County. In some areas, 12-hour precipitation totals exceeded 531 mm. Across large portions of Harris County, rainfall totals exceeded the 1000-year return period.
3. Harvey was an extreme event in terms of flooding. Harvey's extreme rainfall resulted in all watersheds in the greater Houston area to overflow, with most of them reaching water levels never before recorded. Preliminary estimates based on water levels reported by HCFCD suggest that flood levels in many of Harris County watersheds exceeded the 500-year event.
4. Addicks and Barker Reservoirs, built in the 1940s to protect downtown Houston from flooding by storing rainfall-runoff, were opened on August 28 to prevent catastrophic damages to the dams and further flooding in upstream communities. While rainfall continued throughout August 29, and knowing that the water levels in Buffalo Bayou had already exceeded its banks, it is expected that the dam releases contributed to rising water levels in Buffalo Bayou. This exacerbated flooding in communities along the bayou, with an estimated 4,000 homes affected

5. Harvey was an extreme event in terms of its damages. It is estimated from public and media sources that 119,000 homes were affected of which 800 were completely destroyed; 500,000 cars were damaged; 24 storage tanks ruptured; 300,000 people were without power; and 78 fatalities occurred (69% due to drowning). In addition, 3 million barrels per day of refining capacity were down resulting in an increase in gas prices in $0.50 in Texas and $0.20 in New York. The two busiest Houston airports remained grounded for 5 days and more than 10,000 flights were cancelled. Texas Governor Greg Abbott estimated that the total damages from Harvey may ultimately exceed $150 billion, placing Harvey among the costliest tropical cyclones in U.S. history.
6. Flooding from Harvey also raised awareness of the potential environmental damages that can cascade from tropical cyclones and extreme precipitation events. Numerous industrial and chemical facilities were affected by flooding. Most significantly, the Arkema facility in Crosby, Texas lost power (incl. its generators) resulting in explosions and release of toxic chemicals into the environment. Exxon Mobile was forced to shut down two facilities in Baytown, causing the release of more than 5.6 tons of chemicals. In addition, concerns over damages to superfund and other toxic waste sites were raised. In post-event evaluation, it was found that the cap protecting the San Jacinto Waste Pits was damaged and significant releases of dioxin into Galveston Bay had occurred.
7. No large-scale mandatory evacuation was ordered during Harvey and many people were asked to ‘shelter in place’ (i.e., stay at home or at another safe location). However, it appeared that several evacuations were ordered for local areas during the event. For example, some communities downstream of Lake Conroe were evacuated because the Conroe Dam was at risk of failing; communities near the Brazos River were evacuated because of potential levee failures; and communities downstream of Addicks and Barker Reservoirs had to be evacuated because of controlled releases from the dams.
8. During the event, rising waters trapped many people, which necessitated major rescue operations. The capacity of formal rescue organizations was exceeded and volunteers with boats or large trucks were asked to help conduct rescues. In total, more than 10,000 rescues took place and it was estimated that upwards of 20,000 people needed to be housed in temporary shelters in Houston.
9. Social media played an important role during the event, providing additional resources and information when official organizations reached capacity. For example, SOS calls made via twitter, social media, and other sources were gathered and filtered to determine whether rescues were in fact needed. Moreover, in the wake of the storm, social media was used to organized volunteer networks to help aid recovery (e.g., the ‘Muck Map’). It is important to note that in some cases messages distributed through social and regular media were incorrect, triggering unnecessary fear. One example is the incorrect report of a levee failure along the Brazos River near Columbia Lakes which prompted widespread evacuation. Water levels at this location never overtopped the levees.
10. It became apparent during and after Harvey that development patterns in Houston and surrounding areas had contributed to increased flood risk. Sprawling, mono-functional development, characterized by vast swaths of impervious cover (e.g., pavement) have reduced infiltration capacity and increased runoff rates in the region, contributing to increased flood risk in older developments.

8.2. Future research

Drawing from the main findings of this 'fact finding' report, directions and opportunities for further research are presented for the different disciplines involved in this investigation:

With respect to hydrology:

- to study the storm in terms of its rainfall intensities and corresponding return period and how these are influenced by its track and other storm characteristics;
- to study the role of climate change, i.e., warmer temperatures in the Gulf, on hurricane intensity and/or frequencies along the coast;
- to model flood flows and floodplains resulting from the storms extreme rainfall, taking in to account local aspects such as overflowing of bayous, overland flow, dam operation, interbasin transfers, and compound flooding (e.g., tide and surge). Models may be validated using field observations (e.g., 911 calls, flood marks on buildings, stopped clocks, power outages etc.);

With respect to flood management:

- to model damages and validate against observed damages (e.g., using pre- and post-aerial photos, satellite imagery and field observations) to get a complete and verified picture. Also including long term effects such as health and environmental effects and business losses;
- to estimate pluvial flood risks and how these are influenced by local conditions such as reservoirs, interbasin transfers, and storm tide;
- to study the impact of the dam operation in Addicks and Barker dams (and for example Lake Conroe), and opportunities to reduce potential damages during extreme events by optimizing dam operation; and possible human error under stress situations.
- to investigate which interventions and strategies could effectively reduce flood risks in the region.

With respect to damages and land use planning:

- to perform a post-flood damage assessment assessing the various damage types, such as structural and economic damage to houses, infrastructures etc. Also, the longer term social and health impacts of floods need to be identified.
- to investigate in more detail the cascading impacts (e.g. spills and releases due to Harvey) observed in industrial plants. This will provide a basis to mitigate the risks of these natech hazards in the future.
- to create a systematic inventory of where the to create a systematic inventory of where the interplay between natural landscape and the built environment produces the most urgent challenges in the city's lay out by mapping;
- to identify 'hot spots' that require immediate adaptation and/or have the biggest potential to reduce flood risk at the scale of the metropolitan region;
- to make an inventory of both stakeholders and discretionary powers to steer land use at these 'hot spots', and create local strategies with a large effect on the region's flood risk challenge as a whole;
- to investigate whether a comprehensive strategy that reduces flood risk at the scale of the entire metropolitan city is possible.

With respect to evacuation and emergency response:

- to define optimal evacuation strategies using a risk-based approach, taking uncertainties of forecast and consequences into account;
- to develop decision support tools that can be used to support the call for evacuation and determine effectiveness of evacuation strategies, emergency response and planning;

- to study measures airports can take to better prepare and recover from storm disasters;
- to study how information sharing influences coordination between professional responders, digital volunteers, affected populations and state authorities and providing an analysis of opportunities (e.g.; social media) and risks (e.g., fake news);
- to analyze critical infrastructure interdependencies and develop measures to improve critical infrastructure resilience building on this understanding.
- Facilitate the paradigm shift from a command and control approach in emergency response to a coordinated network, inclusive of informal response and community-driven efforts.

Understanding these issues will provide a knowledge base for establishing a coordinated and comprehensive strategy to reduce flood risk for the region.

8.3. Lessons learned for the Netherlands

Both the Netherlands and the Houston region are at risk of various forms of flooding: coastal, river and pluvial floods and their combinations. Over time, both regions have developed strategies and organizational forms to deal with the various flood hazards.

Relevance for The Netherlands

Efforts in the Netherlands over the past decades have largely focused on developing and maintaining large infrastructure to deal with coastal flooding from the North Sea and river flooding from the river Rhine. Over the last years pluvial flooding due to (local) heavy rainfall is gaining attention. It seems that severe rainfall events are increasingly occurring in the Netherlands For example, in 2017 and 2016, when mobile pumps had to be used in order to remove excess water from cellars, streets and tunnels in The Hague. Rainfall intensities in Texas are much higher than in the Netherlands. As extreme events such as Harvey are very rare, they are also important opportunities to learn.

Texas is a test-bed for local best practices of how to deal with extreme levels of rainfall. Most notably, it can provide a test-bed for the study of robust structures that can withstand a certain amount of street-level flooding, or how to include policies for planning, land use and emergency management in the (re)development of Dutch cities. An inventory of these practices can inspire Dutch policy. To stimulate further debate and exploration a number of lessons learned have been formulated in the next section.

Lessons learned

Although flood management in the Netherlands and Houston differ (see §3.6), a number of lessons for the Netherlands can be formulated based on the findings in this report. These lessons are categorized according to the three layers in the multi-layer safety concept.

Figure 7.1. Multi-Layer Safety; from bottom to top: 1) prevention; 2) land use planning; 3) evacuation and emergency response. (Figure courtesy of Rijkswaterstaat)

Layer 1: Prevention of Extreme Events

The first layer focuses on prevention against floods using civil infrastructure such as canals, dams and levees. Typically, the capacity of these systems is determined using a design flood (e.g. rainfall intensity, river discharge or water level) that has a certain probability of exceedance.

Lesson 1: Harvey demonstrated that extreme events that exceed the design flood do occur. In parts of the region more than 1500mm rainfall fell and the estimated return period exceeded more than 1000 years, i.e. much higher than the design standard of 100 years. A lesson is to take into account the performance for "higher than the design flood" events in the design and management of water infrastructure. Where possible, the design can be adapted in such a way that sudden and catastrophic failure is prevented and thus made be more robust.

Lesson 2: In general, the post-Harvey analysis highlighted that he safety standards associated with many of Houston's infrastructure projects has not yet been determined. In fact, flooding from previous events (e.g., Memorial and Tax Day floods) indicated that much of the existing system is not able to handle precipitation events smaller than the 100-year, the volume used to drive flood policy in the U.S.. Although the water infrastructure in the Netherlands is substantially different and has to meet higher safety standards, it also appears that a large portion of the Dutch infrastructure is insufficiently safe according to current standards. For example, the latest safety assessment highlighted that this was the case for one third of the primary flood defenses. In addition, there is no national assessment and overview of the flood risks due to heavy rainfall.

Layer 2: Land Use Planning

The second layer concerns the impacts of floods and land use planning. The following lessons for the Netherlands can be learned from Harvey.

Lesson 3: Many chemical and industrial plants were affected by flooding during Hurricane Harvey, resulting in spills and releases into the environment. In the Netherlands, similar cascading impacts could occur, for example for chemical facilities in unembanked areas in the greater Rotterdam area. In the Netherlands, similar cascading impacts could occur, for example for chemical facilities in unembanked areas in the greater Rotterdam area..

Lesson 4: A (lack of) comprehensive land use planning has increased flood risk in Houston. While the Netherlands mainly relies on prevention for riverine and coastal flooding, there is poor insight in the relationship between land use planning and pluvial flood risk (i.e., rainfall-induced flooding). An important question, both for the Netherlands and Houston, is the role that land use planning and interventions in the built environment play in reducing pluvial flood risks.

Although the Netherlands' possesses a comprehensive set of land use controls, its planning system is yet minimally geared to reduce damages to structures resulting from severe rainfall events. The above-mentioned inventory of best practices from Texas can inspire (integrated) land use policies in the Dutch planning system, contributing to a more flood-resilient urban fabric in the Netherlands.

Layer 3: Evacuation and emergency response

The third layer concerns the management of a disaster happening. The following lessons for the Netherlands can be learned from Harvey.

Lesson 5: To evacuate or not? During Hurricane Harvey, emergency managers decided not to order a mandatory evacuation. If a severe flood were to take place in the Netherlands, it would be very difficult to evacuate the millions of people living in South Holland, as road capacity is insufficient and lead-time is limited. Thus, it is important to gain a better understanding of the factor leading to a decision to call for evacuation, as well as the way in which this decision is communicated and the response of the public and emergency services to the call. Although experiences in the U.S. cannot directly be copied to the Netherlands because of differences in the physical systems and organizational culture, there are still lessons to be learned from Harvey. Examples include the decisions regarding targeted evacuations of high-risk areas and local resources for sheltering-in-place.

Lesson 6: Tens of thousands of people were located in the floodwaters during Harvey and had to be rescued. The capacity of professional rescue organizations (FEMA, Coast Guard) was insufficient to meet these demands and a large "navy" of volunteers was required to assist. Given the expected scale of flooding in the Netherlands (100,000's of people potentially affected) it can be predicted that in case of a flood disaster large-scale rescue operations will be necessary for which emergency services are currently not fully prepared.

Lesson 7: The response to Hurricane Harvey was coordinated by FEMA. However, the breakdown of transportation infrastructures and communication lines along with the sheer magnitude of the response (see above) created an institutional void at local level, which was largely filled by grass-roots initiatives and volunteers. These local initiatives, however, do typically not follow any code of conduct or guidance – and thus there are no mechanisms to ensure that standards such as neutrality or impartiality are respected, that data is handled responsibly, that information is correct and not manipulated, and that resources and tasks are managed in an efficient way. Therefore, partnerships and preparedness of minimum standards and guidance that enables the emergent volunteer communities to support the response will need to be developed.

Lesson 8: Infrastructures are interdependent. Healthcare systems fail without power, and emergency services depend on functioning 911 (TX)/112 (NL) lines. However, critical infrastructure preparedness and analysis often relies on simplified models that study only individual sectors, such as transportation, or energy. Harvey demonstrated that the failure of high-risk infrastructure, such as chemical industry and refineries, can cause environmental pollution and have long term economic repercussions. Models and systems need to be developed that focus on cascading effects and the complex interplay in today's socio-technical system.

Lesson 9: Social media plays an increasingly important role in disaster response. However the use of social media by government agencies is often limited to 'broadcasting' (sharing 1 message to a large audience) or 'analyzing' (supporting the building of situational awareness). Social media is nevertheless also an 'enabler', it allows people to connect, organize and take action. Social media can enable crisis response organizations to be part of that conversation and create synergy between their own and the community efforts. This however requires active participating in the online dialogue.

A more generic reflection focuses on the way various sources of information can be used to evaluate flood events and other calamities. There is a trend, nowadays in The Netherlands and elsewhere, to move from a physical-based modeling, to data-driven approaches (e.g. artificial intelligence), and hybrid combinations of both. The extensive monitoring of extreme events such as Hurricane Harvey helps to evaluate the performance and applicability of different types of modeling techniques and sources of information to come to a better characterization and understanding of these events.

8.4 Closure

The findings put forward in this report demonstrate that flooding is a problem that has multiple (often local) drivers of both physical and social origin. To address the flood risks facing the greater Houston region and other deltas, a wide range of experts from multiple disciplines will be needed.

This report aims to provide a preliminary knowledge basis that can be used to help begin to identify the issues facing flood risk management in Texas and future directions for flood risk reduction. Given the nature of flood risks in Texas, future studies will need to be undertaken to better define the risks associated with coastal, fluvial, and pluvial flooding in the region, and the effects of policy decisions on flood risk.

In addition, this report demonstrates that lessons for the Netherlands can also be drawn from the flood challenges facing Texas, creating opportunities to further exchange local knowledge and expertise, and to work together develop solutions to reduce flood risks in both regions and in other flood-prone areas globally.

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Members of FEMA's Urban Search and Rescue Nebraska Task Force One comb a neighborhood for survivors impacted by flooding from Hurricane Harvey; Houston August 31, 2017 (Image courtesy of FEMA News Photo)

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A Salvation Army food truck patrols a flood damaged neighborhood delivering free meals, Houston, TX (Image courtesy of FEMA News Photo)

Appendix A. Hackathon topics

Table Xa: HARVEY HACKATHON – Topics, Goals, Student Tasks

Topic	Short description	Goal	Student work	Type of task	Outcome
Self-organizing communities in disasters: threat or opportunity *Kenny Meesters, TU Delft TPM – Dept. Multi Actor Systems*	Today communities can organize themselves using social media. And in the aftermath of disaster it is these local communities that provide the most immediate relief. However, self-organizing communities also challenge traditional 'command-and-control' disaster response. How do we leverage the potential of the community for more effective disaster response?	In the USA there is a strong sense of community, and like in many other disasters, the local people are the first responders. These volunteer initiatives and groups are not always part of existing organizations, or familiar with emergency response. Indeed, there are many unbound, spontaneous volunteer initiatives that help the people in need. Social media enables these groups even further. But how are they organized internally? How do identify the needs of affected population? And work / integrate with formal responders?	- Finding and identifying different volunteer groups active in the response to Harvey - Examine their formation (timeline), objective, organization, strategy Their actions and impact	Data gathering, Data assessment / annotation, Mapping / Visualization	Time line
Emergency response decision- making and actions *Nils Rosmuller; IFV - Institute for Physical Safety*	On several ER topics, Dutch Safety regions are preparing for the worse (floodings). Here, we are able to gather rough data and analyze them later on. With the results, we are able to support Safety regions and their partners and vital sectors in preparing for the worse	Acquire rough data related to: - Self rescue, volunteer community support - Emergency response and ER-logistics - Private contribution to emergency response - Evacuation - Crisis communication/role of the media - Psycho social relief programs - Vital processes such industrial sites/chemical plants/port/medical centers - Recovery processes & priority assessment	Gather data including: which institutions are involved, at what moment (time line), what is their role, which issues did they encounter, how did they decide and for what reasons. how did the y inform other parties and monitor the follow up.	Data gathering	Time line
Environmental pollution in Houston metropolitan area due to hurricane Harvey *Pieter van Gelder, TU Delft TPM – Dept. Safety & Security*	We aim to collect spatio-temporal data about environmental pollution by chemical industry and to look for causal factors.	An overview of environmental hazards by floodwaters in Houston metropolitan area.	A mapping of all chemical plants in Houston metropolitan area. A mapping of all sites where environmental pollution occurred. A spatial-temporal mapping of the extent of environmental pollution during hurricane Harvey.	Data gathering, Data assessment / annotation, Mapping / Visualization	Map
Mapping flood extend based on remote sensing *Stef Lhermite, TU Delft CEG- Dept. Geo Engineering*	The potential and advantages of satellite remote sensing for flood mapping are great. We provide a first insight in their achievements during the Harvey flood. Simultaneously, the initial satellite based flood maps failed to detect flooding in highly urbanized downtown Houston.	Outcome: a map of flooding extent based on available post-disaster optical satellite/airborne imagery. Goal: 1) flood extent maps are crucial for calibrating / improving current hydrological flood models 2) flood extent maps are essential to improve the current satellite based automated flood mapping algorithms	Manually mapping the flood extent based on available post-disaster optical satellite/airborne imagery. Basically it comes down to drawing (no-)flood polygons on screen over satellite/airborne imagery.	Data gathering, Mapping / Visualization Students will get some insights in the potential of remote sensing imagery for disaster impact assessment. Moreover they will learn to work with open cloud-based mapping tools	Map

Table Xb: HARVEY HACKATHON – Topics & Student Tasks

Topic	Short description	Goal	Student work	Type of task	Outcome
Mapping flood damage *Toni Sebastian, TU Delft, CEG - Dept. Hydraulic Structures & Flood Risk*		A map showing the locations where flooding (or damage) has been reported, ideally with depths.		Data Gathering; Data assessment	Map
Hurricane Harvey Hazards: communication to the public *Baukje Kothuis, TU Delft, CEG – Hydraulic Structures & Flood Risk*	Just before and during the hurricane multiple formal authorities communicated to the public about the (to be expected) hazards and the do' & don't's. A timeline of this communication combined with a community response time line could help to create insight in (non)effects of formal communication on resident's behavior before and during the event.	A timeline of the communication to the public by formal authorities in the greater Houston area - Concerning HH flooding hazards to be expected and/or happening at the time - Advice on behavior for residents	Data gathering on messages on HH hazards in public media by * Harris County Flood Control District(HCFCD) * Harris County Office of Homeland Security & Emergency Management * City Of Houston - Mayor's Office * Office of the Texas Governor * US Army Corps of Engineers (USACE) * Galveston County Office of Emergency Management (GCOEM)	Data Gathering; Data assessment / Annotation; add to time line using provided excel file	Time line
Response of authorities and choices in evacuation, shelter and rescue *Bas Kolen, TU Delft, TPM – Dept. Safety & Security*	The mayor of Houston has decided not to evacuate the city. His decision was based on earlier negative experiences of evacuation during Hurricane Rita. Evacuations decisions by authorities have considerate impact on safety; but are not always made on best available (probability) knowledge.	The purpose is to map in a timeline how formal decision-making has been about evacuation, which arguments were made and how the population responded.	- Map how the governments (cities, state, federal government, vital infrastructure, army corps or engineers, etc.) have responded to the threat and occurred events - Map what Harvey's Impact was on social life and the recovery afterwards. If possible, we make a distinction in different geographic areas. - Map the assistance (police, firefighters and army in the field) is executed and how much assistance is provided by people themselves.	Data gathering, Data assessment / annotation, Data analysis, Mapping / Visualization	Time line
Struck and stuck: the role of airports in disasters *Bartel van de Walle; TU Delft TPM – Dept. Multi Actor Systems*	Airports are critical hubs for moving people and goods, yet are often vulnerable when a disaster strikes. Infrastructures may be damaged, from access roads to landing strips, making the airport (partially) non-functional.	The expected outcome is an overview of airport disruptions caused by Harvey in the Houston area. The goal is to understand role of airports pre- and post-disaster.	Explore what factors may cause airport closures, what the effects are on people and goods, and how people and airlines respond. In addition, we will look into how fast an airport can be reopened, and what priorities are then decided upon.	Data gathering, Data assessment / annotation	Time line

Table Xc: HARVEY HACKATHON – Topics & Student Tasks

Topic	Short description	Goal	Student work	Type of task	Outcome
Critical Infrastructure Resilience *Tina Comes; TU Delft TPM – Dept. Multi Actor Systems*	Resilience is often referred to as crucial for modern societies, but it is often unclear what resilience actually means, or how to go about measuring it. In this short presentation, I will discuss possible ways to turn this abstract topic into more concrete decision support.	Measuring disaster resilience of critical infrastructures: - develop a timeline of critical infrastructure failures and recovery, including causes (direct / indirect) - this contributes to modeling the disaster resilience of CIs in Houston, and identify key vulnerabilities	Identify critical infrastructure failures in terms of disruptions (time and service level) and reasons for disruption (direct / indirect). Core infrastructures: transportation, communication, energy (possibly others if there is interest). Data sources: official reports, media reports, social media Structured excel sheet for students will be provided	Data gathering, Data assessment / annotation	Time line
Fake-news in the crisis *Amir Ebrahimi Fard; TU Delft TPM – Dept. Multi Actor Systems*	During hurricane Harvey, on several occasions fake-news was communicated	The goal is to collect social network posts (e.g. tweets) about Harvey hurricane fake-news and tag them based on four indicators: (i) attitude [confirms or believes / deny or debunk] (ii) subject [funny/alarming/frightening/ …] (iii) state [pre-revelation / post-revelation] (iv) source [news agencies/verified reporters /ordinary people/…]. At the end it is expected, a brief summary of collected data based on the above indicators is delivered.	(i) data collection: for Twitter, the easiest way is to use its API, but for Instagram and Facebook the best way is manual data collection, (ii) Tagging: Although with ML, all those tasks can be done automatically with an appropriate accuracy, manual tagging is more favorable. experience, (iii) Brief summary: using Excel, Google Sheet or other spreadsheet software to provide basic stats about each indicator in collected data.	Data gathering, Data assessment / annotation, Data analysis	Time line
Zoning and land use: Entities & Jurisdictions *Nikki Brand; TU Delft, Architecture; Dept. Urbanism*	Texas is (in)famous for not wanting to regulate, and not implementing zoning as means to steer land use. However there are other mechanisms that regulate. For certain purposes special entities are created, using something that looks like a permit to self-regulate. Question is where they have jurisdiction…and how many entities there are in practice. I expect that some places have no entity at all…and perhaps some jurisdictions overlap geographically.	An overview of the geographic jurisdictions of local entities that have powers to steer land use patterns. We can use this to see where there is capacity to deal with flooding hot spots! And where there is no one.	Find: - District organizations (like business districts, where local business owners band together to self-regulate, or historical districts). - Residential subdivisions (mostly outside of the city's proper). - Beltway Business Park? - Municipal management districts (22 for sure!), known as MMDs. - Municipal utility districts, known as MUDs – could overlap with MMDS. - Public private partnerships, like the one that reconstructed Buffalo Bayou - The jurisdiction of Houston Ship Channel?	Data gathering	Map
Governance resilience *Lukas Papenborg; Hogeschool Zeeland, Dept. Resilient Delta's*	The aim is to gain insights about pre-arranged US governance resilience activities and strategies in the Galveston Bay area, before Harvey and the implementation of these activities and strategies during Harvey.	More info on undertaken (strategic) US governance resilience activities in the Galveston Bay area; incl. flood protection, spatial adaptation and crisis management.	The students search and document policies and strategy plans, reports etc. that deal with the resilience of the Galveston Bay area, before Harvey and the implementation of these policies, activities and strategies during Harvey.	Data gathering, Data assessment	Time line

Table Xd: HARVEY HACKATHON – Topics & Student Tasks

Topic	Short description	Goal	Student work	Type of task	Outcome
Insurance *Matthijs Kok, ,* *TU Delft, CEG – Hydraulic Structures & Flood Risk*	In a hurricane like Harvey there are different types of damage, for example damage due to wind and damage due to floods. There is not a single insurance or another compensation mechanism that covers all those damages.	Harvey caused much damage, in a lot of economic sectors. But who paid the damage? The individual citizen and the company who suffered the damage? Or are there some instruments like insurance to share the damage? Explore the internet to discover information about compensation. The challenge is to discover what types of insurance policies there are, and how it is divided among the different groups of people (for example rich versus the poor).	1. Find FEMA insurance maps for Houston. These are maps of FEMA: if you are in the 1/100 floodplain, then you have to buy flood insurance when you have a mortgage. Find also other information about insurance of “Harvey damage”, and premiums. 2. Disaster relief. Often, people (and companies?) are compensated by local disaster relief funds. Is there information about these funds about Harvey? Who is paying these funds? Find information on social media about (flood and other types of) insurance, or other types of local or federal disaster relief of the damage 3. Critical infrastructure (hospitals, oil and gas infrastructure, tap water, roads, etc): who is paying damage	Data gathering, Data assessment / annotation	Overview/ map