Case Study

Case Study of Flood Mitigation and Hazard Management at the Texas Medical Center in the Wake of Tropical Storm Allison in 2001

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Abstract: Between June 5 and 9, 2001, Tropical Storm Allison dropped upwards of 50 cm (20 in.) of rain on the Texas Medical Center (TMC) in Houston, causing the worst urban flood in U.S. history. The unprecedented rainfall event flooded hospitals, labs, underground tunnels and garages, and power stations, and resulted in excess of $1.5 billion in damages and the loss of decades of medical research. Tropical Storm Allison served as a severe wake-up call to management at the TMC. In response, they developed a hazard mitigation plan (HMP) to minimize the impact of natural and artificial hazards on the TMC campus and its member institutions in the future. Today, the TMC is the premier example of a world-class institution that has a working hazard mitigation plan. This paper discusses the impacts of Tropical Storm Allison (2001) to the TMC and the measures officials have taken to protect and upgrade the flood infrastructure as an example of hazard management for other large, vulnerable institutions. **DOI:** **10.1061/(ASCE)NH.1527-6996.0000139.**

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Introduction

The Texas Medical Center (TMC) was started in the 1940s with funds from the M.D. Anderson Foundation aimed at the "promotion of health, science, education and advancement and diffusion of knowledge and understanding among people." By 1954, the TMC had 11 institutions: four hospitals, two children's hospitals, a university, a library, a speech and hearing center, a dental school, and an overall planning and coordinating group (TMC 2012). Over the last 50 years, TMC has developed into one of the largest medical, patient care, research, and education facilities in the world (TMC 2010). Today, the TMC is made up of 50 member institutions, including 14 renowned hospitals, 21 academic institutions, including schools of dentistry, public health, and pharmacy, and 15 support service organizations (TMC 2010). Although the member institutions operate largely autonomously, TMC provides a variety of services to its member institutions including a forum for the discussion of coordination and planning of day-to-day operations and long-term growth, emergency planning and response, a police force, property management, and parking.

The TMC campus is located within the Brays Bayou watershed, one of the most urbanized watersheds in Harris County, Texas, which covers an area of approximately 4 km^2 (1,000 acres) and lies in a heavily urbanized area south of downtown Houston surrounded by Rice University, Hermann Park, the Museum District, Reliant Park, and residential neighborhoods (Fig. 1). The TMC was built on a historic channel called the Harris Gully (Fig. 2) and parts of TMC are 1-m (3-ft) lower than surrounding geography, making it one of the lowest points in the area. In the late 1940s, the gully evolved from a natural channel to a boxed culvert system. Today, the TMC drains into two underground pipes that feed Brays Bayou. The line over the aerial map in Fig. 2 represents the underground pipes.

Bayous and urban streams are the primary means of drainage for Houston and when left in their natural state, they are lined by wetlands and floodplains that absorb excess rainfall. Flood reduction programs led by the Harris County Flood Control District (HCFCD) and the U.S. Army Corps of Engineers (USACE) during the 1960s prompted the channelization of many Houston bayous, including Brays and White Oak bayous. Brays Bayou, channelized in 1968, was designed to accommodate a 100-year flood event, but by 2001, 40 years of rapid urban development had reduced the channel capacity to a 5- to 10-year rainfall event [15–18.3 cm (6–7.3 in.) in 24 h] (Risk Management Solutions 2001).

The Gulf Coast is prone to severe flooding from land-falling tropical cyclones and associated extreme precipitation. Flat terrain, thick clay soils, and frequent, high-intensity, short-duration rainfall events contribute to large volumes of rainfall runoff and wide, shallow floodplains. Harris County has one of the highest rates of repetitive losses due to flooding in the United States [National Wildlife Federation (NWF) 1998]. Since 1964, 25 federal disaster declarations have been made for Harris County, the majority of which have been issued because of heavy flooding (FEMA 2011). The federal disaster declaration program is designed to provide local and state government with funds and assistance when their resources become inadequate to address the damage caused by a major disaster (i.e., flood).

On June 9, 2001, Tropical Storm Allison elicited a disaster declaration for Harris County. Damage estimates exceeded $5 billion,

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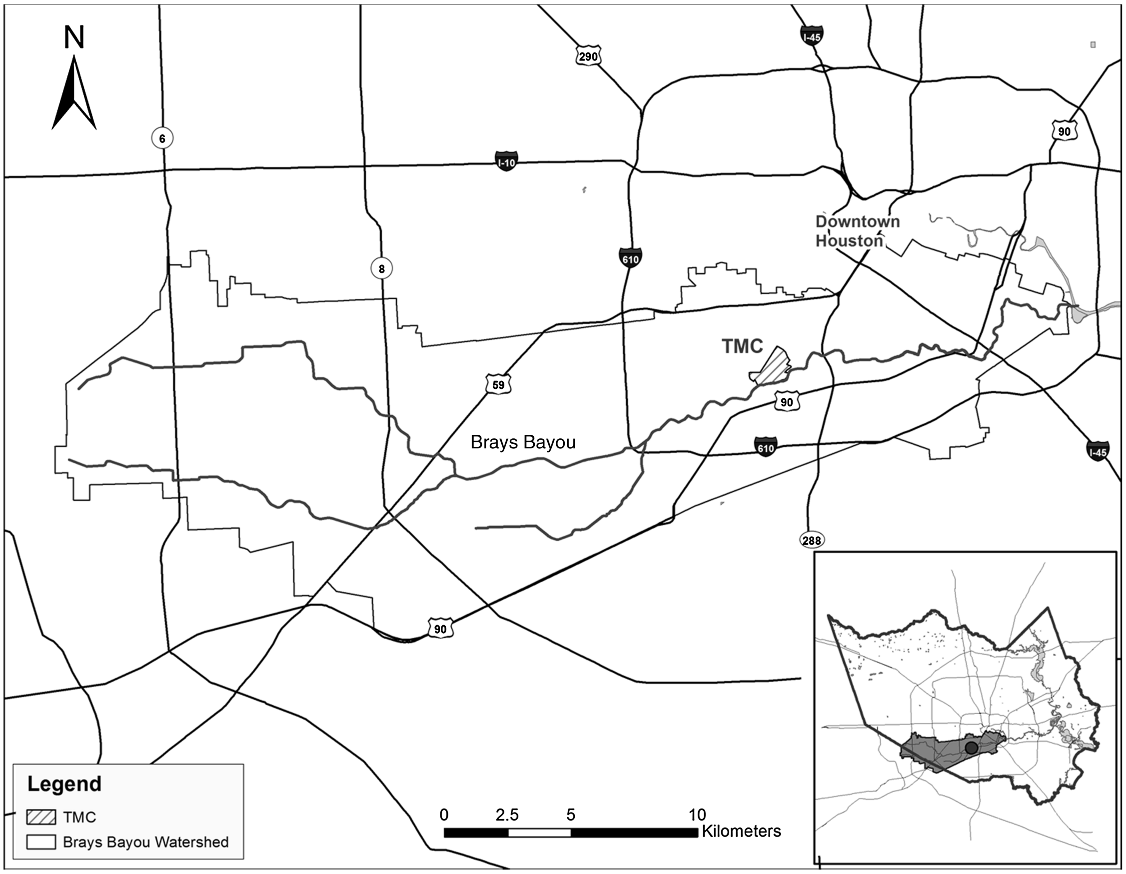

Fig. 1. Study area: the Texas Medical Center Campus and the Brays Bayou watershed [data from Harris County Flood Control District (HCFCD) 2010]

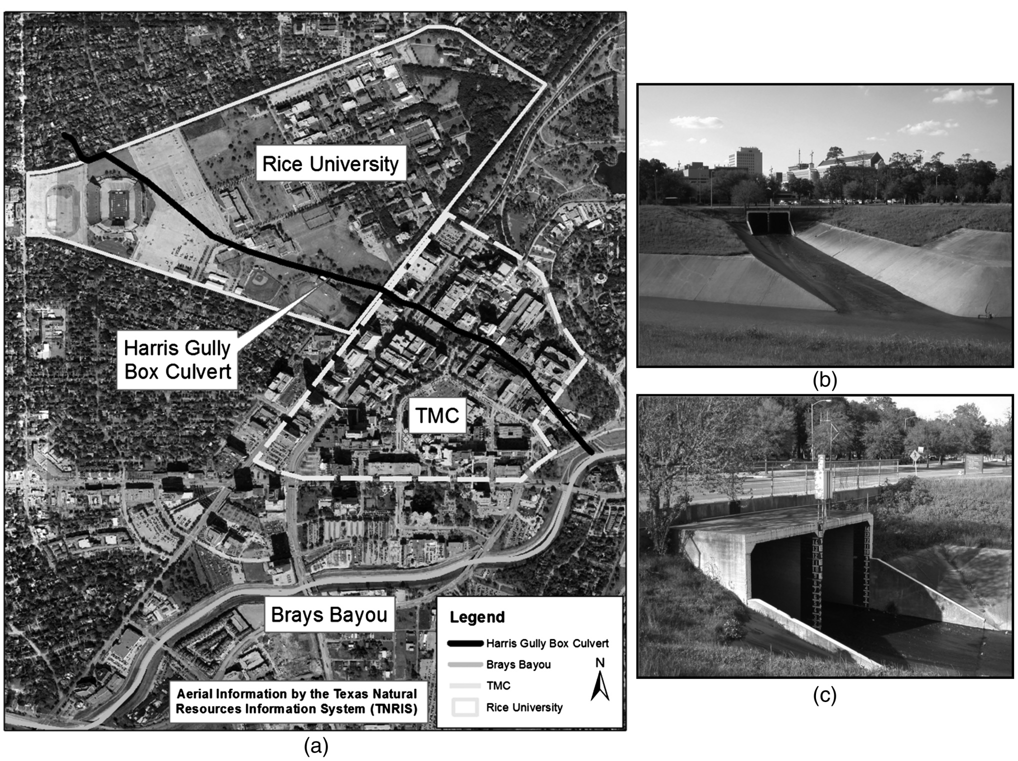

Fig. 2. Harris Gully area and its drainage pipe outlets [imagery and data from Texas Natural Resources Information System (TNRIS) 2013; images by authors]

making Tropical Storm Allison the costliest tropical storm in U.S. history (Blake 2011). The following section describes the impact of Tropical Storm Allison on the TMC and the measures that officials have taken to protect and upgrade the infrastructure to protect from future natural hazards.

Tropical Storm Allison

Tropical Storm Allison made landfall near Freeport, Texas, on June 5, 2001. Between June 5 and 9, the slow-moving storm circulated over the Houston-Galveston region, dropping concentrated amounts of rainfall in three distinct periods. Northeast of Houston, 93 cm (37 in.) of rain was recorded in 24 h [National Oceanic and Atmospheric Administration (NOAA) 2001], approximately equivalent to 80% of the region's average annual rainfall [121 cm (48 in.)] (HCFCD 2010) and more than the 500-year event rainfall calculated for the region (Risk Management Solutions 2001). FEMA reported that the storm dropped enough rain to meet the U.S. water demands for an entire year, or the equivalent of 121 billion m^3 (32 trillion gal.) of water (FEMA and HCFCD 2002). In addition, Tropical Storm Allison had the highest rainfall intensity recorded over a downtown area in the United States, which was one of the major reasons causing severe flooding in the downtown areas of Houston. The northeast Houston area received more than 60 cm over 17 h during the severe storm (Fig. 3).

Five of the six major bayous that drain Houston overtopped their banks, causing serious urban flooding. In Harris County, floods resulted in 22 fatalities and 73,000 damaged residences (FEMA and HCFCD 2002). TMC experienced this major flood on June 9, 2001, with a total rainfall of 37.4 cm (15 in.) within 12 h. (Bedient and Holder 2001). The TMC area that is located at the downstream of the bayou inevitably suffered from flooding during the storm. During the night of June 8, Brays Bayou began rising; predicted flows increased from approximately 425 m^3/s (15,000 cfs) to 765 m^3/s (27,000 cfs) between 11 p.m. and 2 a.m. At 2 a.m., just before power was lost, a Harris County Office of Emergency Management (HCOEM) gauge recorded 12.73 m (41.75 ft) at Harris Gully, or approximately 0.76 m (2.5 ft) above the top of the box. The water continued to rise after power was lost and high water marks indicate that maximum flood elevations reached approximately 1.5 m (5 ft) in the TMC and surrounding areas.

Much of the TMC was flooded via the vast tunnel system that connects the hospitals. Both primary and backup electrical systems

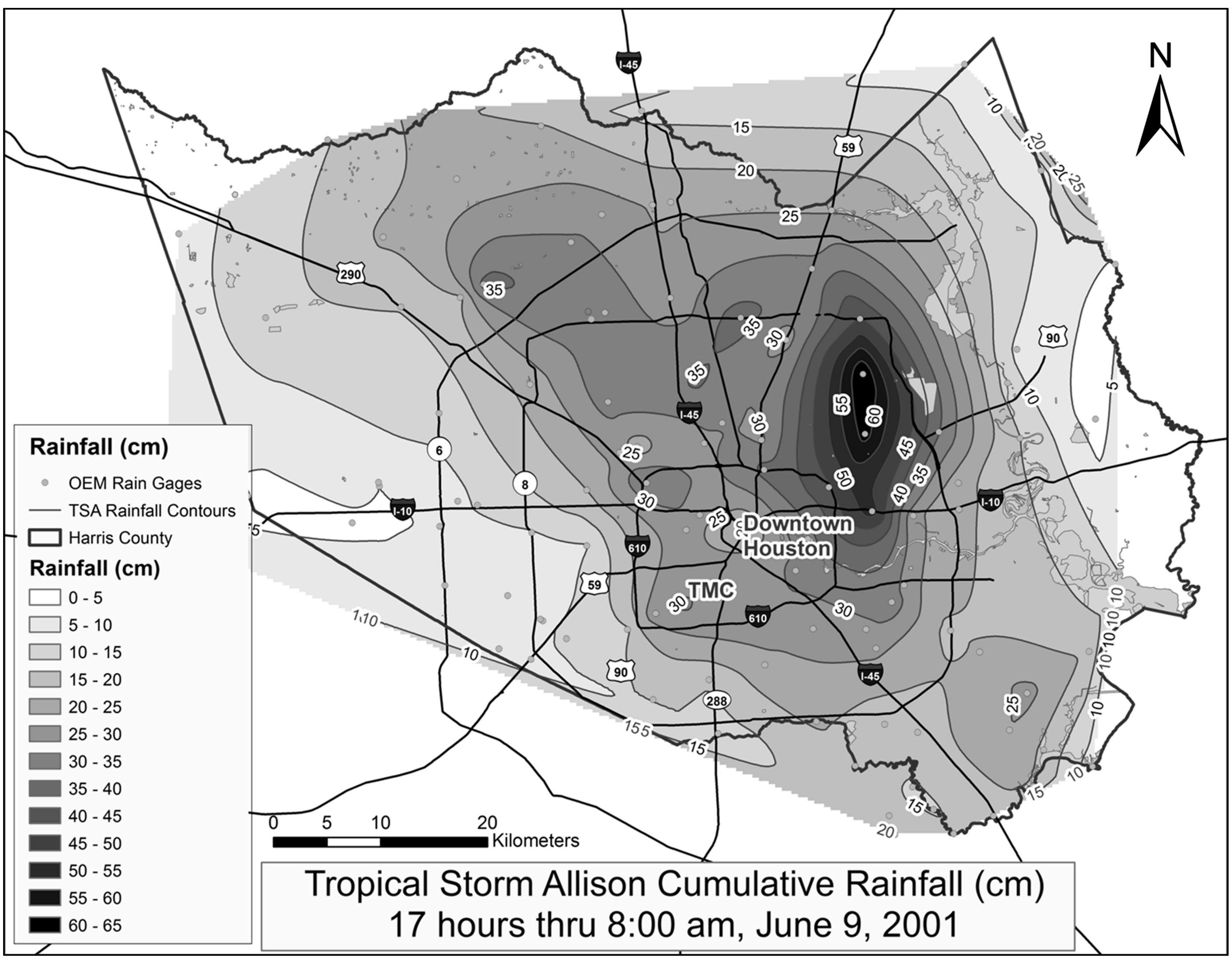

Fig. 3. Seventeen-hour cumulative rainfall contours for Tropical Storm Allison (June 2001) (data from HCFCD 2010)

Table 1. Summary of Damage to Selected TMC Institutions (Adapted from Risk Management Solutions 2001)

Institution name	Cause	Damage description	Damage estimate
Baylor College of Medicine	Basements flooded	Primary and backup power failed; critical storage freezers stopped; lost 90,000 research animals and 60,000 tumor samples	\$495 M
Memorial Hermann Hospital	Basements flooded to depths of 11.6 m (38 ft) through underground connections with other buildings and parking garages	Approximately 50% of water came from one tunnel connection; lost electrical infrastructure, HVAC, diagnostic equipment, morgue, and laboratories; \$60 million in cardiac care equipment damage; it took 4 days to pump water; evacuated 540 patients, all returned after 8 days; 18 months estimated for full recovery	\$433 M
Methodist Hospital	Water entered the Neurosensory building. Flood depths of 12 m (40 ft) in the basement	Damaged 27,871 m^2 (300,000 ft^2) of space; lost water, power, and air; discharged 400 patients and did not fully reopen for 5 weeks; 6 months estimated for full recovery	\$360 M
University of Texas Houston Medical School	The force of floodwaters collapsed unreinforced walls	Lost 5,000 research animals; normal operations restored after 1 month; \$68 million needed to retrofit and prevent future flood damage	\$205 M
St. Luke's Hospital	Second basement level had 2.4 m (8 ft) of water in one area; major flooding occurred in older buildings	Lost primary power; flood doors installed at tunnel connection to reduce damage; backup power for essential services was interrupted; critical patients relocated from older, less protected buildings	\$20 M
Texas Heart Institute	Research laboratories flooded	Pigs for artificial heart transplant tests drowned	\$16.6 M
M.D. Anderson Cancer Center	Minor flooding	Lost primary power	\$3 M

were lost when underground electrical stations were inundated. Without electricity for lights, refrigeration, air conditioning, running water, elevators, vital medical equipment, or life support and life safety systems, 9 of the 13 hospitals were closed and more than 1,000 patients were evacuated via helicoptor (TMC 2002). TMC suffered billions of dollars in damages and the loss of decades of medical research records and ongoing experiments, setting some medical research programs back decades (NOAA 2001). Table 1 shows the damages at many of the facilities within TMC; alone, Baylor, Memorial Hermann, and Methodist hospitals accounted for \$1.5 billion.

By all accounts, Tropical Storm Allison devastated the TMC, but the resolve to rebuild by all parties was resolute; billions of dollars were spent in and around the TMC to protect against future flooding. Although resiliency efforts were driven, in part, by increased FEMA standards, requiring flood prevention systems at critical care facilities to protect up to the 500-year level instead of the 100-year, the TMC went on to develop a hazard mitigation plan (HMP) that guided efforts to reduce future impacts of hazards on the TMC campus and the various medical, research, teaching, and support institutions.

Developing the TMC Hazard Mitigation Plan

At the turn of the century, the U.S. Congress passed the Disaster Mitigation Act of 2000 (DMA) requiring state and local governmental entities to develop hazard mitigation plans to better prepare for and reduce the potential impacts of natural hazards (FEMA 2002). The real strength of the DMA was its emphasis on a deliberate and methodical process for organizing resources, assessing risks, developing and implementing a mitigation plan that could be regularly updated and maintained. Although the TMC is a private organization and not required to follow the guidelines put forth in the DMA, the Hazard Mitigation Plan Report, developed by the TMC in the immediate aftermath of Tropical Storm Allison, documented a similar investigative process as laid out in the DMA to identify hazards that posed a risk to the TMC campus. It focused on storm-water management strategies and projects that could alleviate future flood hazards and resulted in identifying 42 priority projects in and around the TMC. In the end, the report made clear two important conclusions:

1. No one project or initiative will solve the flooding problems. Relief from long-term flooding problems will only come through the deliberate and consistent implementation of multiple projects at a variety of scales.
2. Hazard mitigation projects need to occur within the TMC as well as outside its geographic boundaries.

In some respects, the TMC's assessment of storm-water management strategies has served as a precursor to a much larger, comprehensive, and thorough investigation—the Texas Medical Center HMP, published in August 2003 (TMC 2003). The report characterized the full range of natural and artificial hazards that could impact the TMC and identified and prioritized projects to reduce the risks associated with such hazards. A risk assessment was performed to calculate the expected future damages to physical assets and people from natural and artificial hazards. The purpose of doing such an assessment was to get a baseline concept of what physical and operational elements of an organization might be damaged by hazardous events, and which potential damages might be most appropriate to address in the plan. This information formed the factual basis for making decisions about how to most effectively address the hazards and their effects in order to reduce or eliminate future losses.

Although the hazards of flooding and wind damage were well known, very little effort was invested into the process of objectively analyzing and characterizing them within a structured framework. This was the first time the TMC formulated a comprehensive mitigation plan that integrated research and analysis of hazards, development of a strategy to address vulnerabilities, and stakeholder priorities (TMC 2003). Consequently, it allowed the TMC to be eligible for federal disaster assistance and mitigation grant funds.

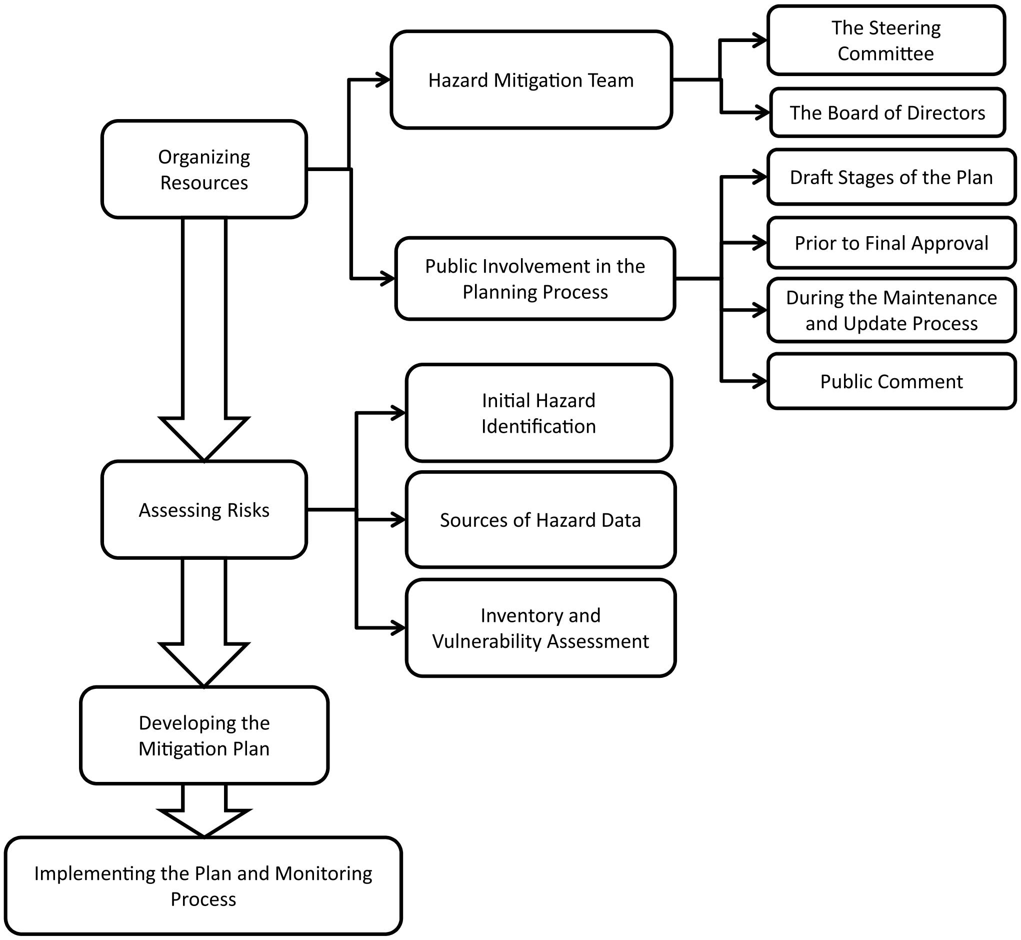

Fig. 4. Flowchart of four phases in the TMC Hazard Mitigation Plan: (1) organizing resources, (2) assessing risks, (3) developing a mitigation plan, and (4) implementing the plan and monitoring process

Four major phases of hazard mitigation planning were incorporated into the TMC Hazard Mitigation Plan as recommended by FEMA: (1) organizing resources, (2) assessing risks, (3) developing a mitigation plan, and (4) implementing the plan and monitoring progress. Fig. 4 shows a flow chart of these four phases in the TMC Hazard Mitigation Plan.

Organizing Resources

The first part of the hazard mitigation planning process was to organize resources, which occurs in two parts: (1) building the planning team and (2) engaging the public in the planning process. A hazard mitigation team (HMT) was established soon after Tropical Storm Allison in 2001 (FEMA 2002). The team was composed of four parts: senior TMC management, TMC Steering Committee, TMC Board of Directors, and TMC consultant. The senior management served as the hazard mitigation coordinator (HMC) and functioned as the primary decision-making group for the TMC and the point of contact for interaction with the consultant. The Steering Committee provided oversight and guidance throughout the process, giving feedback at status update meetings. The Board of Directors was responsible for reviewing and approving the plan. Local engineering firms were hired as the external consultants and provided technical input during the process.

Once a mitigation plan was drafted, the HMT presented the process, the schedule, and the anticipated benefits of the mitigation plan to a group of stakeholders, which is composed of representatives of TMC member institutions and local government and agencies like the City of Houston and the USACE (TMC 2003). The presentation included a discussion of the planning process, the risk and vulnerability assessments, the proposed mitigation actions, and the implementation and monitoring functions. The stakeholder group was invited to comment during the meeting and encouraged to contact the TMC and other members of the HMT with feedback prior to the final approval of the plan. The plan has remained dynamic and is continually updated to include new information. During the annual and 5-year maintenance and update process, the stakeholders were again invited to review and comment on the hazard mitigation progress.

Assessing Risks

Hazard mitigation planning is intended to provide a systematic approach to researching and analyzing the natural and artificial events that can impact a given system. Risk assessment is the most important part of the mitigation planning process. It requires the calculation of expected damages to physical assets and people from a natural or artificial hazard. The information gained during this process forms the factual basis for determining how to most effectively plan for a hazard with the objective of reducing or eliminating its impact.

By nature, hazardous events are very difficult to predict, and often millions of dollars are invested to prevent or reduce the impact of a hazard that never occurs. Therefore, it is critical to focus on hazards that are not only severe, but more likely to occur than others. As a part of the risk assessment conducted for the HMP, the TMC campus and surrounding areas were studied extensively and the existing studies and documentation were reviewed.

More than 100 hazards were identified at the TMC ranging from hurricanes to earthquakes to terrorism. However, the majority of the hazards were related to flooding, and as a result emergency managers focused their hazard identification and risk analysis efforts on flooding. The risks posed by the various possible hazards were narrowed down to three general kinds: physical damage to structures and other physical assets, interruption to the facility operations, and casualties and injuries to people.

Developing a Mitigation Plan

In the third phase of the hazard mitigation planning process, the TMC's HMP was officially published in October 2003. The plan included four major elements: developing mitigation goals and objectives, identifying and prioritizing mitigation measures, preparing an implementation strategy, and documenting the mitigation planning process. This plan was intended to meet FEMA and State of Texas requirements. With this unprecedented mitigation plan, the TMC was able to implement many infrastructure improvment projects to enhance its resilience on the campus.

Implementing the Plan and Monitoring Progress

Once the TMC formally adopted the plan in October of 2003, the HMT began implementing the priority mitigation actions for certain hazards. By closely monitoring the progress and implementation of the plan, the TMC has developed a procedure for updating and amending the plan.

One of the very first implemented plans was to increase flood protection and warning capability for the TMC area. In the aftermath of Tropical Storm Allison in 2001, FEMA funded Rice University to expand and enhance an existing radar-based flood alert system (FAS) to provide additional flood warning and awareness to the TMC (Bedient et al. 2003). This system was tested with good performance during Tropical Storm Allison by warning the TMC emergency personnel several hours before the main flooding occurred (Fang et al. 2011). The flood warning system archived the radar rainfall information as the only complete record of the event due to the loss of power at many rain gauges over the area.

Later in 2008, with the increasing awareness of recent hurricanes' devastating impacts on many coastal areas, the TMC started assessing the storm surge vulnerability on its campus due to its relative geographical location to the receiving bayous. One of the projects was performed to evaluate combined risks of inland flood and coastal surge for the TMC campus using the most current light detection and ranging (LiDAR) information and updated hydrologic and hydraulic models for the TMC campus. Not only does this particular study show vulnerable locations within the campus, but it also demonstrates the enhanced resilience from many infrastructure improvements implemented after Tropical Storm Allison in 2001. The following section introduces several flood hazard prevention measures implemented within the TMC campus.

Flood Hazard Prevention Measures

Prior to Tropical Storm Allison, the TMC had experienced multiple severe flood events and the campus flood characteristics were fairly well understood. Subsequently, many of the institutions had taken individual flood protection measures; however, as a whole the TMC had remained vulnerable to the effects of flooding. During the development of the HMT, the TMC began a number of flood mitigation efforts, most or all of which were designed to protect the facilities to the 500-year flood elevation, although there was extensive discussion whether TMC should be protected to 100-year or 500-year levels. Finally, the 500-year level became the widely accepted standard for critical facilities. To achieve additional protection from flood, the TMC implemented major improvements in four areas:

1. Hydrologic Infrastructure:
   a. Storm drainage systems were improved at many local streets in and around the TMC area. Underneath several major roads (Kirby, Hermann, and Cambridge), the TMC has installed large-sized culverts diverting water away from the TMC into Brays Bayou. This project significantly lowered flood levels within TMC (Bedient et al. 2007). Figs. 5 and 6 show the difference before and after the storm-water improvement projects.
   b. More than 50 watertight flood doors and gates were installed throughout TMC, especially in the tunnel systems (Fig. 7). The flood doors were mainly implemented to protect many hospitals that are connected by the tunnel systems from flooding. These manually operated systems were designed to work individually and/or in coordination with various facilities within the TMC. Exterior perimeter floodwalls, berms, and barriers were constructed to protect facilities up to the 500-year flood level.
   c. In order to reduce flood levels, Brays Bayou is being widened from the TMC area to the Houston Ship Channel in various stages of construction (Fig. 8). Four storm-water detention facilities that will hold approximately 13.2 million m^3 (3.5 billion gal.) of storm water and cover approximately 3.6 km^2 (900 acres) are being constructed along Brays Bayou by the HCFCD, and drainage enhancements like channel and bridge modifications are being added to the main channel (Project Brays 2013).
2. Accessibility
   a. Access to the TMC during high-water events was improved by establishing a new Cambridge Street route to and from the TMC over the Richard Wainerdi Bridge,

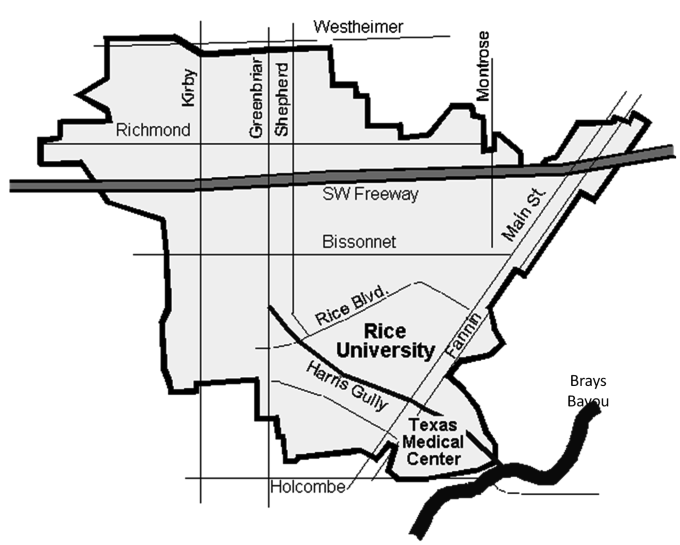

Fig. 5. Historic storm-water systems in Harris Gully (data from HCFCD 2010)

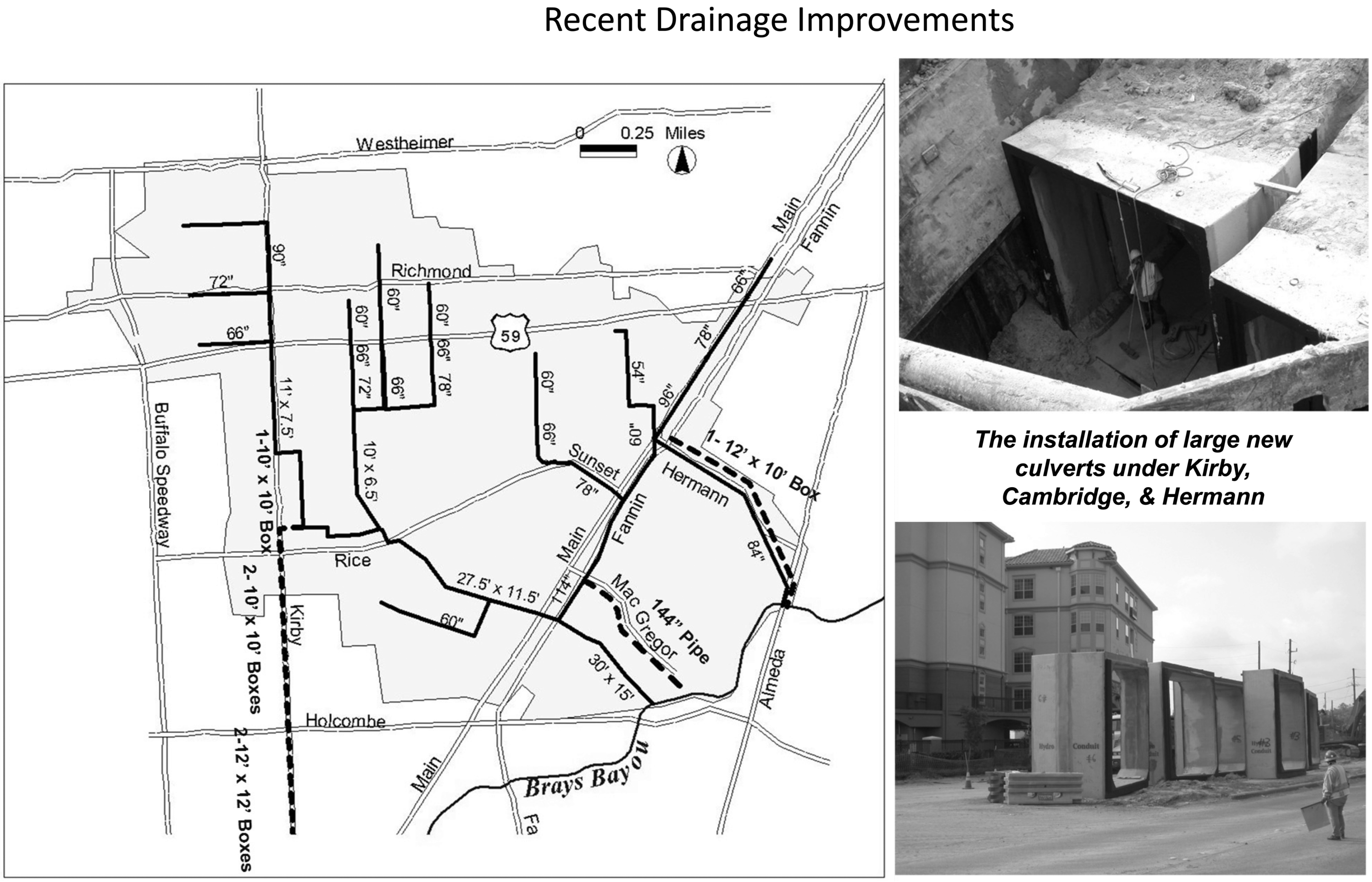

Fig. 6. Current storm-water systems in Harris Gully (data from HCFCD 2010; images by authors)

Fig. 7. Recently installed flood gates to keep flood water from getting into some low-lying areas on the TMC campus (images by authors)

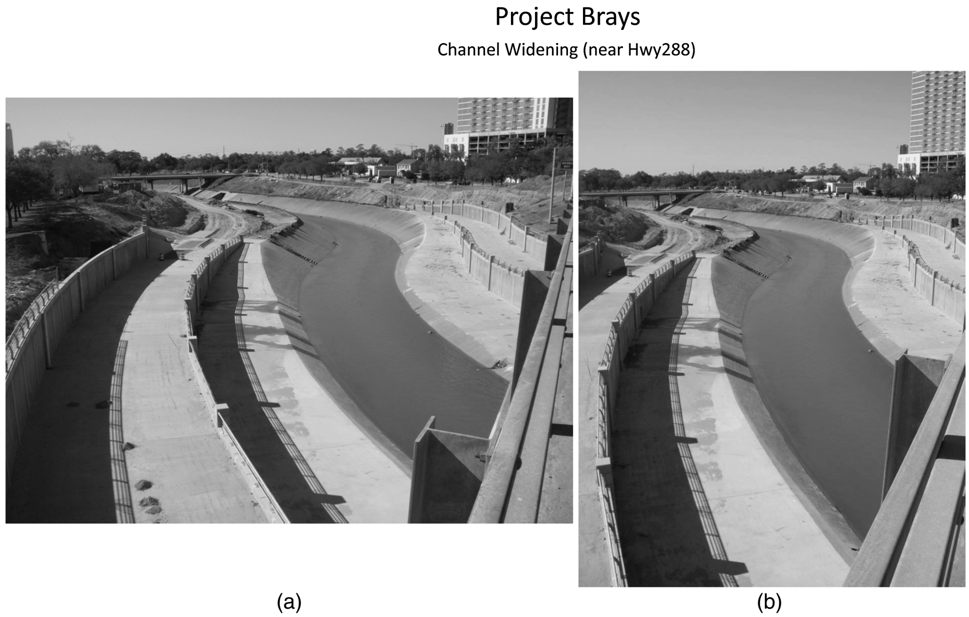

Fig. 8. Widened channel section near Highway 288 crossing Brays Bayou as an example of implementing hydrologic and hydraulic infrastructure to reduce flood levels for the Texas Medical Center campus (images by authors)

and by elevating North and South MacGregor roads, which allows drivers to access the TMC from State Highway 288.

b. Sky bridges that allow pedestrians to walk above ground from building to building have been constructed in many areas in the TMC (Fig. 9).

3. Utilities

   a. Electrical equipment, lab animals, and research experiments were relocated from basements to upper floors in order to protect against the 500-year flood.

   b. Thermal Energy Corporation's capacity to provide steam and chilled water to TMC institutions was recently doubled, and its location was protected with perimeter flood walls and gates above the 500-year flood elevation.

   c. Two backup substations to support the CenterPoint Energy and Grant Substation were built to supply electricity to the TMC.

Fig. 9. Major sky bridge built to allow pedestrians to walk above ground from building to building in the Texas Medical Center (image by authors)

   d. Telecom cell towers were placed on the roofs of several TMC garages to improve and sustain communications.

4. Management

   a. The TMC adopted the new standards as required by FEMA that critical care facilities need to protect their facilities against a 500-year flood event.

   b. The TMC is now included in the City of Houston's and Harris County's annual hazard mitigation plans.

   c. A Texas Medical Center Flood Management Group in 2003 was formed to protect the integrity of the tunnel system, which connects several major facilities from flooding.

   d. The TMC/Rice Flood Alert System, which monitors rainfall and the water level in Brays Bayou and provides early flood-warning predictions to the emergency personnel, has been upgraded based on the funding from FEMA. The state-of-the-art system provides a focal point for many TMC institutions to watch approaching storms and disseminates rapid response to the events in a coordinated fashion. TMC personnel are trained annually on using the systems and upgrades.

Hazard Mitigation Grant Program

Table 2 shows a list of the selected Hazard Mitigation Grant Program (HMGP) Section 404 projects in the TMC with a brief description, location, the estimated cost, and the hazard mitigated by each project. After a major disaster, the HMGP provides up to 75% of eligible damage costs. The funds are generally determined as a percentage of federal assistance for repairing public infrastructure, emergency support, and aid to individuals. Section 404 in the HMGP allows FEMA to contribute an additional 15% to mitigation measures that are cost effective and that will substantially reduce the risk of future damage, hardship, loss, or suffering.

The most expensive project was to improve the storm-water system serving the TMC area at a cost of $61 million. The renovations at the M.D. Anderson Hospital amounted to approximately

Table 2. Major Improvements to the TMC

Project titles	Project description	Highest estimated cost	Project location	Hazard protection
Mitigation plan	Develop a hazard mitigation plan	$500,000	University of Texas Health Science Center	Flood
Electrical equipment improvement	Improve, elevate, or relocate electrical equipment	$5,823,125	M.D. Anderson, Jones Clinic	Flood
Mechanical equipment elevation	Replace and elevate mechanical equipment	$3,944,693	M.D. Anderson	Flood
Telephone switch relocation	Relocate telephone switch above grade	$1,235,000	Memorial Hermann Southwest Hospital	Flood
Power grid disconnect	Power grid disconnect at surface level to shut down service to single facility rather than entire grid	$250,000	St. Luke's Hospital	Flood
Emergency power distribution equipment relocation	Relocate emergency power distribution equipment to above based flood elevation (BFE)	$1,495,000	St. Luke's Hospital	Flood
System relocation	Relocate date center and network communication above flood line	$3,130,000	Memorial Hermann Northwest Hospital	Flood
Fuel storage tank replacement	Replace existing underground fuel storage tank with above-ground unit	$191,412	Memorial Hermann Southwest Hospital	Flood
Detention pond	Enlarge existing detention pond	$1,329,163	Memorial Hermann Southeast Hospital	Flood
Flood gates	Install flood gates to entrances to basement area	$175,000	Hospice at the TMC	Flood
Submarine doors	Install submarine doors and reinforce tunnel walls	$1,800,000	Memorial Hermann Southeast Hospital	Flood
Flood wall	Build perimeter flood wall	$7,631,250	MD Anderson	Flood
Flow channel improvements	Improve existing overland flow channel to detention pond	$868,000	Rice University	Flood
Storm water improvement	Improve storm water systems including storm sewers, pumps, etc.	$61,000,000	City of Houston	Flood
Storm resistant roof system	Install new storm resistant roof system	$800,988	San Jacinto Methodist Hospital	Flood
Flood alert system	Enhance flood alert system for rice and TMC Campus	$300,000	Rice University	Flood

$17.4 million, the most spent at any one facility. Almost $9.8 million was allocated to improve, elevate, relocate, and replace electrical and mechanical equipment at the M.D. Anderson Hospital and an additional $7.6 million was allocated to build a flood wall around the facilities that could not be elevated above the floodplain. Similar flood reduction improvements were made at other facilities. In addition, FEMA allocated $300,000 for enhancing an existing flood warning system to provide timely and accurate information to the campus under severe weather conditions.

Rice and TMC Flood Alert System

Flood warning systems are one type of nonstructural flood protection. They have been widely adopted in the TMC because they initiate preventive measures that can help reduce the risk of damage and loss of life in the case of an impending flood (Bedient et al. 2003; Fang et al. 2008). Flood warning systems have advanced quickly in research in many countries around the globe in light of large floods in recent years (Bedient et al. 2000, 2003; Arduino et al. 2005; Moore et al. 2005; Fang et al. 2008; Mukhopadhyay et al. 2009). Moore et al. (2005) concluded that provision of flood forecasting and warning systems with effective mechanisms of dissemination and human response can yield significant benefits through forewarning of imminent flooding, allowing timely evacuation, relocation of valuables, and management of affected infrastructure.

Since 1998, the Rice and TMC FAS has successfully provided flood warning during more than 50 storm events. This advanced system has evolved through three generations and has played an important role in flood warning and flood control aspects for the TMC. Innovative for its time, the original FAS used radar rainfall and snapshots of water levels in Brays Bayou to predict peak flows and provide up to 3 h of lead time for emergency evacuation (Fang et al. 2008, 2011). The lead time takes into account the travel time from the most upstream of Brays Bayou to the confluence point near TMC. However, Tropical Storm Allison highlighted the need for an enhanced system coupled with an appropriate management strategy.

The TMC and Rice University worked together to develop and improve the system after Tropical Storm Allison. Bedient et al. (2003), Vieux and Bedient (2004), and Fang et al. (2008) presented the second generation of the radar-based flood alert system (FAS2) with evaluation of the system performance during three rainfall events in 2006. Recently, the system has been upgraded to its third generation (http://FAS3.flood-alert.org), which incorporates a hydraulic prediction tool: Floodplain Map Library (FPML). The FPML, a geographical information system (GIS) framed system, can be provided to emergency personnel in real time using Google Maps (Fang et al. 2011). Fang et al. (2011) states that FAS generally performs with average differences of 0.88 h in time of peak and 3.6% in peak flows and R^2 of 0.90 for the overall performance among 11 major rainfall events since 2002. Moreover, this web-based system has an advanced communication module that automatically informs emergency personnel who initiate emergency response. This state-of-the-art system has saved millions of dollars in flood damages for the TMC over the years and serves as a prototype for similar systems in other flood-prone areas.

Summary and Conclusions

In most respects, the impacts from Tropical Storm Allison have been enduring. It served as a wake-up call to managers who originally viewed flooding as a problem that could be solved through mitigation at individual facilities. Management's thinking was insular and focused on the point of intersection between their individual building and the flood. Flood issues are rarely simple and clear cut. Instead, they require a strategic perspective, one that sees the problem in context of a larger set of interdependent and interrelated variables. To do this successfully, a systems management framework was required and eventually evolved within TMC.

One example of successful responses during the event is from Texas Children's Hospital. They relied upon the early warnings to greater extent than any other institution and their damage was less than their peer institutions by a large factor. Randy Right, chief operating officer (COO), Texas Children's' Hospital, attributes it to the management team's extension of the fire safety strategy called *defend-in-place* to flooding. Defend-in-place refers to an occupant-protection strategy that is employed when a person cannot be moved out of the building (i.e., patient on life support equipment). It calls for designing buildings with measures that isolate and protect occupants from threats by installing protection systems such as automatic sprinklers and/or air-tight doors. Texas Children's Hospital did have flood doors installed in their basement and they were closed in a timely manner, blocking the flow of water into the hospital. Modern systems thinking approach within the TMC has allowed a coordinated effort to respond to potential threats of flooding for the institution (McGlown and Robinson 2011).

The HMP created in the wake of Tropical Storm Allison embodies a transformational change in the way the TMC management views flooding. For the first time, the problem of flooding is not seen as a discrete facility problem, but one over the entire watershed. The plan's risk assessment methodology describes how consultants sought to understand the root causes of flooding and the secondary and tertiary effects of various structural and nonstructural mitigation strategies regardless of its location on or around campus. By looking at the interconnectivity of hazards, managers began to understand how drainage worked and to see their problem in the larger context of a watershed problem. The hazard mitigation planning process forced managers to think beyond their immediate area to look for casual relationships beyond their immediate area. Table 2 lists many of the connected improvements made to the TMC over the past decade in response to Tropical Storm Allison. To many practitioners and emergency managers, the planning process and experience that the TMC has gained after this devastating event can be applied to many other similar cases nationally and globally.

Over the past decade, the TMC has experienced tremendous growth. Since 2001, an estimated 15,000 new employees and more than 1.1 million m^2 (12 million ft^2) of space have been added. Looking back at Tropical Storm Allison and the way managers responded, it is clear that long-term thinking about flooding has evolved. Robert Stott, former TMC executive vice president and chief operating officer, regularly reflects on the impact of Tropical Storm Allison: "every hurricane season I worry about our ability to deal with the next big one . . . .and how vulnerable we are. We know another storm like this will happen again because it's the nature of where we live, so we can't become complacent. Mother Nature cannot be second-guessed" (R. Stott, personal communication, 2011).

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