HOSPITAL EXPERIENCES WITH HURRICANE HARVEY IN HARRIS COUNTY, TEXAS

by

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Hospital Experiences with Hurricane Harvey in Harris County, Texas

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Hospitals should be capable of delivering both day-to-day and emergency services at surge capacity during extreme weather events, but flooding causes complications with power generation, provision of clean water, patient safety, communication, and hospital access. The sudden arrival of Hurricane Harvey on the Texas coast served as a reminder that no recent comprehensive study of Harris County's healthcare system vulnerability to extreme flooding events had been conducted. This study first completed a geospatial analysis comparing which hospitals were at risk of flooding pre-Harvey with the actual flooding impacts post-Harvey. The mapping results revealed inconsistencies between the predicted and observed hospital flooding, perhaps reflecting nuances in hospital adaptation efforts that are not captured by mapping alone and necessitating an in-depth qualitative approach. A narrative was then constructed detailing Harris County hospitals' collective experience with Hurricane Harvey and the lessons learned in the aftermath of the storm, through a survey of hospital emergency managers, semi-structured interviews with local organizations involved in public health and emergency management, and an analysis of the media. Evaluation of the hospitals' emergency responses to Hurricane Harvey revealed well-coordinated efforts guided by past experience with extreme flooding (i.e., Tropical Storm Allison) and a strong regional coalition; however, the adoption of additional flood adaptation measures and further planning is still advisable in preparation for future flooding events. Results from this study contribute to efforts aimed at improving critical healthcare infrastructure to better prepare for, respond to, and recover from future flooding events like Hurricane Harvey.

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ACRONYMS

AAR	After Action Report
AMS	American Meteorological Society
ARC	The American Red Cross
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
BFE	Base Flood Elevation
CDC	Centers for Disease Control and Prevention
CMOC	Catastrophic Medical Operations Center
CMS	Centers for Medicare and Medicaid Services
COHGIS	City of Houston GIS
DEM	Digital Elevation Model
DHS	U.S. Department of Homeland Security
DoD	U.S. Department of Defense
DSHS	Texas Department of Health and Human Services
EHR	Electronic Health Records
EMS	Emergency Medical Services
ESRI	Environmental Systems Research Institute
FEMA	Federal Emergency Management Agency
FGI	Facility Guidelines Institute
GIS	Geographic Information System/Science
HCAD	Harris County Appraisal District
HCFCD	Harris County Flood Control District
HCMS	Harris County Medical Society
HCOHSEM	Harris County Office of Homeland Security and Emergency Management
HEICS/HICS	Hospital (Emergency) Incident Command System
HHS	U.S. Department of Health and Human Services
HIFLD	Homeland Infrastructure Foundation-Level Data
HSIP	Homeland Security Infrastructure Program
HUD	U.S. Department of Housing and Urban Development
ICS	Incident Command System
IDW	Inverse Distance Weighting
IPCC	Intergovernmental Panel on Climate Change
IRB	Institutional Review Board

IT	Information Technology
NFHL	National Flood Hazard Layer
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NHRAP	Natural Hazard Risk Assessment Program
OPHPR	Harris County Office of Public Health Preparedness and Response
PDI	Power Dissipation Index
RWA	Ready, Willing, and Able framework
SETRAC	SouthEast Texas Regional Advisory Council
TCEQ	Texas Commission on Environmental Quality
TDEM	Texas Division of Emergency Management
THA	Texas Hospital Association
TMC	Texas Medical Center
TNRIS	Texas Natural Resources Information System
TxDOT	Texas Department of Transportation
TxDPS	Texas Department of Public Safety
USGS	United States Geological Survey
VA	Veterans Administration
WHO	World Health Organization

CHAPTER I—INTRODUCTION

Literature Review

Extreme Flooding Events

The National Oceanic and Atmospheric Administration (NOAA) defines flooding as "any high flow, overflow, or inundation by water that causes or threatens damage" (NOAA, 2017a). Flooding is of massive concern globally because it is perhaps one of the most disastrous forms of natural disaster in terms of lives lost and property damaged (Zahran et al., 2008; Wilby and Keenan, 2012). In the U.S. alone, Federal Emergency Management Agency (FEMA) has estimated that flooding has resulted in over 10,000 deaths since 1900, and NOAA reports billions of dollars worth of flood-related property damage since 1980 (Ashley and Ashley, 2008; Zahran et al., 2008; NOAA, 2017b).

In order to protect lives and property and inform flood insurance decisions, FEMA provides the U.S. public with estimates of flood risk through the designation of 100-year and 500-year flood hazard areas, where a 100-year flood hazard area delineates land with a 1% chance of flooding in any given year and a 500-year flood delineates land with a 0.2% chance of flooding in any given year. Although the FEMA flood hazard areas are revised frequently to portray current flood risk, these estimates are based solely on current hydrology, infrastructure, hydraulics, and land use, and do not take into account whether changing climate factors will influence future flooding events (Popovich and O'Neill, 2017; Skibba, 2017). However, the combination of these changing climate factors with expanded development in coastal areas and floodplains, infrastructure vulnerability, and land-use change does not bode well for the future consequences of flooding (Thomas, 2011; Lowe et al., 2013; Melillo et al., 2014). Several climate factors influencing future flooding outcomes in the U.S.—including precipitation, hurricanes, and sea level rise—are explained in detail below.

Average annual precipitation across the U.S. has increased by approximately 5% over the past decade (Peterson et al., 2013). However, there are striking geographical differences in projections for future precipitation, with areas in the northern U.S. projected to become wetter while the Southwest is projected to become drier (Peterson et al., 2013; Melillo et al., 2014). In addition, The Third National

Climate Assessment also noted observed regional increases in very heavy precipitation events from 1958 to 2012 in all regions across the continental U.S. (Melillo et al., 2014; Chand and Loosemore, 2016). The Northeast, Midwest, and Southeast regions of the U.S. have been particularly impacted over this time frame, with observed percent increases in very heavy precipitation events of 71%, 37%, and 27%, respectively. Projections suggest that the observed regional increases in very heavy precipitation events will continue to increase, even in regions like the Southwest, where annual average precipitation is likely to decrease (Melillo et al., 2014). These projected changes in average annual precipitation and extreme precipitation events will likely increase the risk of major flooding events.

Increases in total hurricane power, or Power Dissipation Index (PDI), have also been observed in the North Atlantic Ocean since the early 1980s (Melillo et al., 2014). Total hurricane power over a season is an aggregate measure of storm intensity, frequency, and duration (Lane et al., 2013; IPCC, 2014; Melillo et al., 2014). Although hurricane development is complex and influenced by more than one factor, recent increases in hurricane activity are closely linked to rises in sea surface temperature (Mann and Emanuel, 2006). There is uncertainty in projections of future Atlantic storm activity, but many global climate models agree that there will likely be an increase in the strongest Category 4 and 5 hurricanes, despite a slight decrease in the total number of tropical storms (Bender et al., 2010). Of course, coastal areas will be most affected by these changes in the frequency and intensity of tropical storms (Lane et al., 2013).

Between the years 1880 and 2009, a combination of *in situ* tide gauge measurements and satellite data revealed an increase of 0.2 meters (0.65 feet) in global average sea level (Church and White, 2011). However, the rate of global sea level rise has nearly doubled since 1992, indicating an acceleration unprecedented within the last 2000 years (Church and White, 2011; Melillo et al., 2014). Projections of future sea level rise predict an increase of sea level by an additional 0.2 meters (0.65 feet) to 2.0 meters (6.6 feet) by 2100, depending on which future emissions scenario is used in the global climate model (Jevrejeva et al., 2012; Parris et al., 2012). Approximately 5 million Americans live within 4 feet of their local high-tide level, meaning that projected sea level rise will put many populous coastal communities

and their infrastructure at risk of flooding during high tides and storm surges (Strauss et al., 2012; Bathi and Das, 2016).

Overall, the combination of extreme precipitation events, sea level rise, and tropical storms is predicted to create the conditions for more frequent and intense flooding events over the next decade. Additionally, changes in urbanization and land use have the potential to intensify flooding across the U.S., even in regions where precipitation is projected to decline, making it increasingly important to focus on the impacts of flooding on society (Melillo et al., 2014).

Vulnerability Framework

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the degree to which a system is susceptible to injury, damage, or harm" (IPCC, 2014). This concept of vulnerability is a function of exposure, sensitivity, and adaptive capacity. Applying this concept to healthcare systems, and hospitals in particular, exposure would be the physical exposure to a hazardous event, such as flooding of a hospital; sensitivity refers to the ability of a hospital to withstand exposures and associated impacts; and adaptive capacity refers to the ability of a health system or hospital to cope with hazards and limit exposure (Bierbaum et al., 2014; IPCC, 2014). This vulnerability framework, including exposure, sensitivity, and adaptive capacity, will be referenced throughout this thesis as it applies to hospitals and flooding events.

Healthcare System Vulnerability to Extreme Flooding Events

The impacts of extreme flooding events on critical infrastructure such as roads, water, and power generation are well documented, but fewer studies have formally outlined how flooding events impact healthcare infrastructure and therefore the delivery of health-related services (Loosemore et al., 2010; Phalkey et al., 2012; Chand and Loosemore, 2016). Ideally, healthcare facilities should be capable of delivering both day-to-day and emergency services at surge capacity during extreme weather events, but extreme flooding is known to cause complications with power generation, provision of clean water,

patient safety, communication, and access (Few et al., 2004; Frumkin et al., 2008; Keim, 2008). Aside from providing care to patients currently admitted, hospitals are responsible for managing additional patients with flood-related health concerns during and after flooding events. These health concerns related to extreme flooding events can be both short- and long-term, including drowning, blunt trauma, access to prescription medication, toxic exposure, communicable disease, water-borne disease, vector-borne disease, mold exposure, and mental health—all requiring the availability of and access to nearby hospitals (Few et al., 2004; Alderman et al., 2012; Phalkey et al., 2012; Lowe et al., 2013; Rufat et al., 2015). Since hospitals in the U.S. were originally designed with few considerations for flooding, our healthcare infrastructure is fragile and vulnerable, with more frequent and intense flooding events threatening the functionality of hospitals across the country (Few et al., 2004; Frumkin et al., 2008; Keim, 2008; Carthey et al., 2009). For example, the U.S. Department of Health and Human Services (HHS) estimates that Hurricane Sandy in 2012 caused 89% of hospitals in the affected area to report having "substantial challenges," whereas Hurricane Katrina in 2005 practically devastated New Orleans' healthcare system (Foley, 2017).

Impacts to the healthcare sector are most obviously a public health and a social threat, but since the healthcare sector comprises 20% of the U.S. economy, extreme flooding events also pose an economic threat (Frumkin et al., 2008; AMS, 2010; The White House, 2014). Several past extreme flooding events across the U.S., including Hurricane Sandy (2012), Cumberland River floods (2010), Mississippi River floods (2008), Hurricane Katrina (2005), and Tropical Storm Allison (2001), demonstrate just how critical it is to address America's healthcare infrastructure vulnerabilities to extreme flooding events (AMS, 2010; Evans, 2013; Guenther and Balbus 2014).

As outlined by a recent report by the U.S. Department of Health and Human Services (HHS), healthcare infrastructure vulnerability to flooding can be divided into the following categories: structural, non-structural, and organizational (Achour et al., 2014; Guenther and Balbus, 2014). Structural vulnerability describes damage and destruction of the physical hospital building or structure, including but not limited to the foundation, walls, floors, and roofs. For flooding in particular, stricter building

codes and improved architectural design can improve the odds of a hospital building surviving an extreme flooding event with little to no structural damage. This could include both dry floodproofing (meaning the ability to resist water infiltration and flood forces by using walls and/or barriers) and wet floodproofing (meaning the allowance of water infiltration but preventing damage by using flood resistant materials) (Arnold et al., 2007; Low et al., 2013). Non-structural vulnerabilities to flooding can include damage or disruption to virtually anything within a hospital building, including communication infrastructure, emergency power generation, air conditioning, stormwater management, waste disposal, electrical systems, mechanical systems, supply storage (food, water, pharmaceuticals), and medical equipment (FEMA, 2013; Guenther and Balbus, 2014). Lastly, organizational vulnerabilities broadly describe any deterioration, miscommunication, or failure of organizational plans or procedures, including staff education and training, evacuation planning, adequate supply storage, patient influx, non-patient shelter, patient safety, prioritization of care, or hospital access by air, road, or water (Guenther and Balbus, 2014). In order to thoroughly address an individual hospital's vulnerability to extreme flooding events, each category of vulnerability, as well as the multitude of issues within each category, need to be considered and matched to an appropriate adaptation strategy.

It is important to note that the aforementioned structural, non-structural, and organizational vulnerabilities to flooding are magnified in aging hospital buildings, where older infrastructure and technology are likely in poor condition and therefore more easily damaged by flooding events. In the U.S., the average age of healthcare infrastructure is now exceeding 20 years old, indicating a trend of aging hospital buildings (Bean, 2016). The consequences of deteriorating healthcare infrastructure are compounded by the high flood-risk locations of many hospitals, due to their historical placement near water, in order to secure a water supply and location for sewage discharge (Guenther and Balbus, 2014).

Despite the aging U.S. healthcare infrastructure, new hospitals are built regularly. New hospital construction minimum requirements are outlined by the Facility Guidelines Institute's (FGI) Minimum Standards for the Design and Construction of Hospitals and Health Care Facilities, which strongly advises against the construction of new facilities in FEMA flood hazard areas unless special design and

construction provisions are made (FGI, 2014). Hospitals are additionally required to abide by zoning and building code minimum requirements as outlined by state and local jurisdictions, which may or may not be strict enough to protect facilities from inundation in the event of extreme flooding. By only setting minimum standards, many hospitals located in risky areas have not been required to floodproof their facilities at all. In the case of older hospitals constructed many years ago when standards were much lower, facility improvements aimed at attaining current construction code standards are a difficult but necessary task (Guenther and Balbus, 2014). Similar to the construction minimum requirements, the flood insurance requirements are also convoluted and relatively lax, leaving many hospitals underinsured or not insured at all. However, hospitals with federally-backed mortgages that are located within FEMA 100-year flood hazard areas are required to be covered by the National Flood Insurance Program (NFIP), which has its own set of minimum requirements, especially regarding elevation of lowest floor and dry floodproofing (Arnold et al., 2007; FEMA, 2013). With several entities enforcing a variety of minimum requirements for hospital construction and flood insurance, neighboring hospitals could theoretically have very different levels of flood preparedness and insurance coverage.

Adaptation Strategies to Improve the Hospital Outcomes of Extreme Flooding Events

Following Hurricane Katrina, a study focusing on New Orleans' hospital disaster preparedness and emergency response outlined several recommended adaptation strategies aimed at developing more resilient healthcare systems, each of which are described in detail below (Rodriguez and Aguirre, 2006). Adaptation, as defined by the IPCC, is the "adjustment of our built environment, infrastructure, and social system in response to actual or expected climatic events or their effects" (IPCC, 2014). These adaptation strategies address issues across the spectrum of hospital vulnerabilities, but are not necessarily comprehensive, as we continue to learn with each disaster response.

A) Emergency response planning, training, and education

It is critical that comprehensive emergency procedures and evacuation plans be designed and implemented before extreme flooding events strike. Without plans, procedures, leadership, and organization, any emergency response is likely to become chaotic and inefficient (Few et al., 2004; Phalkey et al., 2012). The first component of emergency response planning should include training staff members, identifying a hierarchy of personnel involved in emergency response, and assigning responsibilities through the use of the Hospital (Emergency) Incident Command System (HEICS/HICS), a version of the Incident Command System (ICS) tailored specifically to the hospital environment (Institute of Medicine, 2007; CalHopsitalPrepare, n.d.). Using the hierarchical structure and task-specific positions defined by HEICS reduces duplication of effort and allows for smoother and more efficient response coordination during emergency events (WHO, 2010).

The second component of emergency response planning is emergency exercises. Although emergency exercises are often thought of as just one requirement in the accreditation process, they should be conducted frequently, as exercises are the only way to thoroughly assess emergency plans and procedures and ensure all staff are well-equipped to continue delivering healthcare services during emergency situations (WHO, 2010; Bell, 2011; Phalkey et al., 2012). Emergency exercises come in many forms under two broad categories: discussion-based exercises like tabletop scenarios, and operations-based exercises like drills and full-scale simulations (WHO, 2010). Following any emergency exercise or actual emergency event, hospitals are required to write an After Action Report (AAR) documenting observations and evaluating the emergency response in order to identify successes and shortcomings (CalHospitalPrepare, n.d.). Lessons learned through emergency exercises can then be applied in the next round of exercises, or to an actual emergency event.

B) Resilient communications systems

Information technology (IT) systems enabling communication through telephone and internet are subject to service disruption and damage during extreme flooding events (FEMA, 2013; Guenther and

Balbus, 2014). The resulting loss of external communications, such as coordination with outside agencies about road conditions and evacuations, and internal communications, such as within-hospital communication about patient care, can impede disaster response (Phalkey et al., 2012; FEMA, 2013). In a study of risk management of extreme weather events, key stakeholders identified maintaining essential services, such as effective internal and external communications, as a top priority (Loosemore et al., 2010). A strategy many hospitals have begun to implement is redundancy in communication systems, meaning that if telephone and internet systems fail, that there are backup systems available, including technologies like cell phones, pagers, and ham or satellite radios (CalHospitalPrepare, n.d.)

C) Transportable health records

Over the past few decades, hospitals have transitioned from paper patient records to electronic health records (EHR), or digital versions of patient records. In the past, a major concern during flooding events was the susceptibility of paper patient records to water damage. Although on-site computer systems may also be damaged during flooding events, digital patient records are often stored on servers elsewhere, meaning that access to records is less likely to be disrupted in the event of on-site hospital damage (Neal, 2011; Shepard, 2017). Ideally, by transitioning to a cloud-based electronic system, EHR has the potential to create retrievable and transportable health records (Neal, 2011). However, a 2015 study found that only 30% of U.S. hospitals have the ability to share EHR data across hospitals, and fewer actually choose to do so, meaning that patients are responsible for remembering their health information and doctors may duplicate efforts or make uninformed medical decisions (Rapaport, 2017). Additionally, paper-based record-keeping procedures still need to be established in the case of an emergency event causing EHR downtime (Shepard, 2017). The expansion of EHR into a truly shared or transportable information system could improve the coordination, efficiency, and accuracy of healthcare services when patients are forced to receive care elsewhere during emergency events (Rodriguez and Aguirre, 2006; Rapaport, 2017).

D) Community-driven healthcare systems

Successful disaster preparedness and response initiatives are highly sensitive to local context and should involve the community and their local organizations. The creation of resilient community healthcare centers can fill the gaps in delivery of basic healthcare services when nearby hospitals are impacted by flooding events (Rodriguez and Aguirre, 2006; Ebi and Semenza, 2008). Additionally, local health departments are strongly encouraged to identify community vulnerabilities and build resilience at a local level through the development of targeted health interventions (Manangan et al., 2014). For example, communities with large numbers of dialysis patients would benefit from identifying and locating these at-risk individuals ahead of time and providing the resources necessary to guarantee both early dialysis and continuous care throughout flooding events (Davis and Kopp, 2015; Newkirk, 2017). Another strategy is the creation of regional healthcare coalitions, which induce collaboration and partnerships between hospitals, community health centers, and other local entities involved in public health and emergency management. Hospitals participating in regional healthcare coalitions benefit by sharing resources, participating in joint planning and training, and forming relationships with partner organizations—improving emergency management approaches on a regional scale (Institute of Medicine, 2014).

E) Adequate temporary shelter, staff, and supplies

Access to hospitals may be limited during extreme flooding events, leading a variety of issues that advanced planning could help remedy. First, hospitals are likely to experience staff absenteeism and low staff availability, as staff either cannot physically make it to the hospital, or do not wish to work either for safety concerns or to remain with their families (Siegel Spieler et al., 2008). If hospitals are aware of an impending emergency event, such as an extreme flooding event by way of hurricane, it can be advantageous to request staff members (often called a ride-out team) arrive on site in advance (Phillips et al., 2017). By ensuring adequate staffing during an extreme flooding event, hospitals will experience fewer issues with overtime, burnout, and lack of adequate rest for staff. Second, in the case that access is

disrupted and staff cannot physically make it to the hospital, the hospital may call for the activation of a shelter-in-place plan, where the ride-out team is responsible for providing patient care throughout the emergency event. In this situation, provisions should have been made to ensure that staff remaining on site for many days, as well as non-patients seeking temporary shelter, have designated space within the hospital separate from patient treatment areas (Rodriguez and Aguirre, 2006; Phalkey et al., 2012). Lastly, in the case that access to hospitals is limited, hospitals may experience supply shortages due to an influx and extended stay of patients and staff, as well as reduced or cancelled deliveries of critical goods (AMS, 2010). In order to avoid any shortages, hospitals should maintain ample stocks of supplies, such as food, water, linens, and medications on site at all times (Few et al., 2004; CDC and AWWA; 2012; Phalkey et al., 2012).

F) Building design and facility resilience

In an ideal world, critical facilities like hospitals should not be located within FEMA flood hazard areas, but a more realistic approach would be to enforce higher construction standards for hospitals located within these areas (Few et al., 2004; FEMA, n.d.). Both structural and non-structural considerations must be made in order for hospitals to avoid physical damage and the breakdown or complete failure of systems in place within the facilities (Few et al., 2004).

The National Flood Insurance Program (NFIP) delineates a set of requirements for new hospitals that may or may not be more stringent that local or state jurisdiction, but it is important that existing hospital infrastructure built prior to these standards be upgraded to these standards as well. Building codes should ensure that the hospital design and building anchoring systems are strong enough to prevent flotation, collapse, or lateral movement (FEMA, 2013). Critical components of hospitals, such as electrical, mechanical, fuel, and communications systems, should, at a minimum, be elevated above base flood elevation (BFE), which is the highest flood elevation currently anticipated for a 100-year flood (FEMA, 2013). Portions of hospitals located below the BFE must be constructed using flood-resistant materials. Dry floodproofing, which involves the construction of flood barriers or walls, is another

strategy for reducing the likelihood of inundation (FEMA, 2013). Regardless of hospital location inside or outside a FEMA flood hazard area, it is critical that access to the hospital is maintained, whether by air, road, or water, for emergency vehicles, evacuations, and supply delivery (FEMA, n.d.). Additionally, loss of municipal utilities, such as power and water, commonly impacts the functionality of hospitals during extreme flooding events, proving the importance of independent and redundant emergency backup systems (FEMA, n.d.; CDC and AWWA, 2012; FEMA, 2013).

Barriers to Hospital Flooding Adaptation Efforts

Despite the success of adaptation efforts undertaken by many hospitals across the U.S., not all healthcare systems are equally able to address adaptation needs. The American Meteorological Society (AMS) has identified three main barriers to hospital adaptation to extreme weather events. First, there is a general lack of awareness of environmental vulnerabilities on the part of local decision-makers. Second, there is an absence of coordination and communication across federal agencies. Third, financial resources or incentives to encourage structural mitigation or other adaptation efforts for current and projected weather risks are extremely limited (AMS, 2010; Guenther and Balbus, 2014). However, the AMS' findings are not comprehensive and exclude several barriers identified by other studies, including uncertainty about future climate conditions, perceptions of vulnerability, and potential technological limits.

Although there are projections of future climate conditions and models of potential extreme weather event scenarios, there is still some uncertainty about what the future holds. This uncertainty permeates into decision-making conversations at multiple scales, preventing critical conversations within local hospital emergency management and federal government alike. In many ways, decision-makers are less likely to take action when the impending threat of more frequent and intense extreme weather events is not a guarantee (Gersonius et al., 2013; Smith and Katz, 2013; Woodward et al., 2014; Hurlbert and Gupta, 2016). Related to the uncertainty about future climate conditions, there are also differing perceptions of vulnerability to extreme weather events, both in the present and the future. For example,

prior to Hurricane Sandy battering New York City, little consideration had been given to the particular vulnerability of healthcare infrastructure in the city (Redlener and Reilly, 2012; Levinson, 2014). It is also important to remember that not only coastal communities are vulnerable to flooding, but rather, inundation of hospitals can be the result of inland urban flooding, flash flooding, and river flooding as well. Therefore, it is critical that areas previously immune to the effects of extreme flooding events reconsider their perceptions of their vulnerability (Guenther and Balbus, 2014). In addition to the financial challenges that AMS outlines, there are also technological challenges involved in adaptation and mitigation. Innovations in technology have allowed hospitals to make great strides in reducing vulnerability to extreme flooding events, but at some point, there may be a limit to the protection technology can provide (Huang et al., 2011; Rodima-Taylor et al., 2012).

Case Study: Hospitals and Hurricane Katrina

One of the best documented cases of hospital vulnerability to extreme flooding events was demonstrated during Hurricane Katrina, used here as a case study to illustrate the severity of this issue. The city of New Orleans is on average six feet below sea level, although approximately half of the city is above sea level. Due to its unique location surrounded by water, a series of levees and seawalls were built in New Orleans to reduce the high physical exposure to flooding events and protect the city from major inundation (Carter, 2005; ASCE, 2007). However, Hurricane Katrina made landfall in New Orleans as a Category 3 hurricane on August 29th, 2005 and shattered the flood protection infrastructure. Floodwaters exceeded levee capacity, flooding the city with up to 30 feet of water (Rodriguez and Aguirre, 2006; Gajanan and Brait, 2015). When Hurricane Katrina struck, the healthcare system in Louisiana was ranked second to last out of all the states in the country, only behind Mississippi, and served a population of 1.7 million residents, many already socially vulnerable (Cutter et al., 2003; Logan, 2006; Yarnal, 2007). Although the healthcare system in New Orleans in particular had experience preparing for and responding to disaster events, the infrastructure was aging and frail—physically unable to stand up to a Category 3 hurricane (Rodriguez and Aguirre, 2006).

Although hospitals implemented a normal response to a hurricane situation—activating disaster teams, discharging less critically ill patients, and gathering extra supplies—traditional planning simply did not suffice during Hurricane Katrina (Barkemeyer, 2006). Basements that stored food, water, and fuel, were quickly inundated with water, destroying critical stocks of supplies. Similarly, the morgues were inundated, meaning that patients who died during the hurricane were temporarily stored in stairwells. As emergency generators ran out of fuel, the water, sewage, elevator, telephone, and air conditioning systems soon failed. The situation was aggravated by the increased number of patients seeking healthcare due to impacts of the Hurricane, as well as individuals seeking temporary shelter (Gray and Herbert, 2007). Additionally, the federal response was extremely slow and delayed, stranding many patients and doctors in the hospitals (Rodriguez and Aguirre, 2006; Guenther and Balbus, 2014). The following quotes from staff members within New Orleans hospitals reveal the severity of the situation for patients inside:

> "Food was running low, sanitation and electricity weren't working, and temperatures inside soared to 110 degrees. Floodwaters had isolated the hospital […]. Without power to operate medical devices, staff could only provide basic care. Evacuations were sporadic—an occasional boat or helicopter picking up patients." (Johnston, 2005)

> "The languishing patients were receiving little medical care, and their skin felt hot to the touch. Some had blood pressures so low, their pulses weren't palpable, their breathing the only evidence of life. Hand-scrawled evacuation priority tags were taped to their gowns or beds. They indicated that doctors had decided these sickest individuals in the hospital were to be evacuated last." (Fink, 2014)

Doctors even had serious conversations about euthanizing patients who were not expected to survive the ordeal. In fact, at Memorial Hospital, 23 of the approximately 45 patient deaths investigated after the hurricane tested positive for lethal injection drugs, leading to the arrest of a doctor and two nurses (Johnston, 2005; Okie, 2008; Fink, 2014).

Reports during and after Hurricane Katrina, although inconsistent, revealed that perhaps more than half of the hospitals in New Orleans closed during the storm, but none of the hospitals had recovered to the point of operating at their pre-Katrina levels a month later (Associated Press, 2005; Rodriguez and

Aguirre, 2006; Thomas, 2015). Two years after Katrina, only one general hospital had become fully operational, with two others operating at limited capacity and four remaining permanently closed. This left only a third of the original hospital beds open for patients (Rodriguez and Aguirre, 2006; Eaton, 2007). At least half of New Orleans' practicing doctors were displaced while evacuating from Hurricane Katrina, with many never returning, leaving an extreme lack of medical care for the residents who remained in New Orleans (Rudowitz et al., 2006). The doctors that did not leave New Orleans reported that their patients were far sicker than before the storm, due to various reasons such as limited healthcare, chronic stress, and mold exposure (Bourque et al., 2006; Eaton, 2007). There were also reports of hospitals in adjacent parishes being full, as they were forced to carry the weight of the hospitals in New Orleans that remained closed or partially operational up to two years after the hurricane (Eaton, 2007).

In the wake of Hurricane Katrina, it was clear that the remaining hospital infrastructure would not be sufficient to care for the patients of New Orleans, and many of the flooding adaptation measures discussed above were implemented. However, some hospitals, like Charity Hospital and the Veterans Administration (VA) Medical Center, were irreparably damaged by Hurricane Katrina and were eventually replaced by the University Medical Center and the Southeast Louisiana Veterans Health Care System, respectively (Litten, 2016). Although the budget for the new VA hospital was underestimated and the opening was delayed nearly two years, finally opening in November 2016, its sophisticated flood adaptation efforts serve as a model to hospitals across the world. It was designed with a structure upside-down to what most hospitals have, with the kitchen, access points, emergency room, and generators all located above the fourth floor, far above the area's base flood elevation. This facility is capable of operating independently of New Orleans' infrastructure, with a seven-day strategy to self-sustain with up to 1000 occupants. In order to address the issue of patient influx during disasters and non-patients seeking shelter, single-occupancy patient rooms are designed to hold two people in times of need. An energy plant on site stores 320,000 gallons of fuel, enough to power the hospital for a week. Additionally, the hospital can collect and store over a million gallons of water and it boasts a 6,000 square foot warehouse for supplies. Windows were also designed to withstand Category 3 hurricane winds. The hospital is fully

accessible by boat, and travel from building to building can be accomplished entirely indoors (Lanks, 2014). The completion of this hospital should also encourage doctors to return to New Orleans, including those who originally left during Hurricane Katrina, since it aims to employ 220 doctors and 172 medical students and residents (Litten, 2016). Although this is only the account of one hospital's flood adaptation efforts, which have not yet been put to the test by another hurricane, the New Orleans VA hospital provides an example of how sophisticated, large-scale flood preparedness and adaptation measures can be implemented.

Background—Harris County and Hurricane Harvey

Texas provides an interesting study location for extreme flooding events as it consistently sustains the most damage, deaths, and injuries from flooding of all states in the U.S. (Brody et al., 2008). More specifically, Harris County (Figure 1) in coastal Texas is already susceptible to heavy rainfall and storm surge events, but is also projected to experience dramatic increases in both sea level rise and hurricane intensification over the next century (Mousavi et al., 2011; Dart, 2017). Although Harris County boasts two large dams and a network of natural bayous intended to hold and channel water toward the Gulf of Mexico, the dams are at risk of failing and the bayous are often overwhelmed by flood waters (Dart, 2017). This physical vulnerability, paired with the explosive growth in Harris County, or the "Greater Houston Metro Area," from around 2 million to 6.5 million people since 1970, is putting an unprecedented number of people in harm's way during extreme flooding events (Dart, 2017). This is especially true since Harris County's population growth has been anything but dense. Unchecked urban sprawl since 1992 has resulted in the loss of almost 30% of the county's wetlands, which were largely responsible for retaining stormwater (Jacob et al., 2015; Satija et al., 2016). Although a series of extreme flooding events have wreaked havoc on coastal Texas in the past two decades, including Tropical Storm Allison (2001), Hurricane Ike (2008), Memorial Day Flood (2015), Tax Day Flood (2016), many scientists and locals alike questioned whether the Texas coast, and Harris County in particular, were prepared for the next big hurricane (Satija et al., 2016; Scranton, 2016; Hunn et al., 2018).

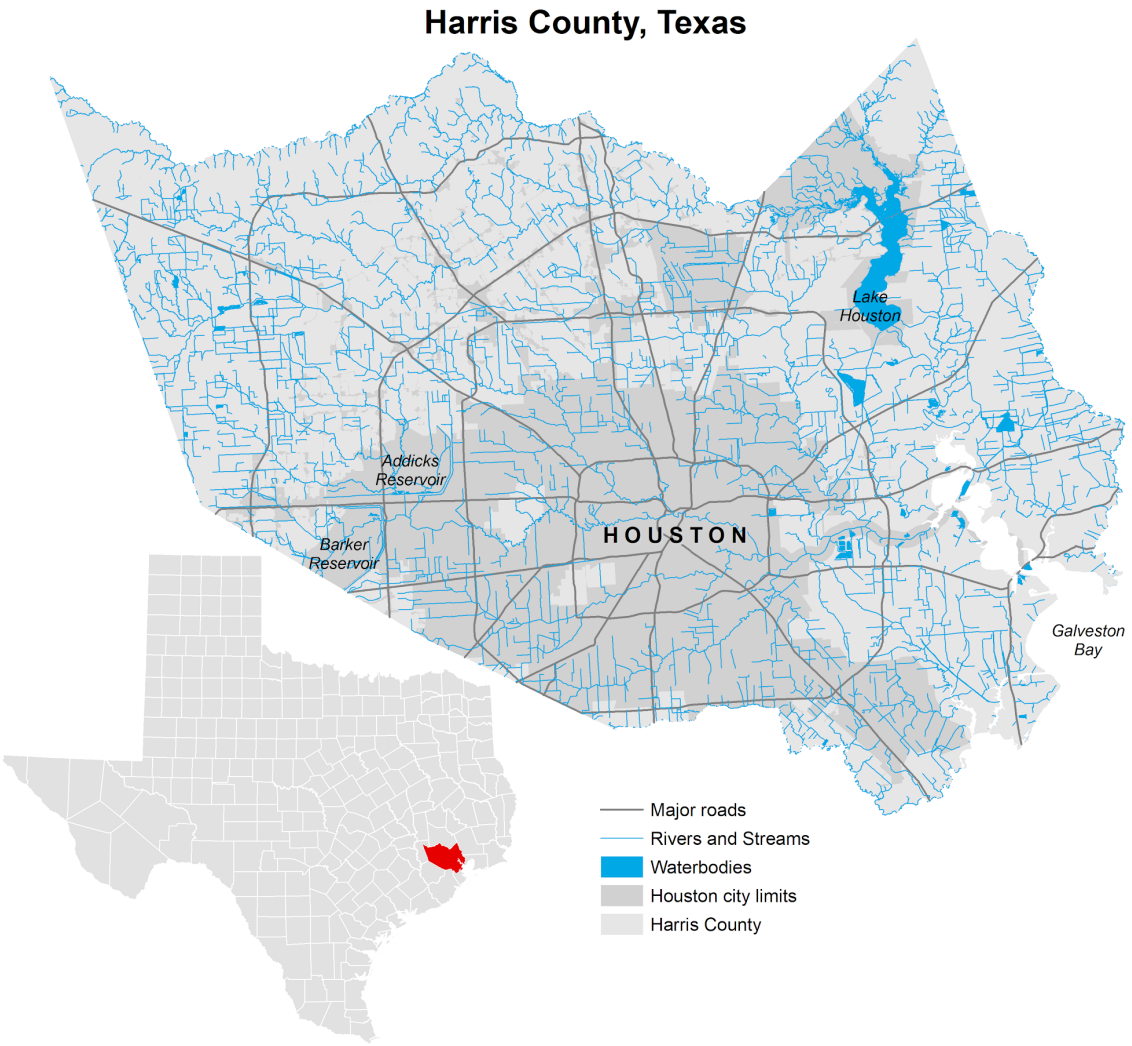

Figure 1: Reference map of Harris County, Texas and its major roads, rivers/streams, and waterbodies. The darker gray area in the main map represents Houston's City Limits within Harris County. The smaller inset map shows the location of Harris County within the State of Texas.

In my previous analyses prior to Hurricane Harvey, 25 hospitals in Houston—the largest city within Harris County—were identified as at risk of flooding due to their location within FEMA flood hazard areas. However, FEMA's flood hazard areas do not necessarily reflect the true nature of flooding risk in Harris County. FEMA flood hazard areas are informed by historical flooding and urban development, but unfortunately, these estimates cannot account for the sheer rate of development in Harris County, and do not take into account the changing climate conditions influencing the likelihood of future flooding events (Popovich and O'Neill, 2017; Skibba, 2017). With these considerations in mind,

my previous work identifying the number of Houston hospitals vulnerable to flooding could have greatly underestimated the potential healthcare-related impacts of an extreme flooding event. The sudden arrival of Hurricane Harvey served as a reminder that no recent comprehensive study of Harris County's healthcare system vulnerability to extreme flooding events had been conducted.

Hurricane Harvey made landfall as a Category 4 hurricane on the Texas coast on August 26th, 2017. With sustained winds of over 130 mph and record rainfall, Hurricane Harvey caused 70 fatalities, 13,000 rescues, and perhaps over $200B in estimated damages (Sullivan et al., 2017; Quealy, 2017; Weber and Lauer, 2017). Areas of Harris County received between 40-60 inches of rain, surpassing the previous single-storm rainfall record in the continental U.S. (Resnick, 2017). The ensuing flooding, while influenced by a variety of factors from urban sprawl to subsidence to controlled water releases, left an estimated 25% of Harris County underwater, with 50% of the total flooding occurring outside of FEMA 100-year and 500-year flood hazard areas (Dart and Helmore, 2017; Pinter et al., 2017; Sullivan et al., 2017).

Hospitals across Harris County scrambled to evacuate patients as their facilities faced basement flooding and damage to kitchens, pharmacies, and supplies (Goldstein and McGinley, 2017). Although many of these hospitals are considered world-renowned and have previous experience with flooding, not all recent building fortifications had been put to the test by a hurricane. Despite the efforts to better prepare for the next big hurricane, Harris County's hospitals had trouble withstanding the flooding, with access roads blocked, winds preventing helicopter landings, and food supplies running low (Fink and Blinder, 2017; Goldstein and McGinley, 2017). In light of these recent events provoked by Hurricane Harvey's relentless rainfall, it is important that the hospitals of Harris County, Texas share their experiences and lessons learned to inform healthcare infrastructure planning for future extreme flooding events in coastal Texas and elsewhere.

Research Questions

This thesis consists of a two-part study focusing on the experiences of Harris County, Texas hospitals during Hurricane Harvey, which serves as a rich case study to analyze healthcare system vulnerability to extreme flooding events.

First, I conducted GIS analysis in order to identify which hospitals were located within FEMA flood hazard areas prior to Hurricane Harvey, as well as identify which hospitals were located within the Hurricane Harvey inundation boundaries created by the Harris County Flood Control District (HCFCD) and FEMA, since these results are indicative of the hospitals with a higher likelihood of experiencing flood impacts related to Hurricane Harvey. These results were then compared to the list I compiled of hospitals that actually experienced flooding, or flood-related impacts, during Hurricane Harvey. I then drew conclusions on whether these two datasets accurately predicted hospital flood impacts related to Hurricane Harvey. This geospatial exploration revealed a need for an in-depth qualitative approach in order to investigate whether flood adaptation efforts potentially played a role in the differences observed.

Second, this thesis constructed a narrative detailing Harris County hospitals' flood adaptation efforts and collective experience with Hurricane Harvey, as well as the lessons learned in the aftermath of the storm. Data collection involved both primary and secondary sources, including a survey of hospital emergency managers and semi-structured interviews with local organizations involved in public health and emergency management, supplemented by an analysis of news reports and other documents from a variety of government agencies, local organizations, and hospitals themselves. Through the synthesis of data on hospitals across Harris County, this thesis intends to evaluate hospitals' emergency responses to Hurricane Harvey and create a compelling argument for the adoption of additional flood adaptation measures in preparation for future flooding events.

Overall, the research questions guiding this thesis are:

- Did the FEMA flood hazard area data and the Hurricane Harvey inundation boundary data accurately predict which Harris County hospitals would flood during Hurricane Harvey? If not, what explained this difference?
- What lessons were learned from Harris County hospitals' experience with flooding prior to Hurricane Harvey?
- What were the successes and challenges in Harris County hospitals during the preparation for and response to Hurricane Harvey?
- What is the current state of flood preparedness and adaptation planning in Harris County hospitals?

This thesis aims to contribute to our understanding of how extreme flooding events can impact and have impacted healthcare systems in the U.S. and, therefore, the delivery of health-related services. Results from this study also contribute to efforts aimed at improving our country's critical healthcare infrastructure to better prepare for, respond to, and recover from future catastrophic flooding events like Hurricane Harvey. Although this study focuses on the evaluation of Harris County's healthcare system response to one specific extreme weather event, the methodologies employed could be easily reproduced in other cities and for other events, improving U.S. healthcare system's resilience to extreme weather events nationwide. With extreme flooding predicted to become more frequent and intense in various regions across the U.S. over the next decade, it is now more important than ever to focus specifically on the impacts of flooding on healthcare infrastructure (Few et al., 2004; Keim, 2008; Bierbaum et al., 2014; IPCC 2014).

CHAPTER II — RESEARCH METHODS

GIS Analysis

Data Sources

A) Ascertainment of Hurricane Harvey Hospital Flooding Impacts in Harris County, Texas

One of the primary objectives of this study was to compile a new dataset detailing the flood impacts of Hurricane Harvey within each of the 80 non-psychiatric hospitals in Harris County, Texas. Psychiatric hospitals were excluded from this analysis due to the fact that psychiatric hospitals do not serve the general public and may not be able to address traditional health concerns during an emergency event such as a hurricane. This new dataset was largely compiled through secondary data collection, and supplemented by primary data collection. In the wake of Hurricane Harvey, many news reports and documents from a variety of government agencies and local organizations were published, serving as crucial secondary sources of information about whether the hospitals in Harris County experienced flooding or flood-related impacts during Hurricane Harvey. These secondary sources were identified through Google searches and categorized as follows: news reports (n = 31), peer-reviewed journal articles (n = 1), documents from government agencies (n = 2), documents from local organizations (n = 3), and hospital websites and social media outlets (n = 10). When secondary sources failed to provide information on whether certain hospitals flooded, primary data was collected through direct phone calls with individual hospitals (n = 14) asking whether ot not the hospital flooded. For the purposes of creating this dataset, the definition of "flood impacts" encompasses any case of water entering a hospital building.

B) GIS Datasets

The datasets used for the GIS analysis of flooding impacts from Hurricane Harvey on hospital infrastructure are explained in detail below, as well as summarized in Table 1. Each dataset was acquired as a freely available shapefile, and the URL where each dataset can be obtained online are also included in Table 1 below. The geographic shapefiles that had a large geographic extent, either nationwide or statewide, were clipped or subset to the Harris County area.

The Homeland Infrastructure Foundation-Level Data (HIFLD) includes all U.S. hospital location information and descriptive characteristics acquired from various state departments or federal sources. All hospital categories (children's, chronic disease, critical access, general acute care, long term care, military, rehabilitation, special, and women's) were included in this study except for psychiatric hospitals. The version of the dataset used in this analysis was created in April 2017.

The Harris County flood hazard areas were designated by the Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL). This dataset is made up of thousands of polygons delineating areas of high flood risk, called 100- and 500-year flood hazard areas, which are created based on current hydrology, infrastructure, hydraulics, and land use. The 100-year flood hazard areas delineate land with a 1% chance of flooding in any given year and the 500-year flood hazard areas delineate land with a 0.2% chance of flooding in any given year. FEMA's flood hazard information is not updated on a regular schedule, but rather using a cost-benefit approach, meaning that high priority communities are chosen for updates when they have had high levels of development or the maps are very outdated. Since no historic versions of the FEMA NFHL are available, the version of the dataset used in this analysis was created in January 2018.

I also acquired two versions of the Hurricane Harvey flood inundation boundary, which is meant to delineate the maximum area of water inundation over the entire course of the hurricane. Two versions were developed, one by Harris County Flood Control District (HCFCD) and another by FEMA's Natural Hazard Risk Assessment Program (NHRAP). The HCFCD inundation boundary uses high water marks to identify where the bayous and tributaries overflowed their banks due to Hurricane Harvey's rainfall (HCFCD, 2018). High water marks are assessed through a series of water monitoring sites and occasionally through human reporting and surveying. The FEMA NHRAP created another version of the inundation boundary by supplementing the initial HCFCD high water marks with United States Geological Survey (USGS) high water marks. For both datasets, the high water marks across Harris County were interpolated into a continuous water surface elevation using the inverse distance weighting (IDW) method, which was then compared to a digital elevation model (DEM) of Harris County, in order

to delineate the true boundary of flood inundation. It is important to note that neither of these inundation boundary estimates necessarily show all flooding impacts throughout Harris County and do not necessarily indicate where structural flooding occurred, since structure elevations and water levels varied widely throughout the inundated areas. Each of the Hurricane Harvey flood inundation boundary datasets used in this analysis were created following Hurricane Harvey in 2017. Since these two versions of the flood inundation boundary used similar data collection methods, the two versions were merged in order to capture the full potential inundation extent of Hurricane Harvey, as assessed by HCFCD and FEMA.

Several additional datasets were utilized in order to create maps with context. These datasets included the Houston city boundary, the Harris County boundary, Texas county boundaries, and major roads, waterbodies, and rivers in Harris County as detailed in Table 1.

Table 1: Datasets Used in the GIS Analysis.

Dataset Description	Source	URL	Version Date
Harvey flood inundation boundary	Federal Emergency Management Agency (FEMA) Natural Hazard Risk Assessment Program (NHRAP)	https://data.femadata.com/FIMA/NHRAP/Harvey/	2017
Harvey flood inundation boundary	Harris County Flood Control District (HCFCD)	https://www.hcfcd.org/hurricane-harvey/countywide-impacts/	2017
Houston city boundary	City of Houston GIS (COHGIS)	https://cohgis-mycity.opendata.arcgis.com/datasets/houston-city-limit	May 2018
Harris County flood hazard areas	Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NHFL)	https://msc.fema.gov/portal/advanceSearch	January 2018
Harris County boundary	Harris County Appraisal District (HCAD)	http://geo-harriscounty.opendata.arcgis.com/datasets/b0223bbaff4041d29eb79bb5a17d9f30_0	2018
Harris County major roads	Texas Natural Resources Information System (TNRIS)	https://tnris.org/data-catalog/entry/txdot-roadways/	December 2015
Texas hospitals	Homeland Infrastructure Foundation-Level Data (HIFLD)	https://hifld-geoplatform.opendata.arcgis.com	April 2017

		/datasets/hospitals	
Texas county boundaries	Texas Department of Transportation (TxDOT)	http://gis-txdot.opendata.arcgis.com/datasets/959bede33a9e445896d97d39be7bce23_0	2018
Texas waterbodies and rivers	Texas Natural Resources Information System (TNRIS)	https://tnris.org/data-catalog/entry/texas-nhd-river-streams-and-waterbodies/	2014

GIS Methods and Analysis

The GIS methods and analysis described in this thesis, including specific tools and processing steps, were completed in ESRI ArcMap version 10.6.1 (ESRI, 2018).

The first goal of the GIS analysis was to use overlay analysis to identify which hospitals were located within the Federal Emergency Management Agency (FEMA) flood hazard areas prior to Hurricane Harvey. I used the *select by location* tool in ArcMap to identify at-risk hospitals located within FEMA 100-year and 500-year flood hazard areas. I used these results to calculate and identify how many hospitals in Harris County, Texas fell within the FEMA flood hazard areas prior to Hurricane Harvey and thus were *more likely to flood* during an extreme flooding event. These results were then compared to the list of hospitals that *actually experienced flooding*, or flood-related impacts, during Hurricane Harvey, based on the primary and secondary data collected to ascertain hospital flooding impacts, as outlined earlier in the methods section. I then drew conclusions on whether the FEMA flood hazard area data accurately predicted the ascertained hospital flood impacts related to Hurricane Harvey

The second goal of the GIS analysis was to identify which hospitals were located within the Hurricane Harvey flood inundation boundary created by FEMA and the Harris County Flood Control District (HCFCD)—this inundation boundary denotes the full extent of flooding that occurred during Hurricane Harvey. I again used the *select by location* tool in ArcMap to identify hospitals located within the flood inundation boundary. I used these results to calculate how many hospitals in Harris County, Texas fell within the inundation zone and thus were *anticipated to have experienced flooding* or flood-

related impacts during Hurricane Harvey. These results were then compared to the list of hospitals that *actually experienced flooding*, or flood-related impacts, during Hurricane Harvey based on the primary and secondary data collected to ascertain hospital flooding impacts, as outlined earlier in the methods section. I then drew conclusions on whether the Hurricane Harvey flood inundation boundary data accurately predicted the ascertained hospital flood impacts related to Hurricane Harvey.

The third goal of the GIS analysis was to assess whether the FEMA flood hazard areas accurately predicted the areas of Harris County, Texas that would flood during an extreme flooding event such as Hurricane Harvey. This was done by mapping the similarities and differences between FEMA flood hazard areas and the Hurricane Harvey flood inundation boundary, which theoretically should have high levels of agreement. I first used the *intersect* tool in ArcMap to create a new data layer delineating the overlap of the two datasets. Each of the two datasets were then subtracted from the overlapping area using the *erase* tool in ArcMap. This produced two additional data layers delineating where each of the original datasets differed from the overlap. These data layers delineating areas of similarity and differences were then qualitatively and quantitatively assessed.

Qualitative Analysis

After the GIS analysis described above, this study aimed to assess what factors played a role in any differences observed between which hospitals were expected to flood (based on FEMA flood hazard area maps), those that should have flooded (based on the flood inundation boundary), and whether the hospitals actually flooding (based on the primary and secondary data collection). To do this, I implemented an in-depth qualitative research approach using surveys, interviews, and secondary sources (described in detail below) in order to investigate whether hospital-level flood adaptation efforts and historical experience with flooding played a role in the differences observed.

Institutional Review Board Approval

This study received approval in the "exempt" review category by the University of Colorado Boulder Institutional Review Board (IRB) under protocol number 17-0559. The IRB Approval Letter can be found in Appendix A. Similarly, the Survey/Interview Questions (Appendix B), Email Invitation to Participate in Study (Appendix C), and the Informed Consent Form (Appendix D) are available for review.

Survey and Interview Development

An online survey was developed for hospital emergency managers representing each of the 80 non-psychiatric hospitals in Harris County, Texas. Since the impacts of Hurricane Harvey were not limited to hospitals located within FEMA flood hazard areas, the survey was tailored to hospitals located inside and outside flood hazard areas, as well as hospitals both affected and non-affected by Hurricane Harvey. The specific survey questions were developed with the Intergovernmental Panel on Climate Change (IPCC) vulnerability framework in mind and an understanding of compelling themes based on a literature review. After a first draft of the survey questions was developed, I then consulted the guidance of a survey expert to refine the questions. Overall, for each hospital, the survey aimed to investigate its experiences before, during, and after Hurricane Harvey, assess experiences with historical flooding, and

evaluate the state of hospitals' flooding adaptation plans for the future. The questions included in the online survey can be found in Appendix B.

Similarly, a key informant interview protocol was developed for interviews with local organizations involved in public health and emergency management in Harris County, Texas. The interview questions were adapted from the hospital survey questions. This decision was made in order to allow for the exploration of the same themes, while modifying/customizing the questions to be better suited toward the target population of local organizations and allowing for a semi-structured format with open-ended answers and natural conversation.

Survey and Interview Procedure

The survey was administered online through Google Forms, in hopes of improving response rate due to ease of access. The survey was available online from May 1, 2018 to December 1, 2018. Although the survey was administered several months after Hurricane Harvey made landfall, memory of the event was still strong and sufficient time had passed to allow for a full understanding of flood-related impacts in the hospitals. Survey results were used to capture the overall vulnerability of the Harris County healthcare system to extreme flooding events, such as that caused by Hurricane Harvey. The survey respondents were each offered a gift card worth $25 in compensation for participating.

The semi-structured key informant interviews were conducted with local organizations involved in public health and emergency management in Harris County, Texas between August 6-9, 2018. The interviews took place at each local organization's main office and lasted approximately 45 minutes each. All of the interviews were audio recorded and comprehensive notes were taken during each interview. Following each semi-structured interview, the audio recordings were used to transcribe each interview verbatim, and these transcripts were then read repeatedly in order to identify key themes. Due to the relatively small number of interviews, no specialist qualitative analysis software (such as NVivo or MaxQDA) was used in the process of transcript coding or key theme analysis. The interview participants were each offered a gift card worth $25 in compensation for participating.

Survey and Interview Participant Recruitment

The initial goal was to survey the entire population of hospital emergency managers without sampling because this population was considered small enough that it would be feasible. However, it was extremely difficult to identify hospital emergency managers. Some hospital emergency managers eligible for the survey were identified through general Google and LinkedIn searches, phone calls and emails with the hospitals, and referrals. Those identified were contacted directly via email and provided with a an invitation to participate (found in Appendix C) outlining the purpose and length of the survey, as well as information on the voluntary yet critical nature of the survey. The online survey also included a consent form to be signed electronically by respondents (Appendix D). However, due to the difficulties in identifying an emergency manager at each hospital to contact directly, the SouthEast Texas Regional Advisory Council (SETRAC) provided assistance in disseminating the invitation to participate to the hospitals via email. In addition to the difficulties identifying and contacting hospital emergency managers, in the case that they were identified and contacted, very few responded and expressed willingness to participate in the survey. These two complications in recruiting survey respondents led to a much smaller sample than initially expected. Out of 80 survey requests, only three hospitals accepted and responded to the survey.

In order to supplement the small number of emergency manager surveys, in-person interviews were conducted with key informants from local organizations heavily involved in public health and emergency management in Harris County. These local organizations were chosen due to their ability to report on hospital experiences during Hurricane Harvey and flood adaptation efforts county-wide. Similar to the survey recruitment, the local organizations interviewed were identified in advance and the interview participants within each organization were contacted directly via email and provided with a solicitation letter outlining the purpose and length of the interview (Appendix C). I performed the interviews once obtaining written consent (found in Appendix D) and arranging a time to meet. Out of six interview requests sent, four organizations accepted and were interviewed.

To protect the identity of the survey respondents and interview participants (Table 2), the individuals were aggregated with their respective hospitals or local organization, which were then de-identified. In this thesis, the hospitals *surveyed* will be referred to with letters (e.g., Hospital A) and local organizations *interviewed* will be referred to with numbers (e.g., Organization 1).

Table 2: Survey and Interview Participants.

Hospital or Organization Identifier	Number of Survey Respondents or Interview Participants	Type of Hospital or Organization	Survey or Interview
Hospital A	1	Large, urban hospital	Survey
Hospital B	1	Large, urban hospital	Survey
Hospital C	1	Large, urban hospital	Survey
Organization 1	2	Public health	Interview
Organization 2	1	Local government	Interview
Organization 3	2	Emergency management	Interview
Organization 4	1	Healthcare association	Interview

Analysis of Survey, Interview, and Secondary Sources

As discussed earlier, this study conducted a limited number of surveys and interviews with hospitals and local organizations. To supplement the surveys and interviews, secondary sources of data were incorporated into the analysis and provided crucial information on the experiences of the hospitals of Harris County, Texas during Hurricane Harvey. Since the same research questions guided data collection from the surveys, interviews, and secondary sources, multiple perspectives were captured on the same topics with the intention of aggregating the information into coherent key themes related to

hospital preparedness and response to an extreme flooding event. This was done using an inductive approach, in which I first compiled extensive raw data, allowing significant and dominant concepts to emerge, and then I condensed and organized the results into key themes. Although the key themes can be influenced by the research questions being asked, the process of identifying key themes through the raw data often minimizes bias from the researchers' preconceptions and assumptions (Thomas et al., 2006). After many close readings of the survey and interview results and secondary sources of data, I was able to identify and define several key themes, which are presented in the results section.

CHAPTER III — RESULTS

GIS Analysis

Through the use of both primary and secondary data sources described earlier, information about Hurricane Harvey's flood impacts was ascertained for 66 of the 80 non-psychiatric hospitals in Harris County included in this study. In general, the 14 hospitals that did not have ascertained flood impact information tended to be smaller hospitals unaffiliated with larger hospital systems. Out of the 66 hospitals for which flood impact information were ascertained, 16 hospitals (24%) reported having actual flood impacts during Hurricane Harvey and 50 hospitals (76%) reported having no actual flood impacts during Hurricane Harvey. A table of flood impacts by hospital can be found in Appendix E.

Out of the 16 hospitals that experienced Hurricane Harvey flooding impacts, only 11 (69%) were located within a Federal Emergency Management Agency (FEMA) flood hazard area (Figure 2), meaning they should have known that they were more likely to flood during an extreme flooding event and perhaps were adequately prepared. This meant that 5 of the hospitals (31%) that experienced Hurricane Harvey flooding impacts were located outside of a FEMA flood hazard area, and were perhaps less prepared due to their lower flood risk on FEMA flood hazard area maps.

The map below depicts this situation—the FEMA 100-year and 500-year flood hazard areas are shown in light orange and dark orange, respectively (Figure 2), with each Harris County hospital plotted on top. The hospitals that experienced Hurricane Harvey flood impacts are shown as green dots, whereas the hospitals with no Hurricane Harvey flooding impacts are shown as black dots. The hospitals for which Hurricane Harvey flood impact was not ascertained are represented as a black "x". Due to the large number of hospitals in close proximity in and around the Texas Medical Center (highlighted in purple), both maps feature a smaller inset map providing additional detail on these hospitals.

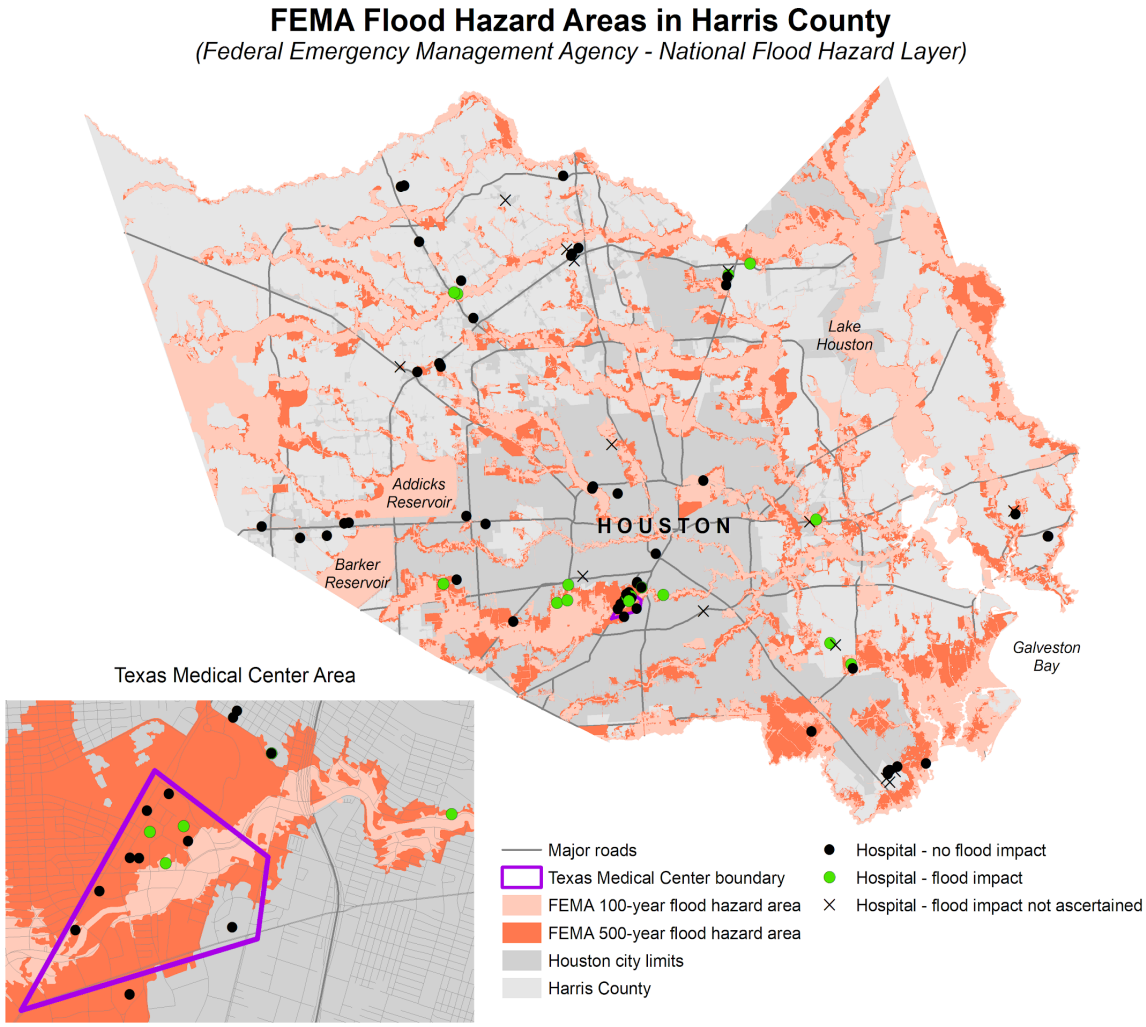

Figure 2: This map depicts the FEMA 100-year and 500-year flood hazard areas, as delineated by the National Flood Hazard Layer. The hospitals of Harris County, Texas are plotted on top, making note of whether they experienced flood impacts related to Hurricane Harvey. The smaller inset map highlights the area surrounding the Texas Medical Center, which is outlined in purple.

Similarly, out of the 16 hospitals that experienced Hurricane Harvey flood impacts, only 8 (50%) were located within the Hurricane Harvey flood inundation boundary (Figure 3), where hospital flood impacts were expected to occur based on where flooding occured. This meant that 8 of the hospitals (50%) that experienced Hurricane Harvey flood impacts were located outside of the Hurricane Harvey inundation boundary, where hospital flood impacts were not expected to occur based on where flooding

did not occur. The map below depicts this situation using the same setup as the map above, except for that the Hurricane Harvey flood inundation boundary is shown in blue (Figure 3).

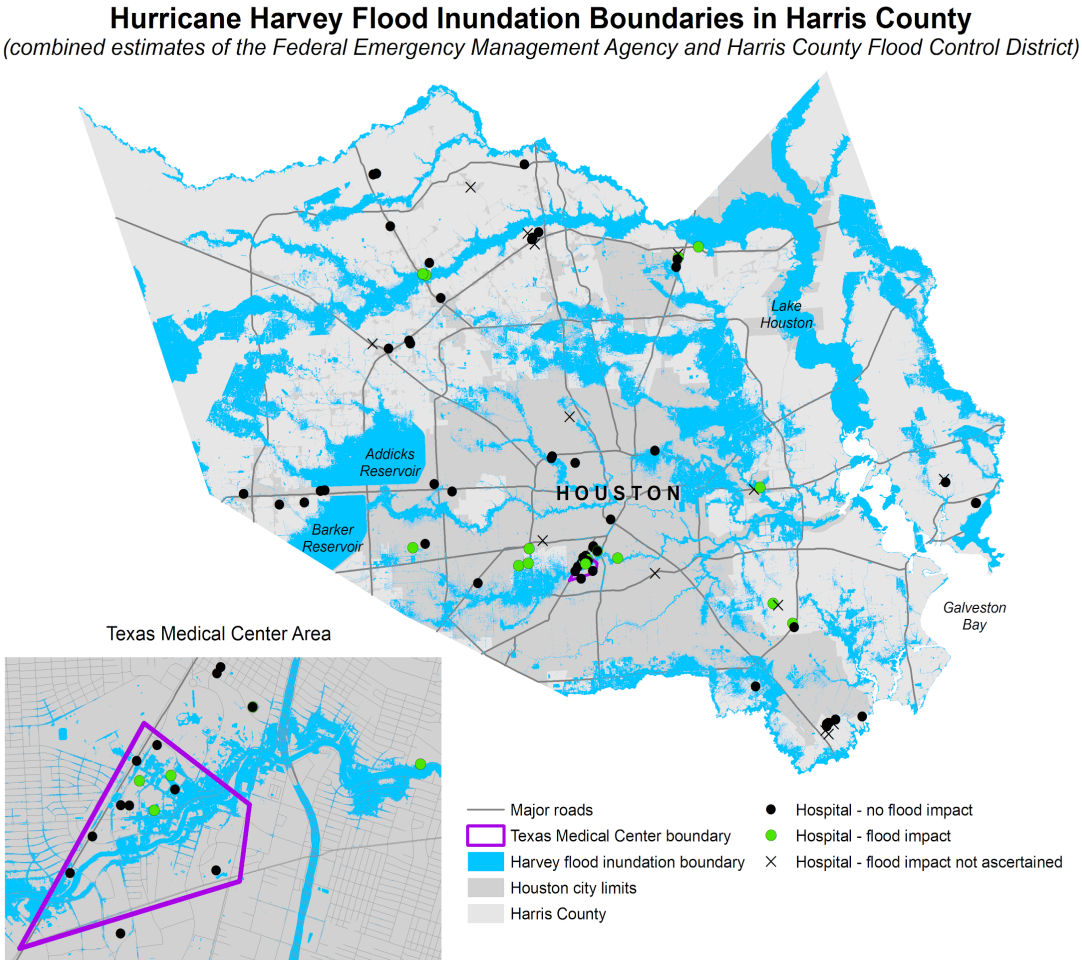

Figure 3: This map depicts the Hurricane Harvey flood inundation boundary, as delineated by FEMA and HCFCD. The hospitals of Harris County, Texas are plotted on top, making note of whether they experienced flood impacts related to Hurricane Harvey. The smaller inset map highlights the area surrounding the Texas Medical Center, which is outlined in purple.

Another helpful way to visualize the inconsistencies between the FEMA flood hazard area dataset, the Hurricane Harvey flood inundation boundary dataset these datasets, and which hospitals experienced actual flooding is in a flowchart (Figure 4). The flowchart walks through which hospitals in Harris County were located inside or outside a FEMA flood hazard area, followed by whether they were located inside or outisde the Hurricane Harvey flood inundation boundary, followed by whether or not

they experienced actual flood impacts during Hurricane Harvey. The results highlighted in green represent hospital flood impacts that were largely expected based on the hospitals' locations, whereas the results highlighted in red represent hospital flood impacts that were highly unexpected based on the hospitals' locations. Lastly, the results in orange represent hospital flood impacts that were slightly confusing, but have potential explanations which I explore later in the discussion of this thesis.

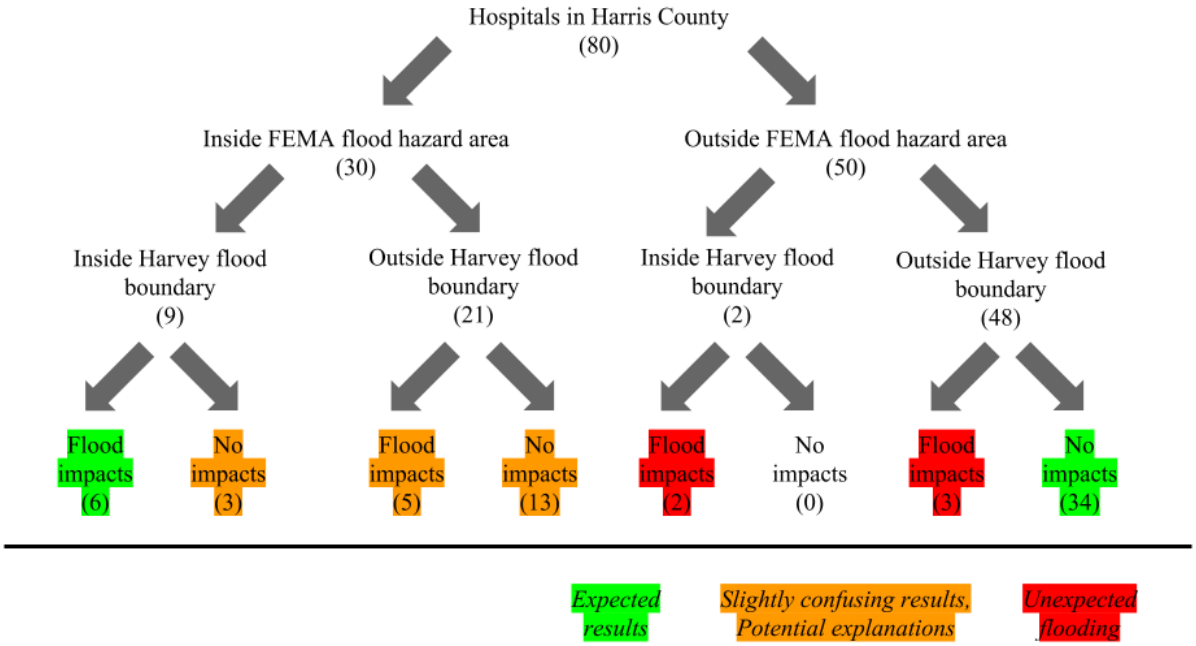

Figure 4: Flowchart of GIS Analysis Results.

This lack of agreement between the FEMA flood hazard areas, the Hurricane Harvey flood inundation boundary, and the actual hospital flood impacts related to Hurricane Harvey reveals that these two datasets (FEMA flood hazard areas and Hurricane Harvey flood inundation boundary) are not perfectly reliable for predicting where flooding will occur in a real-life event like Hurricane Harvey. This finding raised the question of whether the FEMA flood hazard areas and the Hurricane Harvey flood inundation boundary were similar, since the FEMA flood hazard areas should theoretically predict the areas of land that should flood during an extreme flooding event.

By mapping the overlap and differences between the FEMA flood hazard areas and the Hurricane Harvey flood inundation boundary, I found that these datasets have much lower levels of agreement than should be expected (Figure 5). Although there are 382 mi^2 of overlap between the FEMA flood hazard areas and the Hurricane Harvey flood inundation boundary (shown in gray), such as within the Addicks and Barker Reservoirs and around Lake Houston and other major waterways, there are many areas of differences. The areas representing where FEMA flood hazard areas were not inundated during Hurricane Harvey, are shown in orange and totaled 227 mi^2. The areas representing where inundation occurred outside of FEMA flood hazard areas, are shown in blue and totaled 83 mi^2. Although the orange area of disagreement is relatively large area and may represent some concerns with the FEMA flood hazard area data, the blue areas are particularly concerning because they represent areas that flooded but were not predicted to flood.

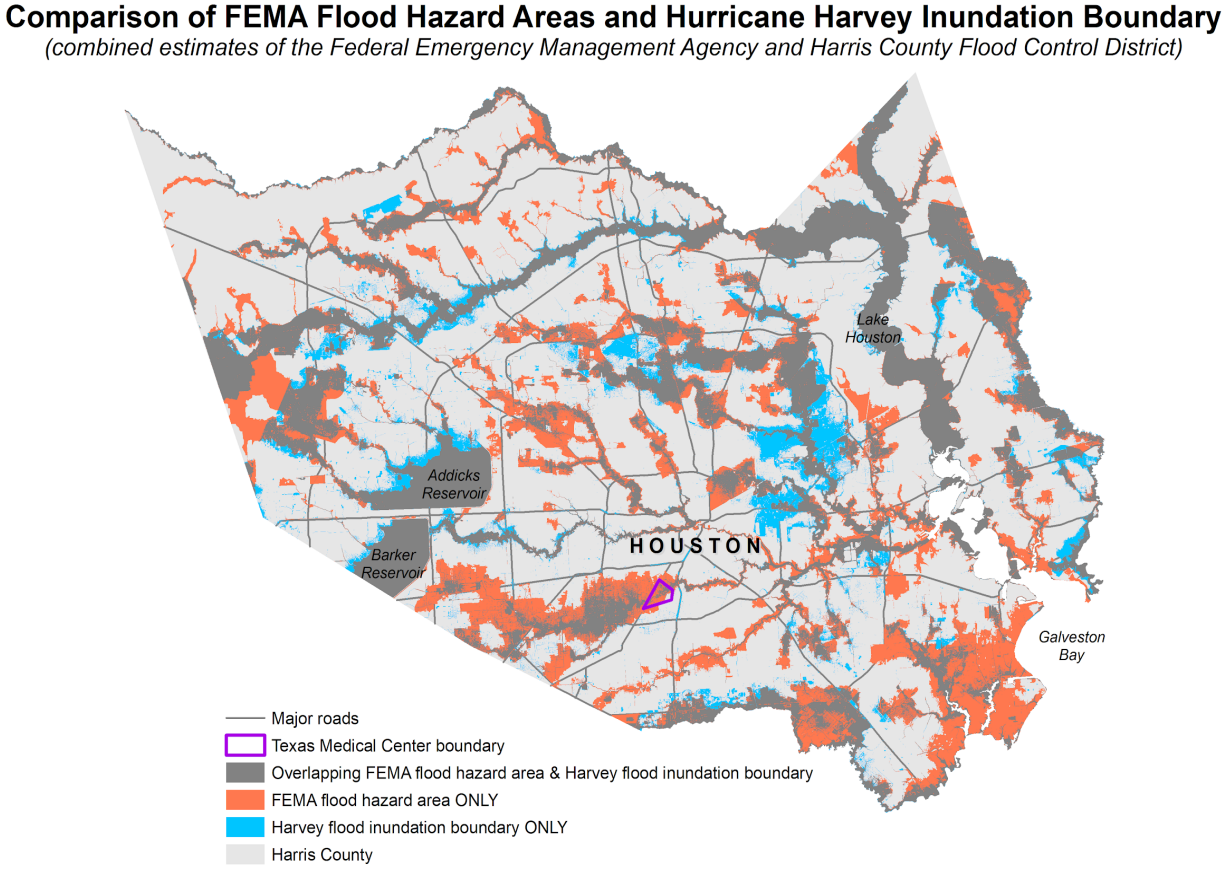

Figure 5: This map shows the agreement (gray) and disagreement (blue and orange) between the FEMA flood hazards area dataset and the Hurricane Harvey flood inundation boundary dataset.

Overall, this mapping revealed that the FEMA flood hazard areas did not accurately predict the areas of Harris County, Texas that would flood during an extreme flooding event such as Hurricane Harvey. More importantly, neither dataset accurately predicted which hospitals would truly experience flood impacts during Hurricane Harvey. Through this GIS analysis, it became apparent that an assessment investigating which factors played a role in the differences observed was necessary. Therefore, an in-depth qualitative research approach using surveys, interviews, and secondary sources was implemented in order to determine whether flood adaptation efforts played a role in the differences observed.

Qualitative Analysis

Historical Experience with Flooding and Levels of Preparedness before Hurricane Harvey

The survey and interviews conducted for this study, as well as an analysis of secondary sources, revealed that most Harris County hospitals learned their most valuable lessons about flood preparedness from experiencing Tropical Storm Allison in 2001, and that select hospitals also had direct experience from the Memorial Day Flood in 2015 and the Tax Day Flood in 2016. Although not directly impacted by Hurricanes Katrina and Sandy, hospitals in Harris County were also able to learn from the experiences of affected hospitals during those flooding events in New Orleans and New York, respectively (Park, 2017). These lessons led to the implementation of several flood adaptation efforts over the past decade across Harris County prior to Hurricane Harvey. The Texas Medical Center, which is home to 11 of the 80 hospitals included in this study, is the largest medical complex in the world and thought to be a leader in flood adaptation.

> "I think the greatest impact on hospitals in our history has been Tropical Storm Allison. The entire Texas Medical Center was impacted, which brought about great opportunities for flood mitigation and the Medical Center now has various flood protection devices installed, which include flood gates, flood walls, submarine doors. So they've made a lot of capital improvements and infrastructure retrofits to protect their buildings and facilities." - *Organization 3*

Additionally, many of the large hospitals within the Texas Medical Center elevated their first floor operations and utilities to the appropriate height, as well as planning for redundancy in their basic operating systems, in order to ensure continuity of services during future flooding events (Goldstein and McGinley, 2017). The Texas Medical Center also boasts skywalk bridges between buildings, which allow for the easy transportation of patients above ground and away from flood waters. After Tropical Storm Allison, some of these skywalks were also fitted with a protective film in order to provide wind resistance and hold broken glass in place. The Texas Medical Center, with assistance from Rice University in Houston, developed the real-time Flood Alert System that utilizes a combination of radar, rain gage

information, flood stage data, and hydrologic modeling to forecast flooding and suggest when flood gates should be deployed (AMS, 2010).

However, not all hospitals in Harris County were able to implement sophisticated flood adaptation efforts after Tropical Storm Allison like the Texas Medical Center. Levels of preparedness varied by hospital, since the resources available to smaller hospitals are much more limited, and some hospitals with little to no experience with flooding may not have the same seasoned perspective as those that have flooded several times. The larger hospitals in the county also coordinate with the SouthEast Texas Regional Advisory Council (SETRAC) to conduct hazard vulnerability analysis, have dedicated emergency management teams, and participate in exercises, but smaller hospitals may not.

Perceptions of Hospital Flood Risk before Hurricane Harvey

Interviews with four local organizations involved in public health and emergency management revealed that there is no general consensus on the exact number of Harris County hospitals located within FEMA flood hazard areas. However, one organization estimated that likely more than half of hospitals were at risk, simply based on the fact that Harris County is covered in flood hazard areas.

> "One of the unique things about Harris County is that it has 22 watersheds, so it's not just one river that we're working with in the community, it's a an entire bayou and drainage system that's pretty complex. Just because [...] your infrastructure is outside that flood zone doesn't necessarily mean you're not susceptible to flooding" - *Organization 3*

Similarly, there was no consensus on whether Harris County hospitals were each aware of their risk, based on their locations within FEMA flood hazard areas. Organization 3 was under the impression that likely not many hospitals were aware of their vulnerability because most emergency management functions are handled by a small team or even one person within facilities management or operations. On the other hand, Organizations 1 and 2 felt confident that hospital emergency managers in Harris County were aware of their hospital's location inside or outside FEMA flood hazard areas. However, all organizations interviewed did express concern that this awareness could change in the future, since

FEMA continually updates the flood hazard areas. Due to these updates, hospitals could suddenly find themselves located within a flood hazard area when they were not previously.

There was seemingly no consensus on the flooding risk Harris County hospitals face, as well as their perceptions and understanding of that risk. However, the local organizations interviewed were able to provide two concrete numbers: 24 hospitals were evacuated during Hurricane Harvey and one closed permanently afterward due to storm-related damage (Deam and Ackerman, 2017).

Hospital Emergency Response Successes during Hurricane Harvey

A) Infrastructure Improvements

An analysis of news reports and documents published by government agencies and local organizations revealed that despite many hospitals reporting being completely surrounded by water, with flooded roads cutting off all access to hospitals, that very few experienced any serious flooding within their buildings (Fink and Blinder, 2017; TMC Pulse, 2017). This finding indicated that the most remarkable success during Hurricane Harvey was the significant infrastructure improvements that prevented most hospitals from experiencing devastation on a level similar to that resulting from Tropical Storm Allison in 2001 (Phillips et al., 2017).

As described above, following Tropical Storm Allison, many hospitals in Harris County implemented a series of infrastructure improvements including flood gates, above ground generators, water pump systems, submarine doors (Galehouse, 2017; Goldstein and McGinley, 2017). In fact, the hospitals within the Texas Medical Center alone invested approximately $50 million in infrastructure improvements that, for the most part, prevented any major flooding inside hospitals during Hurricane Harvey (Fink and Blinder, 2017; O'Brien and McKeon, 2017). Although it is impossible to confirm whether these infrastructure improvements alone caused the discrepancies between predicted and observed hospital flooding impacts, the combination of surveys, interviews, and secondary data sources indicated that infrastructure improvements likely played an important role in flood prevention.

B) Advanced Planning

The second emergency response success during Hurricane Harvey was the several forms of advanced planning that allowed staff to carry out their roles efficiently during the hurricane. The first planning success was the use of the Hospital (Emergency) Incident Command System (HEICS/HICS), which has long been recognized as an effective and successful protocol for preparing hospital staff for emergency (Yarmohammadian, 2013). HEICS proved largely successful during Hurricane Harvey, as hospitals had trained staff members, identified a hierarchy of personnel involved in emergency response, assigned responsibilities, and created a clear set of procedures (Phillips et al., 2017). Additionally, through years of conducting emergency exercises, such as table-top exercises and realistic simulations and drills, hospitals were able to successfully assess and modify emergency plans and procedures in preparation for a crisis scenario like Hurricane Harvey (WHO, 2010; Doiel, 2017). Through the use of HEICS and the experience with emergency exercises, hospitals were able to make quick decisions in advance of Hurricane Harvey's arrival. For example, many hospitals notified patients that all elective outpatient surgeries and non-essential appointments would be cancelled, allowing the hospitals to conserve critical supplies and dedicate staff members to continuing inpatient care, such as chemotherapy and dialysis (Christensen and Edwards, 2017; Park, 2017). Similarly, in the days prior to the arrival of Hurricane Harvey, hospitals began augmenting stockpiles of critical supplies such as linens, medications, food, and water (Phillips et al., 2017).

C) Hospital Staff Dedication

The third emergency response success during Hurricane Harvey was the dedication and commitment to quality healthcare demonstrated by the hospital staff during the hurricane. In preparation for Hurricane Harvey, hospitals each created two main groups of physicians, nurses, doctors, and technicians to form ride-out and recovery teams (Doiel, 2017). The ride-out teams were responsible for arriving before the hurricane and remaining on-site during the onslaught of the hurricane, while recovery teams arrived after the storm in order to relieve the ride-out teams (Phillips et al., 2017). Individuals in

ride-out teams worked grueling 12 hour shifts and slept in makeshift quarters within the hospital (O'Brien and McKeon, 2017; Park, 2017). In many cases, Hurricane Harvey's duration and impacts on access meant that ride-out teams remained on-site for longer than anticipated. This was only compounded by the fact that many hospital staff simply could not access their hospitals due to flooding. Reports indicated that a handful of dedicated staff members actually walked through several feet of water or kayaked in order to reach their hospitals (Memorial Hermann, 2017). Individuals in ride-out teams who were able to access their hospitals found themselves filling many roles outside their job descriptions, simply to meet the needs of the patients in their care (Verduzco-Gutierrez, 2018). In an extreme case, doctors at Lyndon B. Johnson Hospital were required to perform a brain surgery—the first in the hospital's history—because they could not safely transfer the patient to a hospital that regularly performed brain surgery (Harris Health System, 2017). Without the perseverance and resilient culture of hospital staff before, during, and after the hurricane, hospitals likely would have needed to turn patients away or simply close their doors (Phillips et al., 2017).

D) Collaboration

The fourth emergency response success during Hurricane Harvey, which emerged during interviews with local organizations, was the crucial nature of pre-established partnerships and collaboration. During a disaster, when quick response is essential, knowing the contacts for partner organizations and maintaining routine communication is essential.

> "I'm not uncomfortable with where we are. We have such an advanced degree of planning amongst the hospitals and amongst the healthcare related agencies." - *Organization 3*

> "In terms of collaboration, I think we do a really good job. We don't do a good job of publically outlining the collaboration. So most people think we're in two different silos, which is not the case." - *Organization 2*

Despite the resounding agreement regarding the importance of partnerships and collaboration, each of the four local organizations interviewed expressed that staffing needs, time constraints, and costs associated with focusing on disaster preparedness are their largest barriers to collaborating more with the hospitals in the county. Two organizations noted that in an ideal world, they would have a larger team of planners, with at least one individual dedicated to interfacing with other organizations and hospitals, but that is simply not their reality.

> "There is coordination; however, the larger hospitals and more urban geographic areas experience a greater sophistication in their preparedness collaboration. There are areas of the state where coordination exists, yet immediate access to resources can be delayed either because of distance or fewer personnel. The goal of federal agencies, state and local governments, and hospitals is to facilitate as much coordination as possible. " - *Organization 4*

Through the interviews with four local organizations, a vast network of partnerships between organizations and hospitals was identified. These additional organizations (Table 3) were formally involved in hospital emergency preparedness or response, in some capacity, at the national, state, or local levels during Hurricane Harvey. This list is by no means comprehensive and only represents the partnerships as disclosed by the local organizations interviewed for this study.

Table 3: Partner Organizations Identified through Interviews.

National	State	Local
Federal Emergency Management Agency (FEMA)	State of Texas	Harris County Office of Homeland Security and Emergency Management (HCOHSEM)
U.S. Department of Health and Human Services (HHS)	Texas Department of Health and Human Services (DSHS)	Harris County Medical Society (HCMS)
The American Red Cross (ARC)	Texas Department of Transportation (TxDOT)	SouthEast Texas Regional Advisory Council (SETRAC)
U.S. Department of Housing and Urban Development (HUD)	Texas Division of Emergency Management (TDEM)	Catastrophic Medical Operations Center (CMOC)
Centers for Medicare and Medicaid Services (CMS)	Texas Department of Public Safety (TxDPS)	Harris County Citizen Corps/Medical Reserve Corps
U.S. Department of Defense (DoD)	Texas Hospital Association (THA)	Emergency Medical Services (EMS)
U.S. Department of Homeland Security (DHS)	Texas Commission on Environmental Quality (TCEQ)	Harris Center for Mental Health and IDD
		Harris County Flood Control District (HCFCD)
		City of Houston
		Harris County Engineering Department
		City of Houston Mayor's Resiliency Office
		Harris County Public Health Office of Public Health Preparedness and Response (OPHPR)

The surveys, interviews, and secondary source analysis all echoed the fact that the SouthEast Texas Regional Advisory Coalition (SETRAC), which helps coordinate healthcare preparedness and disaster response efforts in 26 southeast Texas counties, is perhaps the biggest asset to the Harris County healthcare community. Since 1989, SETRAC has connected a strong system of local hospitals and organizations and provided leadership in communication, cooperation, and collaboration. Additionally, SETRAC also supports the Catastrophic Medical Operations Center (CMOC), which is responsible for

coordinating hospital closures, patient transport, and medical resource requests during emergency events (Upton et al., 2017; Flynn et al., 2018). Although healthcare coalitions are becoming increasingly common across the U.S., SETRAC is unique in that very few coalitions have been provided with the opportunities to practice and regionally implement emergency preparedness strategies.

> "I think you'll be hard pressed to find any other hospital preparedness program or regional system that's better prepared than here. I think we probably have one of the most advanced, the most complex Catastrophic Medical Operations Center (CMOC) that we know works and has demonstrated it works in the past. And they continue to improve." - *Organization 3*

Overall, the hospital surveys and interviews with local organizations revealed robust partnerships and a high level of collaboration in Harris County, as well as a sense of pride in the collective response to Hurricane Harvey.

Hospital Emergency Response Challenges during Hurricane Harvey

A) Access

Perhaps the most salient challenge hospitals faced during their emergency response to Hurricane Harvey was issues with access—not flooding within the hospitals themselves. As Organization 3 noted in an interview, a hospital's location outside a FEMA flood hazard area does not ensure a hurricane response experience without flood impacts. Many major roadways were underwater for extended periods of time during Hurricane Harvey, preventing the transportation of hospital staff and individuals in need of care, as well as shipments of much-needed hospital supplies, such as food and medications (Christensen and Edwards, 2017; THA, 2018). In response to these widespread hospital access issues, Organization 2 mentioned in an interview the importance of strengthening partnerships with the Texas Department of Transportation (TxDOT) in order to improve transportation resilience during future flooding events.

B) Planning

Despite excellent planning overall, the nature of Hurricane Harvey itself created some unanticipated challenges that advanced planning failed to address. Hurricane Harvey was not only a historic rainfall event lasting over a week, but its sheer strength was largely unexpected (Resnick, 2017). SETRAC reported that Harris County hospitals would have made preparations for the storm much earlier had they known that Hurricane Harvey would make a relatively direct landfall as a Category 4 hurricane (Blau, 2017). Even with procedures in place, hospitals were given very little warning of the impending hurricane and flooding. This led to hastened decisions of whether to evacuate patients or shelter in place with ride-out teams, and very few at-risk hospitals managed to evacuate all patients in advance of the flooding (Goldstein and McGinley, 2017; U.S. HHS ASPR, 2018). Because there is a high level of risk involved in moving injured and ill patients, only patients in the most critical conditions were considered for evacuation once Hurricane Harvey and the associated flooding began. Additionally, transporting patients during a hurricane can be a difficult task since each patient needs to be individually matched with a hospital that is both far from the hurricane's path and willing to take in patients in critical condition (Blau, 2017; Foley, 2017; Hsu and Sullivan, 2017).

Another unplanned situation arose due to a lack of communication with first responders, who were responsible for delivering individuals plucked from home evacuations and high water rescues to safety. Roadway flooding often meant that these individuals were dropped off at the nearest hospital, rather than the nearest shelter, even when no medical attention was needed (AHA, 2018; THA, 2018). Similarly, hospitals had issues maintaining their phone lines, since they were deluged with calls from individuals trapped at home with health issues, such as those needing dialysis, as well as calls from other hospitals trying to evacuate their patients (Hsu and Sullivan, 2017; Ortiz, 2018). Lastly, retail pharmacies were similarly impacted by the flooding, so in the cases that pharmacies were not accessible or had trouble maintaining sufficient stock of important medications, hospitals were bombarded by requests from the general public to fill prescriptions (Phillips et al., 2017). This influx of individuals, calls, and requests

overwhelmed the available resources at the receiving hospitals to the point that advanced planning simply broke down (THA, 2018).

C) Staffing

Although hospital staff demonstrated remarkable dedication, as detailed above, many hospitals still struggled with a variety of staffing issues during Hurricane Harvey. One of the biggest complaints, echoed in the survey with Hospital A, was that hospitals delayed making the decisions to declare a ride-out, meaning that ride-out teams composed of critical personnel were sorely understaffed in many cases, since staff were either unavailable or could not reach the hospital in time (Verduzco-Gutierrez, 2018). Hospital A also pointed out that understaffing, paired with a lack of situational awareness within the Hospital Emergency Incident Command System (HEICS) structure, meant that the established hierarchy and staff responsibilities crumbled under pressure in some hospitals.

Additionally, with so many staff remaining on site in order to complete their 12-hour shifts, hospitals were forced to create makeshift quarters separate from the patients that were capable of providing sleeping space for many staff members, often on cots and air mattresses (Hospital B survey; Evans, 2017; Wentling, 2017). Due to the extreme stress of balancing work responsibilities and personal life, many hospital staff members in ride-out teams experienced anxiety and burnout, which would have benefited from support services developed specifically for hospital staff and their families (Doiel, 2017; THA, 2018).

Barriers to Hospital Flooding Adaptation and Preparedness Efforts in Harris County

Thanks to an abundance of experience with extreme flooding events, the hospitals surveyed and local organizations interviewed in Harris County appeared to have few perceived barriers to hospital adaptation and preparedness efforts. As one hospital emergency manager put it:

> "I don't believe we have barriers—because of past problems, the organization is now fully committed to disaster preparedness" - *Hospital A*

However, the other survey and interview participants mentioned, in some way, that financial issues and staffing are the biggest barriers preventing adaptation and preparedness efforts in hospitals. Organizations 1 and 2 explained that both for-profit and not-for-profit hospitals are responsible for balancing the need for flood preparedness/adaptation efforts and the associated costs of implementing projects and hiring dedicated staff. Most survey and interview participants agreed that there is not much political resistance to emergency preparedness efforts in their hospitals. Additionally, the survey and interview participants reported that they do not perceive any adaptation or preparedness barriers tied to uncertainty about future flooding conditions, since they all rely on well-informed regulatory agencies to provide guidance on future flooding.

Two unpredicted barriers to flooding adaptation efforts, both involving local utilities, were identified through the interviews with local organizations. First, many hospital facilities in Harris County, and within the Texas Medical Center in particular, are fully integrated into the City of Houston's utility services, which include water and sewage. This can create massive issues for hospitals in the case that these utilities fail during extreme flooding events. These hospitals would ideally prefer an independent system separate from the city, but that would be a huge capital infrastructure project. Another barrier to flooding adaptation efforts stems from Harris County's power lines, which are still strung above-ground on poles and are often damaged during high wind events, creating extensive power outages. However, unlike many other Texas cities, there has been hesitancy to bury the power lines underground because Harris County in particular is susceptible to flooding and subsidence, which similarly pose a threat to power lines. These two utilities-related challenges to flooding adaptation were echoed by the U.S. Department of Homeland Security's 2018 National Preparedness Report, which identified infrastructure interdependencies as a top challenge to disaster response and recovery across the country (U.S. DHS, 2018).

CHAPTER IV — DISCUSSION AND CONCLUSION

This thesis consisted of a two-part study investigating the impacts of Hurricane Harvey on the hospitals of Harris County, Texas. First, I conducted GIS analysis to assess whether two datasets—the Federal Emergency Management Agency (FEMA) flood hazard area and the Hurricane Harvey flood inundation boundary—accurately predicted which hospitals in Harris County experienced flood impacts related to Hurricane Harvey. Second, I used survey and interview methods, as well as a collection of secondary data sources, to assess Harris County hospitals' flood adaptation efforts and collective experience with Hurricane Harvey, as well as the lessons learned in the aftermath of the storm.

The GIS analysis discovered rather large inconsistencies between the hospitals that experienced Hurricane Harvey flood impacts and those that were predicted to experience flood impacts due to their location within FEMA flood hazard areas or within the Hurricane Harvey flood inundation boundary. This issue is especially concerning for the hospitals in which flooding impacts were reported despite being located outside of a FEMA flood hazard area. In addition, the GIS mapping also revealed that the FEMA flood hazard areas did not accurately predict the areas of Harris County, Texas that flooded during Hurricane Harvey, an extreme flooding event. This result is not surprising, considering there is a large body of literature demonstrating the pitfalls and inaccuracies of the FEMA flood hazard area data and its impacts on risk perception (Houston et al., 2017), and particularly in the coastal Texas area (Blessing et al., 2017).

Although it is plausible that the FEMA and Hurricane Harvey flood inundation boundary datasets are flawed or inaccurate, it is also possible that there are other reasons for inconsistencies between these datasets and which hospitals experienced flooding, as shown in Figure 4. In the cases in which flooding impacts occurred when hospitals were located outside the Hurricane Harvey flood inundation boundary, it is possible that the hospital flood impacts were related to rainfall leaks rather than sheer water inundation, but I was unable to confirm this without additional information from the hospitals. In the cases in which no flooding impacts occurred when hospitals were located in the Hurricane Harvey flood inundation boundary, it is possible that the hospitals had implemented flood adaptation strategies and avoided

flooding. Overall, this geospatial exploration revealed a need for an in-depth qualitative approach in order to investigate the experiences of hospitals and whether their flood adaptation efforts potentially played a role in the differences observed between predicted and observed flood impacts.

The analysis of surveys, interviews, and secondary data clearly revealed that Harris County hospitals learned their most valuable lessons about flood preparedness through their direct and repeated experience with flooding from Tropical Storm Allison (2001), Memorial Day Flood (2015), and Tax Day Flood (2016), as well as indirectly through Hurricanes Katrina (2005) and Sandy (2012). These lessons led to improved preparedness and the implementation of several sophisticated flood adaptation projects over the past decade across Harris County prior to Hurricane Harvey. The most remarkable hospital emergency response success was the infrastructure improvements in many hospitals across the county that prevented devastation similar to that from Tropical Storm Allison. Although this study was unable to confirm whether hospital adaptation efforts explain the difference between predicted and observed hospital flood impacts, the survey and interview results indicated that infrastructure improvements likely played an important role. Additional successes included hospital staff dedication and resilience, advanced planning and preparation aided by the use of emergency exercises and the Hospital Emergency Incident Command System (HEICS) structure, and pre-established collaboration with local partner organizations (SETRAC, in particular) and government agencies at multiple levels.

Despite these successes, hospitals still faced challenges, such as prolonged roadway flooding that restricted the transportation of supplies, patients, and staff to hospitals. The latter resulted in issues with understaffing, since many staff were unable to reach their hospitals, and staff burnout, as staff who arrived ahead of Hurricane Harvey were often working on-site for many days at a time. Overall, Hurricane Harvey's path and strength was unanticipated, leading to a breakdown of advanced planning, particularly related to evacuating and transporting patients out of the area while simultaneously managing an influx of patients, phone calls, and requests. These results are consistent with the findings of several reports written after Hurricane Harvey (Upton et al., 2017; Flynn, 2018; THA, 2018).

The current state of flood preparedness and adaptation planning in Harris County hospitals is rather advanced and mature, and this has been validated by the tangible sense of pride in the collective preparation and response to Hurricane Harvey. However, as this study's GIS analysis revealed, extreme flooding events like Hurricane Harvey can be unpredictable, meaning that hospitals located outside of FEMA flood hazard areas with a lower perceived flood risk may still experience flood impacts. In light of this, Harris County needs to take steps to ensure that hospitals with fewer resources and less direct flood experience are equally as prepared as those with resources, connections, and experience. Thanks to an abundance of experience with extreme flooding events and informed guidance on how to prepare, the survey and interview participants reported very few perceived barriers to flood preparedness and adaptation efforts in Harris County hospitals, including financial barriers, lack of dedicated staff, and concerns related to local utilities. Despite these barriers, in the year following Hurricane Harvey, hospitals have already started preparing for the next big hurricane by updating policies, creating an inter-institutional information portal, seeking funding to improve transportation resilience, and purchasing high-water vehicles (George, 2018). Harris County as a whole has also approved a $2.5 billion bond to support a variety of flood-control projects, many of which are likely to improve hospital flood outcomes in the case of another extreme flooding event (Pulsinelli, 2018).

One of the main strengths of this study is the implementation of a mixed methods research design, using both quantitative (GIS analysis) and more qualitative analysis methods. Additionally, within the qualitative methods used to construct a narrative detailing Harris County hospitals' collective experience with Hurricane Harvey and flood adaptation efforts, as well as the lessons learned in the aftermath of the storm, I used both primary and secondary data sources. Through the combination of a survey of hospital emergency managers, semi-structured interviews with local organizations involved in public health and emergency management, and a variety of news reports and other documents, I was able to synthesize multiple perspectives into key themes related to hospital preparedness and response to Hurricane Harvey. Additionally, the timing of this study benefited the results, since memory of Hurricane

Harvey was still strong at the time of data collection, but enough time had elapsed to allow for a full understanding of the range of flood impacts.

Despite the strengths presented above, this study had a few limitations worth noting. First and foremost, this study focused specifically on the impacts of Hurricane Harvey on hospitals in Harris County, Texas, meaning that the results may not be generalizable to other coastal cities. However, the successes, challenges, and lessons learned presented in this study are valuable and have the potential to motivate other coastal cities to engage in hospital emergency preparedness and flood adaptation efforts, perhaps without previously experiencing a hurricane or similar extreme flooding event of their own. Such transfer of information has already proven beneficial, since the hospitals and local organizations of Harris County, Texas specifically cited that hospital experiences with Hurricane Katrina (2005) and Hurricane Sandy (2012) elsewhere in the U.S. were just as informative as their previous personal experience with Tropical Storm Allison (2001). Similarly, the results of this study were specific to the context of healthcare infrastructure affected by flooding from Hurricane Harvey, but may provide valuable insights that are transferable to healthcare preparedness planning for other extreme weather events across the U.S., such as wildfires, earthquakes, and inland flooding.

Second, the survey responses were not only limited in number, but limited in reach. For example, although a variety of hospitals were contacted and invited to participate in the survey, I only received responses from three large, urban hospitals. Those that participated all have substantial resources at their disposal, allowing for the optimal level of flood preparedness and adaptation efforts, which is not necessarily representative of the average hospital in Harris County, Texas. In an attempt to supplement the information gathered through the survey, I sought additional perspectives through semi-structured interviews with local organizations and the synthesis of news reports and documents from government agencies, local organizations, and hospitals themselves. By combining information sources and multiple perspectives, I was able to complete a more comprehensive and in-depth analysis of the experiences of Harris County's hospitals.

Another potential limitation of this study was the singular focus on hospitals, rather than the healthcare system as a whole, which could have included walk-in emergency rooms, doctor's offices and clinics, nursing homes, dialysis centers, pharmacies, and emergency medical services, including ambulances and paramedics. This study similarly did not investigate the experiences of the patient population of Harris County, Texas that was attempting to access these hospitals for healthcare during Hurricane Harvey. Lastly, this study only focused on historical and current flood preparedness and adaptation in relation to Hurricane Harvey, and did not specifically address the potential impacts of future climate change. Although these three factors—additional healthcare system components, patient population, and climate change implications—are crucial parts of the Hurricane Harvey narrative that should not be understated, they were outside the scope of this master's thesis and each deserve focused studies of their own.

Future work should also consider implementing a more standardized (and therefore, reproducible) approach to evaluating hospital emergency preparedness and response to extreme weather events, in which all hospitals in the study area are represented in a survey. McCabe et al. (2010) have developed a guiding framework to fill this need, proposing that "the commonplace expression 'ready, willing, and able' (RWA) represents a simple, easily understandable framework for planning, implementing, and evaluating efforts to ensure high-quality individual and organizational responses to public health emergencies" (McCabe et al., 2010). Although the RWA framework is in the beginning phases of applied investigation, it has the potential to provide a standardized approach to evaluation of emergency preparedness that can easily be applied to organizational responses to emergency events, including within the healthcare sector.

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APPENDIX

Appendix A: Institutional Review Board Approval Letter

APPROVAL

24-Sep-2018
Dear Emmanuelle Hines,

On **24-Sep-2018** the IRB reviewed the following protocol:

Type of Submission:	Amendment
Review Category:	Exempt
Title:	Healthcare system vulnerability in Houston, Texas following Hurricane Harvey
Investigator:	Hines, Emmanuelle
Protocol #:	17-0559
Funding:	None
Documents Approved:	17-0559 Consent Form (24Sep18); 17-0559 Protocol (24Sep18); 17-0559 Recruitment Material (24Sep18); 17-0559 Survey (24Sep18);
Documents Reviewed:	HRP-213 Amendment-v2;
Description:	- Expansion of study subject population and timeframe. - Update to data collection questions.

The IRB approved the protocol on **31-Oct-2017**.

Click the link to find the approved documents for this protocol: Summary Page Use copies of these documents to conduct your research.

In conducting this protocol you must follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
Douglas Grafel
IRB Admin Review Coordinator Institutional Review Board

Appendix B: Survey/Interview Questions

General Background Information

The following questions will ask about general background information about the survey respondent and your hospital.

1. What is the name of your hospital? (open answer)
2. What is the job title of the survey respondent? (open answer)
3. In what year was your hospital built? (open answer)
4. Since the building was originally constructed, have there been any renovations, updates, or structural retrofitting? (Y/N/NA)
    a. If yes, please provide details about what was done and in what year. (open answer)
5. Does your hospital have flood insurance? (Y/N/NA)
    a. If yes, does it cover mold? (Y/N/NA)
    b. If yes, does it cover water damage? (Y/N/NA)
6. Is your hospital currently located within a flood hazard zone (either 100-year or 500-year)? (Y/N/NA)
    a. If yes, which one?
    b. If yes, how do you know? (open answer)
7. Was your hospital located within a flood hazard zone before and during construction? (Y/N/NA)

Past Experience with Flooding

The following questions address this hospital's past experiences with flooding. When answering, please consider only events occurring prior to Hurricane Harvey.

8. Has your facility experienced flooding since the year 2000, excluding Hurricane Harvey? (Y/N/NA)

If yes to Question 8, please answer the following questions. If no to Question 8, move on to Question 21.

9. How many feet and inches of water flooded your hospital? (_____ ft, _____ in)
10. What was the source of the flooding and when did it occur? (open answer)
11. Did any portion of your hospital close for any amount of time? (open answer)
12. Did any portion of your hospital become non-operational for any amount of time? (open answer)
13. Was your hospital forced to evacuate patients? (scaled response or NA)
    - Yes, all patients were evacuated
    - Yes, some patients were evacuated
    - No, no patients were evacuated
14. If patients were evacuated, which ones? (open answer)
15. What challenged hospital functionality during past flooding events? (open answer)
16. Did your hospital experience mold due to the flooding? (Y/N/NA)
17. If yes, has your facility been remediated for mold damage from flooding before Hurricane Harvey? (scaled response or NA)
    - No remediation
    - Superficial remediation
    - Partial remediation
    - Complete remediation
18. Did your hospital experience water damage due to the flooding? (Y/N/NA)
19. If yes, has your facility been remediated for water damage from flooding before Hurricane Harvey? (scaled response or NA)
    - No remediation

- Superficial remediation
- Partial remediation
- Complete remediation

20. Did non-patients seek shelter at your hospital? (Y/N/NA)

Experience with Hurricane Harvey

The following questions address this hospital's experiences with flooding due to Hurricane Harvey. When answering, please consider only events directly related to Hurricane Harvey.

21. Did your hospital flood during or immediately after Hurricane Harvey? (Y/N/NA)

If yes to Question 21, please answer the following questions. If no to Question 21, move on to Question 32.

22. How many feet and inches of water flooded your hospital? (_____ ft, _____ in)
23. Did any portion of your hospital close or become non-operational for any amount of time? (open answer)
24. Did any portion of your hospital become non-operational for any amount of time? (open answer)
25. Was your hospital forced to evacuate patients? (scaled response or NA)
    - Yes, all patients were evacuated
    - Yes, some patients were evacuated
    - No, no patients were evacuated

25a. If patients were evacuated, which ones? (open answer)
26. What challenged hospital functionality during and after Hurricane Harvey? (open answer)
27. Did your hospital experience mold because of flooding during Hurricane Harvey? (Y/N/NA)
28. If yes, has your facility been remediated for mold damage after Hurricane Harvey? (scaled response or NA)
    - No remediation
    - Superficial remediation
    - Partial remediation
    - Complete remediation

29. Did your hospital experience water damage because of flooding during Hurricane Harvey? (Y/N/NA)
30. If yes, has your facility been remediated for water damage after Hurricane Harvey? (scaled response or NA)
    - No remediation
    - Superficial remediation
    - Partial remediation
    - Complete remediation

31. Did non-patients seek shelter at your hospital? (Y/N/NA)

Flood Preparedness and Adaptation Plans

The following questions address the state of flood preparedness and implementation of flood adaptation plans at this hospital.

32. Do you know who to contact for help during and after a flooding event? (Y/N/NA and open answer)

33. Does your hospital have any flood preparedness/adaptation plans in place? (Y/N/NA)

If you answered yes to Question 33, please indicate to which degree your hospital has flood preparedness and adaptation plans in place. If you answered no plans to Question 33, move on to Question 35.

34. Does your hospital's flood preparedness and adaptation plan address the following items in one way or another? (scaled response)

Item	Fully implemented	Partially implemented	Only plans	No plans	NA
Abandon basement					
Anchor buildings					
Floodwalls or levees					
Site drainage					
Sewage system					
Floodproof or flood resistant materials					
Kitchen located above BFE					
Access points located above BFE					
Emergency room located above BFE					
Generators located above base flood elevation					
Roads for vehicle access					
Helipads for air access					
Boat ramps for boat access					
Emergency generators					
Fuel storage					
Water storage					
Food storage					
Windows that open					
Supply warehouse					
Electronic medical records					
Communications including phones and internet					
Evacuation plans					
Prioritization system for patient evacuation					
Prioritization system for patient treatment					
Medical staff training and education					
Adequate temporary staff					
Adequate temporary shelter					
Adequate temporary supplies					

35. Can your hospital currently operate independently of The City of Houston's water supply and electric grid for any amount of time? (open answer)

Barriers to Adaptation

The following questions address perceived barriers that may prevent your hospital from putting in place flooding preparedness and adaptation plans.

36. Please rate how much you agree or disagree with the following factors acting as a barrier to implementing flooding preparedness and adaptation plans in your hospital:

Factor	Strongly agree	Agree	Somewhat agree	Neutral	Somewhat disagree	Disagree	Strongly disagree	NA
Uncertainty about future climate conditions								
Uncertainty about future flooding conditions								
Uncertainty about future socioeconomic vulnerability conditions								
Perceptions of vulnerability to flooding								
Financial challenges								
Political challenges								
Technological limits								

Ready, Willing, Able Framework

Framework explanation:

McCabe et al. 2010 propose "that the commonplace expression 'ready, willing, and able' (RWA) represents a simple, easily understandable framework for planning, implementing, and evaluating efforts to ensure high-quality individual and organizational responses to public health emergencies."
Readiness has two components: 1) individuals and/or agencies are available for prompt action, service, or duty, and 2) individuals and/or agencies possess the human and material resources necessary for timely responses, such as adequate and appropriate plans, policies, personnel, equipment, and supplies.

Willingness refers to the state of being inclined or motivated to participate in specific emergency responses. Components of willingness can include confidence in training, trusted relationships and partnerships, and political imperatives.

Ability refers to the actual operational power of an individual and/or agency to perform a task. Components of ability can include skills, know-how, knowledge, competencies, and proficiencies.

Framework questions:

The following questions apply the Ready, Willing, Able Framework to your hospital or organization. Imagine that another hurricane similar to (or stronger than) Hurricane Harvey was headed toward Houston at this moment. Using the questions below, please provide an estimate of how Ready, Willing, and Able your entire hospital or organization is when it comes to providing a quality emergency response to this theoretical hurricane. The scale is 0 to 10, where a 0 indicates least Ready and 10 indicates most Ready, etc.

37. On a scale of 0 to 10, how Ready is your hospital or organization right now. Why? (open answer)
38. On a scale of 0 to 10, how Willing is your hospital or organization right now. Why? (open answer)
39. On a scale of 0 to 10, how Able is your hospital or organization right now. Why? (open answer)

Appendix C: Email Invitation to Participate in Study

Sample Email Request

From: Emma Hines
Sent: Spring 2018
To: Hospital Administrator or Local Organization Representative
Subject: Invitation to Participate in Survey on Hospital Vulnerability to Flooding

Dear Hospital Administrator or Local Organization Representative,

My name is Emma Hines and I am a graduate student at the University of Colorado Boulder. I am leading a study assessing healthcare system vulnerability in Houston, Texas following Hurricane Harvey. Because you represent a hospital in Houston, Texas either as an emergency preparedness administrator or a representative from a local emergency management organization, I am inviting you to participate in this research study through an in-person survey.

This in-person survey aims to investigate the experiences of flood-affected and non-flood-affected hospitals before, during, and after Hurricane Harvey and evaluate these facilities' flooding adaptation plans for the future. Questions will cover general hospital information, past experience with flooding, the physical impacts and health implications of flooding caused by Hurricane Harvey, and the state of flood preparedness and adaptation planning. Ideally, this survey will allow for a complete census of Houston hospital administrators. I will administer this survey by December 2018.

The survey should take approximately one hour to complete. It is composed of both closed answer and open answer questions, for a total of 39 questions. Following completion of the survey, participants will be compensated $25.00 in the form of an electronic Amazon giftcard, which will be sent to your email address and redeemed on Amazon through a claim code. There is no known risk of participating. The benefits to you of the survey is that the results of the study may enable our country's critical healthcare infrastructure to better prepare for, respond to, and recover from future catastrophic flooding events like Hurricane Harvey. You will be provided with consent form prior to being administered the survey, if you choose to participate. Participation is strictly voluntary and you may refuse to participate at any time.

If you are willing to participate in this in-person survey, please respond to this email indicating your availability for a meeting by December 2018.

Thank you very much for your time and cooperation.

Sincerely,

Emma Hines
817-680-0438
emmanuelle.hines@colorado.edu
CU Boulder Geography Department

Appendix D: Informed Consent Form

Permission to Take Part in a Human Research Study

Title of research study: Healthcare system vulnerability in Houston, Texas following Hurricane Harvey
IRB Protocol Number: 17-0559
Investigator: Emmanuelle Hines

Purpose of the Study
The purpose of the study is to investigate the experiences of affected and non-affected hospitals before, during, and after Hurricane Harvey and evaluate these facilities' levels of preparation and flooding adaptation plans for the future. Overall, through hospital administrators and local emergency management organizations, we hope to survey all hospitals in Houston, both those affected by Hurricane Harvey, as well as non-impacted hospitals, about their experiences and lessons learned to inform future healthcare infrastructure planning for future extreme flooding events in Texas and elsewhere.
We invite you to take part in this research study because you represent a hospital in Houston, Texas, either as an emergency preparedness administrator or as a representative of a local emergency management organization.

We expect that the survey will take a total of two hours. We expect about 100 hospital administrators and organization representatives will be in this research study.

Explanation of Procedures
This research will be conducted in the form of a short, in-person survey composed of both closed answer and open answer questions, for a total of 39 questions. The survey questions will cover general hospital information, past experience with flooding, the physical impacts and health implications of flooding caused by Hurricane Harvey, and the state of flood preparedness and adaptation planning. The surveys will be administered in-person by the Principal Investigator, Emmanuelle Hines, at the participant's respective hospital or organization by December 2018. We expect that you will be in this research study for a total of two hours, which includes pre-survey tasks such as scheduling a visit. The visit with a participant to complete the survey should take one hour maximum.

Voluntary Participation and Withdrawal
Whether or not you take part in this research is your choice. You can leave the research at any time and it will not be held against you. If you stop being in the research, already collected data may not be removed from the study database.

Potential Benefits
We cannot promise any individual benefits to you or others from your taking part in this research. However, there are several benefits to society. Results from this study may enable our country's critical healthcare infrastructure to better prepare for, respond to, and recover from future catastrophic flooding events like Hurricane Harvey. This study will most obviously benefit society through its direct impacts to healthcare system resilience, which will improve the well-being of individuals in society who rely upon hospitals for care in general and in cases of extreme natural disasters. By focusing attention on proactive measures such as flood preparedness and adaptation planning, this study also aims to reduce the future costs of extreme weather events on U.S. healthcare infrastructure and those who rely upon it for care.

Confidentiality

Information obtained about you for this study will be kept confidential to the extent allowed by law. Research information that identifies you may be shared with the University of Colorado Boulder Institutional Review Board (IRB) and others who are responsible for ensuring compliance with laws and regulations related to research, including people on behalf of the Office for Human Research Protections. The findings from this research may be published for scientific purposes at the aggregate level such that no one hospital or administrator or organization could be identified from the publication. Your identity will not be released.

Payment for Participation
Following completion of the survey, participants will be compensated $25.00 in the form of an electronic Amazon giftcard, which will be sent to your email address and redeemed on Amazon through a claim code.

Questions
If you have questions, concerns, or complaints, or think the research has hurt you, talk to the research team at emmanuelle.hines@colorado.edu or 817-680-0438.

This research has been reviewed and approved by an Institutional Review Board (IRB). You may talk to them at (303) 735-3702 or irbadmin@colorado.edu if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

Signatures
Your signature documents your permission to take part in this research.

Signature of subject _____ Date _____

Printed name of subject _____

Signature of person obtaining consent _____ Date _____

Printed name of person obtaining consent _____

Appendix E: Hurricane Harvey Flood Impacts in the Hospitals of Harris County, Texas

Hospital Name	City	Type	Inside FEMA Flood Hazard Area?	Inside Harvey Inundation Boundary?	Harvey Flood Impacts?	Harvey Flood Impacts Description	Harvey Flood Impacts Confirmed By
Advanced Diagnostics Hospital East LLC	Houston	General Acute Care	500-year	No	Not ascertained		
Altus Baytown Hospital	Baytown	Special	500-year	No	Not ascertained		
Bay Area Regional Medical Center	Webster	General Acute Care	No	No	No	remained operational with no structural damage	Bay Area Regional Medical Center, 2017; Ismail, 2018
Bayshore Medical Center	Pasadena	General Acute Care	No	Yes	Yes	had flooding, evacuated patients	phone call; Christensen and Edwards, 2017
CHI St Luke's Health - Springwoods Village	Spring	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
CHI St Luke's Health Baylor College Of Medicine Medical Center	Houston	General Acute Care	500-year	Yes	No	no flooding, evacuated some patients, remained operational	phone call; Christensen and Edwards, 2017; Feigen and Sixel, 2017
Clear Lake Regional Medical Center	Webster	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
Cornerstone Speciality Hospitals Bellaire	Houston	Long Term Care	100-year	Yes	Yes	had flooding, closed temporarily	phone call; Ackerman, 2017
Cornerstone Speciality Hospitals Clear Lake	Webster	Long Term Care	No	No	Not ascertained		
Cornerstone Speciality Hospitals Medical Center	Houston	Long Term Care	No	No	Yes	had flooding	phone call
Cypress Fairbanks Medical Center	Houston	General Acute Care	100-year	No	No	no flooding	phone call
East Houston Regional Medical	Houston	General Acute	100-year	Yes	Yes	closing due to damage from	website; Deam and Ackerman, 2017

Center		Care				Hurricane Harvey	
Encompass Health Rehabilitation Hospital of Cypress	Houston	Rehabilitation	No	No	No	remained operational	Ackerman, 2017; Encompass Health Corp, 2017
Encompass Health Rehabilitation Hospital of Humble	Humble	Rehabilitation	No	No	No	remained operational	Encompass Health Corp, 2017
Encompass Health Rehabilitation Hospital The Vintage	Houston	Rehabilitation	No	Yes	Yes	closed temporarily, evacuated patients	Encompass Health Corp, 2017
First Street Surgical Center	Bellaire	Special	100	Yes	Yes	had flooding, cases moved elsewhere	Nobilis Health Corp, 2017
First Texas Hospital CyFair	Houston	General Acute Care	No	No	No	remained open	First Choice Emergency Room, 2017
Harris Health System Ben Taub General Hospital	Houston	General Acute Care	500-year	No	Yes	had flooding	Blau, 2017; Fink and Blinder, 2017; Goldstein and McGinley, 2017; Christensen and Edwards, 2018
Harris Health System Lyndon B. Johnson General Hospital	Houston	General Acute Care	No	No	No	maintained operations, took in evacuees, surrounded by water	Harris Health System, 2017; Vartorella, 2018
Harris Health System Quentin Mease Hospital	Houston	General Acute Care	No	No	Yes	closed during harvey	Vartorella, 2017
Hermann Drive Surgical Hospital	Houston	General Acute Care	No	No	No	remained operational	Nobilis Health Corp, 2017
Houston Methodist Hospital	Houston	General Acute Care	500-year	No	Yes	had flooding, remained operational, elective surgeries cancelled	phone call; Marshall, 2017
Houston Methodist San Jacinto Hospital	Baytown	General Acute Care	No	No	No	remained operational, elective surgeries cancelled	Marshall, 2017
Houston Methodist San Jacinto Hospital Alexander	Baytown	General Acute Care	No	No	No	remained operational, elective surgeries cancelled	Marshall, 2017

Campus							
Houston Methodist St. Catherine Hospital	Katy	Long Term Care	No	No	No	remained operational, elective surgeries cancelled	Marshall, 2017
Houston Methodist St. John Hospital	Nassau Bay	General Acute Care	100-year	No	No	remained operational, elective surgeries cancelled	Marshall, 2017
Houston Methodist West Hospital	Houston	General Acute Care	No	No	No	remained operational, elective surgeries cancelled	Marshall, 2017
Houston Methodist Willowbrook Hospital	Houston	General Acute Care	No	No	No	remained operational, elective surgeries cancelled	Marshall, 2017
Houston Northwest Medical Center	Houston	General Acute Care	No	No	No	remained operational, elective surgeries cancelled	Marshall, 2017
Houston Physicians' Hospital	Webster	General Acute Care	No	No	Not ascertained		
Icon Hospital	Humble	Long Term Care	No	No	Not ascertained		
Kindred Hospital Bay Area	Pasadena	Long Term Care	500-year	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital Baytown	Baytown	Long Term Care	No	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital Clear Lake	Webster	Long Term Care	No	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital Houston Medical Center	Houston	Long Term Care	500-year	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital Houston Northwest	Houston	Long Term Care	100-year	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital Spring	Houston	Long Term Care	No	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital The Heights	Houston	Long Term Care	100-year	No	No	remained operational	Kindred Healthcare, 2017
Kindred Hospital Tomball	Tomball	Long Term	No	No	No	remained operational	Cruz, 2017

		Care					
Kindred Hospital Town & Country	Houston	Long Term Care	No	No	No	remained operational	Kindred Healthcare, 2017
Kindred Rehabilitation Hospital Clear Lake	Webster	Rehabilitation	No	No	No	remained operational	Kindred Healthcare, 2017
Kindred Rehabilitation Hospital Northeast Houston	Humble	Rehabilitation	500-year	Yes	No	remained operational	Kindred Healthcare, 2017
Memorial Hermann Greater Heights Hospital	Houston	General Acute Care	500-year	No	No	remained operational	Feigen and Sixel, 2017
Memorial Hermann Hospital	Houston	General Acute Care	500-year	No	No	closed submarine doors to prevent flooding	Gooch, 2017; Park, 2017
Memorial Hermann Katy Hospital	Katy	General Acute Care	No	No	No	no flooding, but had leaks from rainfall, remained operational	Brust, 2017; Feigen and Sixel, 2017
Memorial Hermann Memorial City Medical Center	Gonzales	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
Memorial Hermann Northeast Hospital	Humble	General Acute Care	No	No	Yes	had flooding, remained operational	Feigen and Sixel, 2017; Feuk, 2018
Memorial Hermann Orthopedic and Spine Hospital	Bellaire	General Acute Care	500-year	No	Yes	temporarily closed	Ellison, 2017
Memorial Hermann Rehabilitation Hospital Katy	Katy	Rehabilitation	No	No	No	remained operational	Feigen and Sixel, 2017
Memorial Hermann Southeast Hospital	Houston	General Acute Care	500-year	No	No	declared weather emergency, remained operational	Feigen and Sixel, 2017; Memorial Hermann, 2017
Memorial Hermann Southwest Hospital	Houston	General Acute Care	No	No	No	no flooding, took on patients from other hospitals	Slabodkin, 2017
Memorial Hermann Tomball Hospital	Tomball	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
Michael E.	Houston	Military	No	No	No	no flooding,	Wentling, 2017

Debakey VA Medical Center						remained operational	
New Life Hospital	Houston	General Acute Care	No	No	Not ascertained		
Nexus Children's Hospital	Houston	Children	No	No	No	no flooding, took on patients from other hospitals	Nexus Health Systems, 2017
North Cypress Medical Center	Cypress	General Acute Care	500-year	No	Not ascertained		
Pam Rehabilitation Hospital Of Clear Lake	Webster	Rehabilitation	No	No	Not ascertained		
Park Plaza Hospital	Houston	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
Pine Valley Specialty Hospital	Houston	Long Term Care	No	No	Not ascertained		
Plaza Specialty Hospital	Houston	Long Term Care	No	No	No	remained operational	Feigen and Sixel, 2017
Providence Hospital of North Houston LLC	Houston	General Acute Care	No	No	Not ascertained		
Shriners Hospitals For Children	Houston	General Acute Care	500-year	No	No	no flooding	phone call
Spring Excellence Surgical Hospital LLC	Spring	General Acute Care	No	No	Not ascertained		
St. Joseph Medical Center	Houston	General Acute Care	No	No	No	closed floodgates to prevent flooding, declared weather emergency, remained operational	phone call; Evans, 2017
St. Joseph Medical Center In The Heights	Houston	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
St. Luke's Hospital At The Vintage	Houston	General Acute Care	100-year	Yes	Yes	had flooding, evacuated patients	Fink and Blinder, 2017
St. Luke's Patients Medical Center	Pasadena	General Acute Care	100-year	No	Yes	closed temporarily	Feigen and Sixel, 2017

Surgery Specialty Hospitals of America Southeast Houston	Pasadena	General Acute Care	No	No	Not ascertained		
Texas Children's Hospital	Houston	General Acute Care	500-year	No	No	closed floodgates to prevent flooding, cancelled outpatient services but continued inpatient services	phone call; Christensen and Edwards, 2017; Park, 2017; Sullivan and Wootson, 2017; Vartorella, 2017
Texas Children's Hospital West Campus	Houston	Childre n	No	No	No	no flooding, cancelled outpatient services but continued inpatient services	phone call; Vartorella, 2017
Texas Orthopedic Hospital	Houston	Special	500-year	No	No	remained operational	Feigen and Sixel, 2017
The Woman's Hospital of Texas	Houston	General Acute Care	500-year	No	No	remained operational	Feigen and Sixel, 2017
TIRR Memorial Hermann	Houston	Rehabili tation	500-year	Yes	No	closed submarine doors to prevent flooding, declared disaster, remained operational	phone call; Feigen and Sixel, 2017; Toppo, 2017; Verduzco-Gutierrez, 2018
Tomball Regional Medical Center	Tomball	General Acute Care	No	No	No	remained operational	Feigen and Sixel, 2017
TOPS Surgical Specialty Hospital	Houston	Special	No	No	No	no flooding, remained operational, cancelled elective surgeries, issues with access	phone call
Townsen Memorial Hospital	Humble	General Acute Care	500-year	Yes	Yes	had flooding, closed for nearly a year due to Harvey damage	Shelton, 2018
United Memorial Medical Center	Houston	General Acute Care	No	No	Not ascertained		
University of Texas M.D. Anderson Cancer Center	Houston	Special	100-year	Yes	Yes	flooding in lobby, cancelled outpatient services but continued inpatient services	phone call; Christensen and Edwards, 2017; Goldstein and McGinley, 2017
West Houston Medical Center	Houston	General Acute Care	100-year	No	Yes	evacuated patients and suspended services	Slabodkin, 2017

Westside Surgical Hospital	Houston	General Acute Care	No	No	Not ascertained		

**Only non-psychiatric hospitals located in Harris County, Texas were included in this study. The City and Type variables were taken from the original HIFLD dataset (see methods section for more information). The additional columns were created based on the analysis conducted in this study. The terminology in the Harvey Flood Impacts Description column was slightly standardized, but largely left in the words of the source, hence the wide variation in content and detail.