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Evaluating the Effects of Project Brays Mitigation Using Unsteady HEC-RAS Hydraulic Modeling: Application to Meyerland in Houston, TX

By

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ABSTRACT

Repetitive flooding has devastating consequences on human lives and property annually in cities. The Brays Bayou watershed is one of the most repetitively flooded urban watersheds in the US. Project Brays, a two-decade-long, $480 million regional flood mitigation project, sought to alleviate flooding in Brays Bayou watershed with channel widening as one of its main components. Though the watershed has been studied extensively for its vulnerability to flooding, no study has ever evaluated the effects of Project Brays’ channel modifications with actual channel design configurations. Meanwhile, while there has been some general estimation of Project Brays’ effects, none focuses on Meyerland, one of the most flood-prone neighborhoods inside the Brays Bayou watershed. To fill this knowledge gap, this study evaluates the effects of Project Brays’ channel widening focusing on Meyerland via modeling with actual channel configurations.

This study first combines Harris County’s HEC-HMS and HEC-RAS models of the Brays Bayou watershed and incorporates the new Project Brays channel configurations. This approach makes it possible to compare the change in the flood depth, extent of flooded area and number of houses flooded before and after channel widening for a variety of design storms. We found that the channel widening has alleviated flooding upstream of I-610 but has created additional flooding in some areas downstream of I-610 due to the increased conveyance for all four design storms tested. Driven by this unexpected result, we propose a detention opportunity, in which two golf course properties immediately upstream of Meyerland are converted to detention basins to reduce flooding. Our modeling shows that detention has better flood mitigation effects than Project Brays’ channel widening does. Finally, based on the Meyerland case, we recommend the optimal flood mitigation strategies for similar flood-prone neighborhoods in the US.
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Chapter 1

Introduction

Flooding is the deadliest natural disaster in the US, according to National Oceanic and Atmospheric Administration (NOAA) (Smith, 2020). Over a hundred people die annually due to flooding. Furthermore, economic damages caused by flooding in the last 10 years average $9.7 billion in the US. Urban flooding is a type of flooding that tends to occur in cities where the topography is flat, the land is highly developed, and the extreme rainfall events are frequent. Houston, Texas, a metropolis located near the northwest side of the Gulf of Mexico where extreme rainfall is likely to form, qualifies for all the above requirements to have frequent urban flooding.

In the past two decades, Houston was severely flooded during Tropical Storm (TS) Allison (2001), Hurricane Katrina (2005), Memorial Day Flood (2015), Tax Day Flood (2016), Hurricane Harvey (2017), TS Imelda (2019), and TS Beta (2020) (Smith et al., 2020). Out of the above, Hurricane Katrina (2005) and Hurricane
Harvey (2017) have caused damage of $170 billion and $131 billion (2020 value), ranking top 2 of all tropical cyclones that has impacted the US (Blake et al., 2020). The frequency and intensity of Houston being repetitively flooded indicates Houston needs flood mitigation immensely.

1.1. Meyerland

The Meyerland neighborhood is one of the most flood-prone neighborhoods in Houston. Located in southwest Houston along the Brays Bayou, Meyerland has over 800,000 households with 2 million population. In Meyerland, the median household income is $81,408, compared to the average of $46,187 in Houston (COH, 2015). Regardless of it being a wealthy neighborhood, it was heavily damaged by repetitive flooding, with over 5,500 houses flooded during Harvey 2017. Figure 1.a shows Meyerland flooded during Harvey (Houston Chronicle, 2017).

![Figure 1.a: Flooding in the Meyerland Neighborhood During Harvey (Houston Chronicle, 2017)](image)
Meyerland suffered from repetitive flooding throughout the past two decades. Tropical Storm Allison in 2001, Memorial Day Flood in 2015, Tax Day Flood in 2016, and Hurricane Harvey in 2017 all did severe damage to Meyerland. In the past decade, many homeowners in Meyerland have taken actions including elevating homes to avoid being repetitively flooded.

Meyerland is selected as the area of focus of this study for three reasons: 1. It is repetitively flooded by riverine flooding; 2. Being a high-income neighborhood, Meyerland houses have high prices and suffers from huge loss when flooded; 3. Living in a historical neighborhood, Meyerland residents are reluctant to move away from the neighborhood, and therefore buyout is not an option (Atoba et al., 2021). Therefore, a flood mitigation project that does not involve buyout, such as Project Brays, is desperately needed in Meyerland.

1.2. Project Brays

The Brays Bayou watershed is one of the most flood-prone watersheds in Houston. Every one out of four households in the watershed are inside the new 100-year floodplain in the Brays Bayou Watershed. The Brays Bayou Flood Damage Reduction Project, commonly known as Project Brays, is a $480 million regional flood mitigation project. It encompasses three main parts: the widening of 12 channel segments, the construction of 4 detention basins, and the modification of 32 bridges. All three parts of Project Brays are reviewed in detail in Section 2.2.
This study focuses on the channel widening component of Project Brays to examine the effects of channel widening in a highly developed watershed with neighborhoods that are repetitively flooded by fluvial flooding. The reasons why Project Brays’ detention and bridge modifications are not the focus of this study are explained in 2.2.

### 1.3. Detention Opportunity at Two Golf Course Locations

**Upstream of Meyerland**

Aside from Project Brays’ four detention basins that provide limited direct flood mitigation effects on Meyerland, we also looked at an alternative scenario where two extra stormwater detention basins are added at two locations that can likely affect Meyerland directly.

These two locations are Braeburn Country Club and Westwood Golf Club, with 166 acres and 161 acres in area, respectively. (Figure 1.b) Braeburn Country Club is located downstream of Gessner Road and upstream of Fondren Road, and Westwood Golf Club is located downstream of Beechnut St and upstream of US-59.
With large land adjacent to the Brays Bayou upstream of Meyerland, these two locations provide ideal detention basin sites for the repetitively flooded downstream neighborhoods such as Meyerland. With proper inflow/outflow inline structure designs, the detention basins can capture flood water when the flow in the channel is at its peak and prevent the captured water from further flooding the downstream neighborhoods, including Meyerland. This opportunity is further explored in Section 3.2.2 of this thesis.

In this study, a total of 16 floodplain maps are generated in this study for four scenarios (Before, Middle, Completion, Detention) in four design storm events (old 100-year, old 500-year, Atlas 14 100-year, Atlas 14 500-year). Besides serving as the foundation of the comparison of channel widening and detention in this study, the updated floodplains maps generated from this study not only help flood alert
systems make accurate predictions, but also help developers and homeowners to make better decisions about where and how to build new constructions.

1.4. Objectives

This thesis seeks to evaluate the flood mitigation effects of Project Brays, a $480 million regional flood mitigation project which spanned from the 1990s to 2022, with a focus on the Meyerland Neighborhood in Houston, TX, by performing hydrologic and hydraulic modeling in HEC-HMS and HEC-RAS, the most widely used pair of hydrologic and hydraulic modeling tools in the US. From studying Project Brays’ channel widening, the initial key question that this thesis aims to answer is: What are the effects of channel widening in a highly developed watershed with repetitive fluvial flooding?

Later, driven by the less-than-satisfying results of the effects of channel widening, we also propose the opportunity to add detention at two golf courses upstream of Meyerland for flood mitigation. This brings up our second objective: to evaluate the effect of detention that is immediately upstream of a repetitively flooded neighborhood. Combining these two objectives, our goal is to provide insights for future planners, administrators, and engineers for flood mitigation in similar watersheds and neighborhoods.
1.5. Thesis Structure

After the introduction in Chapter 1, we proceed to background and literature review in Chapter 2, in which we review the increasing rainfall and flooding in Houston, Project Brays, previous work related to the Brays Bayou, the Flood Alert System (FAS) on Brays Bayou, previous studies on flood damage and flood risk, and hydrologic and hydraulic modeling in the US.

Chapter 3 describes the methodology used to model Project Brays' channel widening, including details of the model setup and simulation processes. We demonstrate how we applied changes of Project Brays to the M3 HEC-HMS and HEC-RAS models (see description in literature review), which are the publicly available hydrologic and hydraulic models provided by HCFCD. We also explain the peak-shaving technique that we used to model the effects of our proposed detention basins at the golf course locations.

In Chapter 4 we validate the HEC-HMS and HEC-RAS models with the recent triple-peak Tropical Storm Imelda in 2019. The models are proved to be valid with high NSE scores and with two of the three peaks have been closely matched. It is a good match that is unusually seen for a triple-peak event.

In Chapter 5 we analyze the results of modeling to evaluate the effects of Project Brays. We share our discovery that channel widening decreased flooding upstream of I-610, but also created additional flooding downstream of I-610. We also compare our modeling results of the detention at the two golf course locations.
with that of Project Brays’ channel widening, and share our finding that detention has better flood mitigation effects.

In Chapter 6 we conclude the study and make recommendation for flood-prone neighborhoods that are like Meyerland, as well as for future work.
Background and Literature Review

2.1. Increased Flooding in Houston, Texas Due to Extreme Rainfall and Urbanization

Houston has been severely flooded repeatedly in the last two decades. In 2001, Tropical Storm (TS) Allison hit Houston, causing a total of $5 billion-worth damage in the Harris County (FEMA, 2020). The Texas Medical Center (TMC) on the Brays Bayou alone has had $1.5 billion in damage, loss of decades of research, and had patients’ lives at risk (Fang et al., 2014). We will review more about the impact of TS Allison at the TMC in the subsequent 2.4 section. In response to TS Allison, the Federal Emergency Management Agency (FEMA) partnered with Harris County
Flood Control District (HCFCD) to launch the Tropical Storm Allison Recovery Project (TSARP). It remapped 1,200 stream miles in 22 watersheds of Houston, with the scope of the model covering 35 communities that were flooded during TS Allison (FEMA, 2020).

TS Allison was only the beginning of Houston’s 20-year long history of flooding. In 2008, Hurricane Ike hit the Gulf of Mexico, with Houston being impacted by both strong winds that caused power loss and flooding. In 2015, 2016, and 2017, Houston was severely flooded annually by major flood events. (Smith et al., 2020) In 2015, during the Memorial Day Flood, Houston received as much as 11 inches of rain, causing flooding of over a thousand homes in the Brays Bayou Watershed alone (Bass, 2017). In 2016, the Tax Day flood dropped over 17 inches in Houston, which lead to severe flooding again (Holmes et al., 2018). The unprecedented Hurricane Harvey hit Houston, TX with severe flooding in 2017, leaving behind damage worth $125 billion (unadjusted value), matching the historic high of Hurricane Katrina (Smith et al., 2020).

In 2018, in response to the series of extreme storm events in the past decades, NOAA published the new Atlas 14 Volume 11 rainfall standard for Texas, where the frequency rainfall is re-calculated based on updated past rainfall events and a new statistical methodology named L Moments. Atlas 14 concluded that overall, there has been a trend of increased number and intensity of increased rainfall in southeast Texas. Big cities in southeast Texas such as Houston, Austin, San Antonio, and Corpus Christi all experienced increases of 100-year rainfall intensity
from 10% to 40% (Perica et al., 2018). Figure 2.a shows the increase in the new Atlas 14 rainfall compared to the old TP40 rainfall in Texas, indicating that the 100-year, 24-hour frequency rainfall has increased in most of Texas including Houston.

![Figure 2.a: Atlas 14 VS TP40 for 100-year, 24-hour rainfall, where green shows where Atlas 14 rainfall is higher than the TP40 rainfall, with Houston in the green zone. (Source: Perica et al., 2018)](image)

In the online precipitation frequency (PF) estimate tool by created NOAA, the new 100-year, 24-hour rainfall has increased from 13 inches to 17 inches, which is the previous 500-year 24-hour rainfall level, in Houston. In other words, the probability for the previously 500-year (0.2% probability) rainfall level has increased to 100-year (1% probability), indicating the increasing likelihood of Houston flooding from extreme rainfall events. In response to the publishing of Atlas 14, the Harris County Flood Control District (HCFCD) published its guidelines in 2019 to update its drainage policy procedure and criteria (HCFCD, 2020). The
publishing of the document marked that Atlas 14 has become the core of new flood management criteria to be complied within Harris County.

Urban Flooding was extensively studied due to its importance and damage in flood-prone cities like Houston. Highly developed urban areas are more prone to flooding. This is because urbanization can increase flooding in three ways. First, urbanization increases imperviousness, which is positively related to the volume of rainfall converted to overland flow during a storm event. Second, in urbanized areas, turf replaces natural vegetation, which reduce the infiltration capability of soil, and increases overland roughness (Garner, 2020). Third, drainage density increases with urban development, leading to faster accumulation of stormwater with the high conveyance rate of pipes and channels in an urban setting (Gori, 2018). Figure 2.b shows the impacts of urban development in runoff hydrographs in a watershed due to increased drainage density (Bedient et al., 2019).
Figure 2.b: Increased drainage density changes the watershed’s response to rainfall events by making the flow peaks higher and peak time faster. Adapted from (Bedient et al., 2019)

Brody et al. (2008) calculated property damage result to identify that flood damage is impacted by environment factors such as wetland alteration and impervious surfaces, both of which are largely affected by urbanization. In 2014, from flood insurance data analysis, it was further concluded that surrounding Land Use and Land Cover (LULC) has an impact on flood losses (Brody et al., 2014). In 2019, Sebastian et al. found that in Houston, urban development increased the peak discharges by 54% (±28%) alone, while climate change increased peak discharges by 20% (±3%). Peak discharges in Houston increased by 84% (±35%) with effects from urban development and climate change combined (Sebastian et al., 2019).
2.2. Project Brays

The Brays Bayou watershed is among the most frequently flooded watersheds in Houston. The Brays Bayou Flood Damage Reduction Project, commonly known as Project Brays, is a joint effort to reduce flood damages in the Brays Bayou Watershed by the US Army Corps of Engineers (Corps) and the Harris County Flood Control District (HCFCD) (HCFCD, 2021). Though it was originally proposed by the Corps in 1988, HCFCD took over the planning and implementation of Project Brays in 1998 and signed the Project Cooperation Agreement (PCA) for the upstream Brays Bayou in 2000 and the downstream Brays Bayou in 2010. A large portion of Project Brays was completed after Hurricane Harvey in 2017, which drove the issuance of the necessary funds to finish the project.

Overall, there are three major components of Project Brays: channel widening, detention, and bridge modifications. The details of each component are reviewed in the following text (2.2.1 – 2.2.3).

2.2.1. Channel Widening

The channel widening work of Project Brays is the focus of hydrologic and hydraulic modeling of this study. Channel widening focuses on creating extra volume inside the channel of Brays Bayou by excavating the upper half of the channel. It starts from where the Brays Bayou converges with Houston Ship Channel and goes all the way upstream to Fondren Road. That part of the Brays Bayou channel is depicted in the Figure 2.c below by colors purple, green and orange for its
status when this map was created in 2015. In 2007, the channel widening work started from the most downstream segment near the Houston ship channel. The last segment was finished in 2020.

![Map of Project Brays Overview](image)

Figure 2.c: Project Brays Overview (HCFCD, 2015)

Illustrated in the sketching below (Figure 2.d), a typical channel widening work in Project Brays is the widening of the upper half of the channel. The goal of the work is to reduce the risks of overbanking. Channel widening achieves this goal by both adding linear storage of water in the Brays Bayou and improving the Brays Bayou's conveyance of water during a major storm event. According to Manning's equation (Equation 2.a), in a widened channel where both A (area) and R (hydraulic radius) are increased, Q (flow) increases.
Figure 2.d: Project Brays Channel Widening Sketch

\[ Q = \frac{1.49}{n} A R^{2/3} \sqrt{S_0} \]

Equation 2.a: The Manning’s Equation

Where:
- \( Q \) = flow rate (cfs);  
- \( n \) = Manning’s roughness coefficient;
- \( A \) = flow area (ft\(^2\));  
- \( R \) = Hydraulic Radius (ft);  
- \( S_0 \) = channel slope

2.2.2. Detention

To capture rainfall before it flows into the channels and causes flooding, four regional stormwater detention basins were constructed in Project Brays. They are:

1. Eldridge Stormwater Detention Basin; 2. Old Westheimer Road Stormwater Detention Basin; 3. Arthur Storey Park Stormwater Detention Basin; and 4. Willow Waterhole Stormwater Detention Basin. Locations of these four detention basins are shown below. (Figure 2.e)
These four detention basins hold a total of ten thousand acre-feet of storage volume. The costs to construct the four detention basins add up to be $90.4 million. As an example, Figure 2.f is a look at the Arthur Storey Park Stormwater Detention Basin, which can contain up to 3300 acre-feet of water during a flood event. The following Table 2.a shows the detailed maximum stormwater retention volume, cost, greenspace area, and completion time for each of the detention basins. The detention basins in the table are ranked by their locations, from upstream of the Brays Bayou to downstream.
All four stormwater detention basins are major components of Project Brays and capture substantial amount of water during a storm event. However, previous modeling shows that none of the four detention basins have a direct flood mitigation effect on Meyerland. For the first three basins, the limited effect is likely due to the far distance between Meyerland and the first three detention basins (6~10 miles).
Furthermore, the Willow Waterhole Stormwater Detention Basin is attached to the Willow Waterhole Bayou, a tributary of Brays Bayou that feeds into the main channel downstream of Meyerland. Therefore, we concluded that all four detention basins have relatively small flood mitigation effects on the Meyerland neighborhood during a major flood event, and thus were not selected as a modeling priority of this study.

### 2.2.3. Bridge Modifications

Project Brays modifies, extends, or replaces 32 bridges over the Brays Bayou, according to the Project Brays website. As a supplement to channel widening, bridge modifications are designed to reduce the backwater effect and allow for better water conveyance in the Brays Bayou during a storm event.

Bridges, when having one or multiple piers in the channel when there is a high amount of flow, create the backwater effect. This will cause a reduced flow velocity upstream of the bridge, leading to a higher water surface elevation that contribute to flooding. With many bridges creating the backwater effect in the channel during a storm event, especially when water rises to full-bank conditions, the flow throughout Brays Bayou is slowed down by the backwater effect, creating more to flooding. The bridge modifications of Project Brays reduce the bridges’ interference with the channel flow, and thus reduces the backwater effect of bridges, improves the conveyance of the channel, and thus reduces risks of flooding. Figure 2.g is an example of Project Brays’ bridge modification work on Chimney Rock Road.
where bridge piers are removed from the center part of the channel to reduce the backwater effect.

![Figure 2.g: Bridge on Chimney Rock Road Before (left) and After (right, artist rendering) Project Brays bridge modifications. (HCFCD, 2020)](image)

Replicating the modifications in all 32 bridges in a computer model is an extensive undertaking that requires the commitment of teams of professionals in an extended length of time, as well as detailed actual construction drawings. In this study where such requirements cannot be met, we chose to focus our modeling efforts on Project Brays’ channel widening work, which is introduced earlier in 2.2.1.

### 2.3. Previous Work Related to Flooding and Flood Alert on the Brays Bayou

The frequently flooded Brays Bayou has been the area of interest of many studies since the 1990s. In 1998, Bedient et al. developed the real-time Flood Alert
System (FAS) that uses Next Generation Weather Radar (NEXRAD) for Texas Medical Center (TMC) (Bedient et al., 2003). In 2000, the authors conducted two simulations on the Brays Bayou with HEC-1 and NEXRAD rainfall, compared the outflow hydrographs with stream gages, and concluded that the radar proved to be accurate (Bedient et al., 2000). In 2005, Vieux et al. conducted an improved real-time urban runoff simulation with Vflo, a physics-based distributed hydrologic model in the Brays Bayou watershed. The authors used quantitative precipitation estimates (QPE) derived from radar data to prove that radar and distributed hydrologic model can produce accurate runoff estimates (Vieux et al., 2005).

NEXRAD Rainfall, FAS and FPML on the Brays Bayou are further reviewed in section 2.4.

In the wake of the Memorial Day Flood in 2015, Bass et al. (2017) evaluated Project Brays by recreating the Memorial Day flood for different progress stages of Project Brays. Focusing on the addition of the four stormwater detention basins (introduced in the Background section), the authors found certain levels of floodplain reduction by Project Brays. However, no study before has recreated the completed channel widening work of Project Brays with actual design drawings provided by HCFCD. Therefore, the flood mitigation effects of widening the channels of Project Brays remain largely unclear, as more comprehensive hydrologic and hydraulic modeling are required to provide a clear estimate.

In 2019, the flood response in different development scenarios of the channelized Brays Bayou watershed was compared with those of its unchannelized
neighboring watershed ---- the Buffalo Bayou watershed (Juan et al., 2019). The study showed that the flood response in a channelized watershed like the Brays Bayou Watershed is much more sensitive to urban developments than that in an unchannelized watershed. In other words, urbanization increases flooding more greatly in a channelized watershed like Brays than in an unchannelized watershed. The study also projected that through time, the 100-year floodplain of Brays will increase by 60% in 30 years (2011-2040) due to the high conveyance of its drainage system. In comparison, the 100-year floodplain of the Buffalo Bayou watershed will only increase by 3% in 30 years (2011-2040).

In the same year, Maulsby (2019) conducted a risk-based analysis within the Brays Bayou watershed. Annual flood risks were evaluated using risk-based damage curve modeling, producing parcel-level flood risk profiles for various return periods as an outcome. The results in Figure 2 show the annual flood risk as a percentage of house value inside the Brays Bayou watershed. It is important to point out that the highest flood risks are concentrated around the Meyerland Neighborhood, the area of interest in this study.
2.4. Flood Alert System (FAS) on the Brays Bayou

In highly developed urban settings like the Brays Bayou watershed, stormwater accumulates and forms a flood quickly, usually within hours. In Brays, an intense rainfall event can cause flooding in the downstream as quickly as three hours after the rainfall starts. Therefore, it is critical to inform key administrators and emergency personnel about the upcoming flood event in advance to allow time for them to react (Bedient et al., 2003). Only then can emergency reactions be taken to greatly reduce the damage of flooding (Lendering et al., 2016).

Texas Medical Center (TMC), located inside the 500-year floodplain of the Brays Bayou Watershed, is the largest medical city in the world. During Tropical
Storm (TS) Allison in 2001, TMC was heavily impacted by the flash flood because of the tropical storm (Bedient et al., 2003). Flooding occurred in hours after the intense rainfall, striking TMC unprepared of emergency reactions. Due to the flooding, many of the hospitals have lost powers including backup generators, making the hospitals unable to power the essential equipment such as ventilators that keep hospitalized patients alive. The hospital had to evacuate thousands of patients with helicopters, and important research data were lost. The TMC had a total damage of over 1.5 billion dollars due to the flooding event of TS Allison. This has driven the TMC to continue to work with Rice to develop the Flood Alert System (FAS).

FAS, tested on over 40 storms since its launch in 1997, is still the currently used flood forecasting system at the TMC. The flood alert system uses real-time 5-min NEXRAD (Next Generation Weather Radar) rainfall data as input, runs HEC-1, a real-time hydrologic model, and sends out various levels of flood alerts when the simulated flow has exceeded set threshold values. Bedient et al. (2007) found with hydrologic/hydraulic modeling that Harris Gully near TMC worsened flooding by limiting stormwater outflow. In 2008, Fang et al. developed a floodplain map library (FPML) on the Brays Bayou to link NEXRAD rainfall data with improved hydrologic and hydraulic modeling results (Fang et al., 2008). During a storm event, FAS automatically selects the closest floodplain map inside a pre-calculated Floodplain Map Library (FPML), which provides real-time visualized information to viewers. FAS then sends the alerts to the emergency personnel, allowing lead time for TMC to take emergency actions. The most recent generation of FAS (FAS5) was launched in
2020 and has been active since then. The three key technologies that drive the FAS system are: real-time NEXRAD rainfall, real-time HEC-1 simulations and FPML.

FAS utilizes the Next Generation Weather Radar (NEXRAD) as the real-time input (Bedient et al., 2000). Developed by the National Weather Service (NWS), NEXRAD's high spatial and temporal coverage makes it optimal for flood alert purposes. Its first application to the Brays Bayou watershed date back to the late 1990’s, where it was found to be useful and accurate after the modeling results produced by it was compared to rain and stream gages.

FAS’s mechanism is as follows (Bedient et al., 2019). During a storm event, FAS’s HEC-1 program, which is reviewed in an earlier part, runs real-time to simulate hydrologically the upcoming flow hydrograph at the TMC on Brays Bayou in the next 3 hours. Next, given real-time rainfall, an algorithm selects a floodplain map from a pre-calculated FPML with the closest corresponding rainfall. Finally, the system sends out hydrographs and selected floodplain map to emergency personnel as an alert (Fang et al., 2008). Figure 2.i shows a flowchart diagram of FAS.

FAS laid foundation for many flood warning systems later. Juan et al. (2017) designed a radar-based flood alert system for Sugarland, Texas based on FAS. Panakkal et al. integrated FAS with road infrastructure to provide enhanced mobility prediction during a flood event. Based on the floodplain selection mechanism of FAS, Bedient et al. (2021) developed the Flood Information and Response System for the City of Houston (FIRST).
2.5. Previous studies on Flood Damage and Flood Risk

Repetitive flooding, such as the fluvial flooding in Brays Bayou and Meyerland, causes severe damage to properties, leaving households in hundreds of thousands of dollars of debt. If flooded, households usually require third party sources to help with their recovery. Typically, households rely on flood insurance policies as the main source of flood relief and recovery (Brody et al., 2011).

Since the 1927 Mississippi Delta Flood, the demand for a national flood insurance grew largely. In 1968, Congress launched the National Flood Insurance Program (NFIP), which provided homeowners with flood insurance subsidized by the federal government. Additionally, NFIP also started a national effort to map the special flood hazard area (SFHA), specifically the 100-year floodplain, which is the
area that has a 1% chance of being flooded (Bedient et al., 2019). The program was significantly amended in 1969, 1973, and 1994 (Burby, 2011).

To become eligible for subsidized flood insurance, participants of NFIP must comply with minimum floodplain regulations such as only building in certain locations inside the SFHA, obtaining permits for development inside the SFHAs, elevating new structures above the base flood elevation, and to not contribute to floodplain growth by building new structures (Highfield et al., 2014). In addition, in 1990, FEMA also introduced the Community Rating System (CRS) to encourage local flood management authorities to set base floor requirement standards beyond NFIP’s minimum requirement. It is important to note that the database of insurance claims from the NFIP from 1968 to present provides valuable and comprehensive information containing inundation depths and damage (Brody et al., 2011).

As we understood more about the hydrology and statistics behind flooding, the way that flood damage and risks are quantified have evolved. Many studies and models connect the extent and depth of flooding with economic damage. Since the 1980s, depth-damage curves have become the most widely used tool to estimate the relationship between the flood depth in an area and the corresponding direct and indirect losses (McGrath, 2019). Since then, many additional adjustment factors have been taken into consideration for the depth-damage curves to provide more accurate and reliable estimates (McBean et al., 1988). In 2003, Dutta et al. proposed an integrated distributed hydrologic and mathematical model to estimate flood loss (Dutta et al., 2003).
Traditionally, the flood risk is considered in two ways conceptually: the probability of flooding multiplied by consequences of flooding, and the intersection of hazard and vulnerability. Later, from these two concepts, a more compound relationship between flooding probability, exposure determinants and vulnerability of receptors was recognized. (Klijn, 2015) In 2020, through an Environmental Impact Assessment (EIA) approach, a publicly available flood risk assessment model was published to quantify economic impacts of flooding for both current and the climate adjusted future (Armal, 2020).

FEMA HAZUS, first published by Federal Emergency Management Agency in 1997, is a hazard analysis tool based on GIS (geographic information system). HAZUS Flood, part of the HAZUS software package that focuses on flooding, is a Geographic Information System (GIS)-based software that studies the risks of flooding with various inputs. Given a certain flood event, there are three main categories of losses that HAZUS estimates. First, it estimates the quantitative losses such as damage in structures, debris, displacement of people, and costs of repairment and replacement. Second, HAZUS also estimates functionality loss such as failure of critical facilities, hospitals, electricity, and water supply systems. Finally, HAZUS estimate the extent of induced hazards that are due to the potential flooding of hazardous materials (FEMA, 2018).
2.6. Hydrologic and Hydraulic Modeling in the US

Complex rainfall and overland flow patterns, such as the ones in the Brays Bayou Watershed, require advanced computer models to simulate. Starting from the 1970s, various computer models have been developed to simulate the rainfall-runoff process for a storm event. The most widely used hydrologic model is developed by Hydrologic Engineering Center (HEC), namely the original HEC-1 Flood Hydrograph Package (HEC, 1981) and the subsequent HEC-HMS (Hydrologic Modeling System) (HEC, 1998, 2006, 2010, 2016).

HEC-HMS, originally named HEC-1, was first designed in 1967 and released in 1973, later became the most widely used hydrologic model in the US. The main use of the model was to simulate hydrologically the rainfall and runoff process within a watershed. The model divided the watersheds into sub-areas so that parameters such as area and imperviousness. In 2000, The functions were combined with many other HEC products such as HEC-1F (HEC, 1989), PRECIP (HEC, 1989) and HEC-IFH (HEC, 1992) to form the modern day HEC-HMS software in the C++ language with a graphical interface. (HEC-HMS, 2018)

To evaluate the extent, damage, and duration of a flood event, with overland flow known from the hydrologic analysis, it is important to conduct hydraulic analysis to translate flow amount to inundated area and flood depth. While there are many widely used hydrologic models in the US, HEC-RAS is the main hydraulic model in the US. The program was first introduced by HEC in 1982 as HEC-2 and was later upgraded to HEC-RAS with a graphical user interface in 1995. The main
use of the program is to compute water surface elevation with physics-based mathematical equations given flows and channel configurations. It is the predominant tool for flood event analysis, flood hazard zone evaluation and flood insurance studies in the US (Bedient et al., 2019).

In 2016, HEC published the two-dimensional (2D) unsteady-flow modeling option for HEC-RAS, as well as combined 1D and 2D modeling. 2D HEC-RAS divides its area of study into a mesh of cells and makes calculations of flows across the mesh cell network based on the Saint Venant equations, also known as the diffusion wave equations (HEC, 2016). The significant amount of calculation often leads to a prolonged time for computers to complete the simulation. The methodology chapter of this thesis discusses in detail about the mathematical and physical basis of the HEC-RAS program's simulations.

Because of the versatility of HEC-HMS and HEC-RAS, the models are widely used for flood-related studies in the Houston area. For example, Ray et al. (2011) established a connection between storm surge and inland flooding through dynamic modeling in HEC-RAS. Christian et al. (2013) evaluated uncertainty in floodplain delineation in a Gulf Coast watershed. Blessing et al. (2017) found a disconnection between the 100-year floodplain and where actual loss takes place in a flood event. Gori et al. (2020) assessed the accessibility and recovery of Houston roadways during Hurricane Harvey. Garcia et al. (2020) integrated reservoir operations and flood modeling with HEC-RAS 2D.

There are many other widely used flood modeling tools beside HEC-HMS and HEC-RAS. Vflo, first published in 2004, is a distributed hydrologic modeling tool that uses physics-based calculations to simulate the overland flow of stormwater across a network of cell grids (Vieux, 2016). Vflo has high applicability for studies involving infiltration changes and low-impact development. Doubleday et al. (2013) and Juan et al. (2017) used Vflo to evaluate the benefits of low-impact development in Houston, TX. With Vflo, Sebastian et al. (2019) evaluated the impacts of human and environmental change, and Juan et al. (2020) evaluated floodplain evolution in urban watersheds in Houston, TX.

Another widely used rainfall-runoff model is the Storm Water Management Model (SWMM), which is a sophisticated and comprehensive model designed for urban runoff and drainage design. (Huber and Dickson, 1988). On the other hand, a spatially distributed and physics-based model, LISFLOOD, is a popular modeling tool developed by the flood group of the Natural Hazards Project of the Joint Research Center (JRC) of the European Commission (EU) (Burek et al., 2013). Capable of performing subgrid-scale channel modeling over large areas (Neal et al., 2012),
LISFLOOD is one of the most widely used flood forecasting model in Europe (Horritt et al., 2002). Other models include MIKE URBAN (DHI, 2011) and HSPF (Hydrological Simulation Program – Fortran) (EPA, 2007). The following Table 2a lists the major hydrologic models in the US since 1970 (Bedient et al., 2019).

<table>
<thead>
<tr>
<th>Model</th>
<th>Author</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEC-HMS</td>
<td>HEC</td>
<td>2006, 2010, 2016</td>
<td>Hydrologic modeling system</td>
</tr>
<tr>
<td>HEC-RAS</td>
<td>HEC</td>
<td>2006, 2010, 2016</td>
<td>River analysis system</td>
</tr>
<tr>
<td>HEC-RAS (2D)</td>
<td>HEC</td>
<td>2016</td>
<td>Hydraulic analysis system using 2D mesh cells</td>
</tr>
<tr>
<td>Vflo</td>
<td>Vieux</td>
<td>2004</td>
<td>Distributed hydrologic modeling system using grid cells</td>
</tr>
<tr>
<td>SWMM</td>
<td>Huber and Dickinson</td>
<td>1971, 1988, 2005</td>
<td>Storm water management model</td>
</tr>
<tr>
<td>LISFLOOD</td>
<td>JRC, EU</td>
<td>1996</td>
<td>Python-based spatially distributed model focusing on European catchments</td>
</tr>
<tr>
<td>MIKE URBAN</td>
<td>DHI</td>
<td>2011</td>
<td>Modeling and GIS for wastewater and storm water collection systems</td>
</tr>
<tr>
<td>MIKE FLOOD</td>
<td>DHI</td>
<td>2011</td>
<td>Combined river, sewer, and floodplain modeling</td>
</tr>
<tr>
<td>HSPF</td>
<td>EPA</td>
<td>2007</td>
<td>Hydrological simulation program—Fortran</td>
</tr>
</tbody>
</table>

Table 2.b: Major Hydrologic Simulation Models in the US (Bedient et al., 2019)
Chapter 3

Methods

The research workflow below (Figure 3.a) is an overview of how this study uses modeling to combine the collected data, perform simulations in HEC-HMS and HEC-RAS, evaluate the flood mitigation effects of Project Brays channel widening and our proposed golf course detention, and reaches its final conclusions.

Overall, we used HEC-HMS for hydrologic simulations and HEC-RAS for 1D unsteady hydraulic simulations. The following sections 3.1-3.3 are dedicated to explaining our HEC-HMS and HEC-RAS simulation processes, model setup for channel widening and detention, and rainfall selection.
3.1. HEC-HMS and HEC-RAS

HEC-HMS and HEC-RAS are the most widely applied and proven flood modeling tools in the US. Their history and example studies are reviewed in section 2.6. HEC-HMS (the US Army Corps of Engineers Hydrologic Modeling System) is a lumped model that simulates the precipitation-runoff process in a watershed. Usually operated within the unit of a watershed, HEC-HMS divides the watershed into smaller subbasins that each have their own hydrologic characteristics. The user chooses mathematical models for the loss, transform, canopy and surface methods to simulate the precipitation-runoff process in the subbasin. The user also chooses from various river routing methods to perform river routing calculations. Combining subbasin simulations with river routing, HEC-HMS performs watershed-
wide hydrologic simulation of rainfall events within the scope of a watershed. In the end, the results of a HEC-HMS simulation are exported to HEC-RAS as hydrograph inputs. Figure 3.b is a flowchart diagram that shows how HEC-HMS performs its simulations.

Figure 3.b: HEC-HMS Flowchart

HEC-RAS (the River Analysis System) is a physics-based computer modeling software that performs river hydraulics analyses. To construct a HEC-RAS run, there are two elements: the geometric data and the flow data. The geometric data contains physical information of the studied reach, such as channel configuration, over-bank conditions, bridges, culverts, inline structures, and lateral structures. Figure 3.c is the geometric data interface in HEC-RAS representing the Brays Bayou watershed. The flow data contains boundary conditions, peak flows for steady flow analysis, and hydrographs for unsteady flow analysis. The geometric data and flow data are
integrated by a plan file. Figure 3.d is a flowchart that shows how HEC-RAS integrates the inputs and performs its simulations.

Figure 3.c: The Overview of the Geometric Data of the Brays Bayou HEC-RAS Model
The hydraulic simulation is executed using built-in mathematical and physics models in HEC-RAS. An unsteady flow simulation in HEC-RAS is guided by the Saint-Venant Equation. It is a very complex equation set that can only be solved numerically via a computer. During the computation, the HEC-RAS software searches for the optimal implicit solution to the equations.

The Saint-Venant Equation has two parts: the continuity equation and the momentum equation.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

Equation 3.a: The Saint-Venant Continuity Equation
Where:
\( Q = \text{Flow}; \quad A = \text{Area of cross-section of flow}; \quad x = \text{distance downstream}; \quad t = \text{time} \)

The continuity equation above (Equation 3.a) demonstrates the conservation of the incompressible water volume. In the equation, \( Q \) is Flow, \( x \) is distance downstream, \( A \) is the Area of the cross-section of the flow, and \( t \) is time.

\[
\frac{1}{A} \frac{\partial Q}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + g \frac{\partial y}{\partial x} - g \left( S_o - S_f \right) = 0
\]

Equation 3.b: The Saint-Venant Momentum Equation

Where:
\( Q = \text{Flow}; \quad x = \text{position} \quad S_o = \text{Channel Slope} \)
\( A = \text{Area of cross-section of flow}; \quad g = \text{gravity constant} \quad S_f = \text{Friction Slope (Manning’s)} \)
\( t = \text{Time} \quad y = \text{head} \)

The momentum equation above (Equation 3.b) demonstrates the conservation of momentum. The five terms in the above Momentum Equation are respectively: the local acceleration term, the convective acceleration term, the pressure force term, the gravity force term, and the friction force term. An alternative form of the Saint-Venant Equation simplifies it by introducing \( V \) as velocity \((V=Q/A)\) (Equation 3.c).

\[
\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial y}{\partial x} - g \left( S_o - S_f \right) = 0
\]

Equation 3.c: The Saint-Venant Momentum Equation (Alternative Form)
Different approximations of the wave can be achieved by simplifying the Saint-Venant Momentum Equation. First, if only considering the gravity force term and the friction force term, then the equation becomes the Kinematic Wave Steady Uniform Flow equation, only driven by gravity. Next, if the pressure force term is also considered, then it becomes a Diffusion Wave Equation for steady non-uniform flow, driven by gravity and pressure. Finally, if the local acceleration term and the convective acceleration term are taken into consideration, the equation becomes a Dynamic Wave Equation that assumes unsteady non-uniform flow.

HEC-HMS and HEC-RAS are widely used in the United States by researchers and engineers to understand, design and modify factors that impact water flow in rivers. Harris County Flood Control District (HCFCD) has a database of Hydrologic and Hydraulic Models (HMS and RAS) for all major watersheds county-wide, including the Brays Bayou Watershed named Model and Map Management (M3). All M3 models are publicly available for download. M3 models are often used for policy making, planning and floodplain mitigation research. In this study, the HEC-HMS and HEC-RAS models of the Brays Bayou Watershed were downloaded from the HCFCD M3 website (m3models.org). The two models were last updated by Harris County in 2007.
3.2. Model Setup

3.2.1. Project Brays Stages

In this study, over 200 cross-sections in HEC-RAS are manually changed in the M3 HEC-RAS model across the entire area that Project Brays’ channel widening has covered (Figure 3.e). To model how Project Brays’ channel widening changed the response of the watershed to storms through time, it is important to model different stages of Project Brays. We did so by modeling three different stages of Project Brays via HEC-RAS. Specifically, we modified the geometry model of the Brays Bayou in HEC-RAS according to time that each segment is finished provided by the website of Project Brays. Figure 3.f is a picture of the channel widening work of Project Brays in the real world on Main St and Kirby Dr in 2017.

Figure 3.e: Project Brays Channel Widening Area in HEC-RAS
We divided the progress of Project Brays into three stages in Figure 3.e: Before, Middle, and Completion. This study considers the status of the project in 2007 as Before, in late 2017 as Middle, and in 2020 as Completion.

**The Before stage (2007):** The Before stage is based on the HEC-RAS model from the Harris County Flood Control District (HCFC) built in 2007. The model was downloaded from m3models.org, an online database of HCFC.

**The Middle Stage (2017):** The Middle Stage aims to reflect the progress of Project Brays when Hurricane Harvey hit Houston in August 2017. Modifying based on the Before stage, new Lidar data of 2018 are imported into the model to regenerate new cross-sections, from Houston Ship Channel to Buffalo Speedway, that are completed before Hurricane Harvey in 2017. The “cut cross-section” function of the HEC-RAS geometry editor was used to change the old cross-sections into ones that correspond with the 2018 Lidar data.
Figure 3.g shows the difference between the old and new channel surface, for example. In this process, 500 new points are automatically generated at each cross-section in HEC-RAS to depict the surface of the 2018 Lidar data at the cross-section. The design drawings and construction drawings of Project Brays provided by HCFCD are used to verify the Lidar data at each cross-section.

Figure 3.g: The cross-section of the Brays Bayou near Greenbriar Dr in HEC-RAS. Dotted: original channel sides, grey: new channel sides in the 2018 Lidar Data.

**The Completion stage (2020):** For the newly constructed segments west of Buffalo Speedway after 2018, the drawings were used as a reference for us to manually adjust the cross-section coordinate points in the HEC-RAS model. This includes all segments from Buffalo Speedway to Fondren Road. Given that most of
the channel excavation is in the form of “terracing” (expanding only the upper portion of the channel to increase the channel’s capability of transporting water), we manually moved the coordinate points in HEC-RAS accordingly to replicate the channel excavation. In the drawings, we measured the distance between the original channel and the newly excavated channel and applied the horizontal distance change to the coordinate points in the cross-section editor of HEC-RAS. As described on Project Brays website, all channel widening work was completed in 2020.

3.2.2. Detention Modeling at the Golf Course Locations

To model the flood mitigation effects of the two extra proposed detention basins at the golf courses, we used the area-depth technique to estimate the total volume of the detention basins (Table 3.a). As listed in the introduction, the area of the golf courses that can be used as detention basins are 166 acres and 161 acres. With a maximum depth of 15ft and utilization rate of 2/3 due to the bottom slopes, the detention basins can provide a stormwater storage volume of 1660 acre-ft and 1610 acre-ft, respectively. That makes the total volume 3270 acre-ft.
Table 3.a: Preliminary Design of Westwood and Braeburn Detention Basins

Knowing the maximum detention volume possible, we proceeded to use the peak-shaving technique to model the effects of the detention basins in HEC-HMS. Since our unsteady 1D HEC-RAS model uses lateral inflow as a hydrologic input, we had to modify the lateral inflow directly, rather than capturing the flow in the main channel directly, which is commonly done in otherwise steady 1D HEC-RAS models.
We decided to do peak-shaving at the lateral inflow point from Keegan Bayou, one of Brays Bayou’s tributaries that feeds into Brays in between the two golf courses (Figure 2.g). Figure 3.h shows where we used peak-shaving on the inflow, where orange is the stormwater detention volume that was shaved from the hydrograph. Therefore, we were able to estimate the flow-reduction effect of the two detention basins via modeling.

3.3. Precipitation for Model Validation and Simulation

Rainfall data is an important input for hydrology analyses in HEC-HMS. Data that is specific to subbasins in a watershed is essential to accurately model a non-uniform storm event. In this study, we simulated TS Imelda for validation (details in
Chapter 4). For rainfall data, we used radar rainfall records from the archives of the FAS4 system, which was introduced in the background section of this thesis. Thus, using NEXRAD rainfall data, we were able to simulate dropping Tropical Storm Imelda onto our HEC-HMS model.

The HEC-HMS program divides the Brays Bayou Watershed into 70 subbasins that each has its own parameters (rainfall, infiltration, overland flow, etc.) A benefit of using the NEXRAD rainfall data for HEC-HMS simulations is that precipitation is already preprocessed into 5-minute subbasin-specific rainfall volumes, so that no further processing is needed before inputting the rainfall data into HEC-HMS. Figure 3.i shows the Brays Bayou watershed being divided into 70 subbasins in the NEXRAD precipitation data.

Alternatively, a common practice in the field would be to create a Thiessen Polygon with the eight HCFCD rain gages on Brays Bayou and derive rainfall volumes using proximity of the rain gages (Faisal et al., 2012). However, we consider the rainfall data from Thiessen Polygon method to be less precise than using the NEXRAD rainfall, given that the former is heavily dependent on a single gage that is the closest to the subbasin, and is prone to mistakes in the case that a gage fails.
In addition to the NEXRAD rainfall used for the validation process, we used the built-in old 100-year and 500-year rainfall in the M3 HMS model, as well as the new Atlas 14 100-year and 500-year rainfall data from the NOAA Online Point Precipitation Frequency Estimates (Perica, 2018) to generate all the results in Chapter 5.
Chapter 4

Model Validation

4.1. Setup

The Model Validation process is important to make sure that our modeled Brays Bayou replicated its real-world counterpart. Often, one or two historical storm events are simulated in the HEC-HMS and HEC-RAS models to see whether important result parameters such as peak flows, water surface elevation (WSE) associated to peak flows, and time to peak match with the historical observations of the storm.

In this study, we selected Tropical Storm (TS) Imelda, which took place when most of the channel widening work of Project Brays was completed. In this way, we assume that the After Completion stage of the model represents the realistic condition of the Brays Bayou during TS Imelda. The USGS (United States Geological
Survey) gage data of the Brays Bayou on Main Street and on Gessner Road are used for model Validation.

TS Imelda had 10 inches of rainfall in 3 days. We selected it for validation for three reasons: 1. Water did not flow over the bank, reducing the complexity of validating a hydraulic model; 2. The flows peaked and recessed quickly, unlike flows during Harvey 2017 that peaked for days; 3. Imelda is a recent storm that reflects most recent updates of Project Brays.

### 4.2. Validation Results

First, we performed the HMS simulations for TS Imelda using NEXRAD rainfall Data of the Brays Bayou. Afterwards, we used the flow results of HMS as an input for the RAS simulation. Results show that the WSE and flow results are close to the gage data for the second and third peak of TS Imelda, as shown by Figure 4.a and Figure 4.b below.

<table>
<thead>
<tr>
<th>Peak WSE (ft)</th>
<th>Peak Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modeled</td>
</tr>
<tr>
<td>1st Peak</td>
<td>32.49</td>
</tr>
<tr>
<td>2nd Peak</td>
<td>32.12</td>
</tr>
<tr>
<td>3rd Peak</td>
<td>38.86</td>
</tr>
<tr>
<td>NSE</td>
<td>0.73, 0.82 after time adjustment</td>
</tr>
</tbody>
</table>
Table 4.a is a summary table of the comparison of WSE and flow for all three peaks of TS Imelda between the modeled results and gage data on Main Street. The NSE (Nash-Sutcliffe model Efficiency) values for WSE and flow are 0.73 and 0.81, respectively.

While these scores already indicate that the model has good capability of prediction, we noticed that NSE can be further improved by adjusting the hydrograph’s timing. Specifically, we noticed that the time-to-peak is off by 90 minutes for our model and gage data and is negatively impacting the NSE given that stage and flow can change vastly in a short period of time. Since time-to-peak is not the modeling priority for our purpose and will not affect any of the results in this study, we adjusted the timing so that time-to-peak difference no longer negatively affects the NSE. After the adjustment, our NSE for WSE and flow are 0.82 and 0.92.

Figure 4.a: Modeled WSE vs. Gage WSE Data at Main St. During TS Imelda
It is notable that in the above Table 4.a, the WSE at the second and third peak are nearly identical between the modeled results and gage data. The WSE difference at the second peak is 0.1 ft, and the difference at the third peak is 0.32 ft. This indicates that the model reacted similarly to Brays Bayou in real life during TS Imelda. Our modeling results has successfully matched the gage data during TS Imelda.
Imelda, even though it is typically difficult to match storms with three peaks like TS Imelda. The high NSE values and low peak WSE differences further show that our model has passed the validation.
Chapter 5

Results

5.1. Channel Widening Modeling Results

As described in the methodology section, we performed HEC-HMS and HEC-RAS simulations for four frequency storms (old 100-year, old 500-year, Atlas 14 100-year, and Atlas 14 500-year) using three stages of Project Brays (Before, During Harvey, and After Completion). In total, we have simulated 12 frequency rainfall events and obtained 12 floodplain maps regarding channel widening. For best comparison, we only present results for the before and completion stage of Project Brays’ channel widening in this thesis.

5.1.1. Number of Houses Flooded Difference for Channel Widening

Comparing the change in floodplains affected by Project Brays is critical to understanding the flood mitigation effects of Project Brays. To do so, we calculated
the net difference of the depths in frequency storm floodplains before and after Project Brays. This was done by using the raster calculator in ArcGIS.

In all the result sets, there is a common trend that the extent and depth of the Brays Bayou floodplain has decreased upstream of I-610 but increased downstream of I-610. (Figure 5a) shows the net change in the new 100-year floodplain depth before and after Project Brays, where blue means that there is less flooding and red means that there is more flooding.

![Map showing flood depth changes](image)

Figure 5.a: Change in flood depth before and after Project Brays channel work in an Atlas 14 100-year flood. Blue is where flooding has decreased, and red is where it has increased.

To quantify floodplain changes, we use the number of houses flooded in a design storm as an indicator. The number is calculated from the number of Harris County House Parcels inside the floodplain of each design storms in ArcGIS. In an identical storm event, we compare the watershed’s response before channel
widening and after channel widening by subtracting the number of houses inside the floodplain from each other. We selected three areas for comparison: Meyerland, Braeswood and the entire Brays Bayou watershed. The results for these three areas are summarized in Table 5.a. For simplicity, only results for old 100-yr and Atlas 14 100-yr storms are presented.

Though channel widening has overall decreased the number of houses flooded in the entire watershed and in Meyerland, more houses are flooded in Braeswood. For example, in an old 100-yr storm, 797 additional houses in Braeswood have become flooded compared to the 584 Meyerland houses that are no longer flooded. In short, project Brays' channel widening merely moved flooding from Meyerland to Braeswood.

<table>
<thead>
<tr>
<th>Houses</th>
<th>Brays</th>
<th>Meyerland</th>
<th>Braeswood</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Old 100-yr</strong></td>
<td>-1477</td>
<td>-584</td>
<td>+797</td>
</tr>
<tr>
<td><strong>Atlas 14 100-yr</strong></td>
<td>-868</td>
<td>-432</td>
<td>+608</td>
</tr>
</tbody>
</table>

Table 5.a: Number of Houses Flooded Difference Before and After Channel Widening (Blue: Decrease due to channel widening; Red: Increase)

In addition to the number of houses flooded, we also compared the depth difference before and after Project Brays' channel widening. In Figure 5.a, the maximum flood depth difference also shows that the channel work of Project Brays has decreased flooding in areas upstream of I-610 but has increased flooding in downstream of I-610. Due to project Brays, the maximum flood depth during an
Atlas 14 100-year storm has decreased by 1.5 ft upstream of I-610 but has increased by 1.3 ft downstream of I-610. In the next subsection, we further compare the hydrographs upstream and downstream of I-610 to confirm this observation.

5.1.2. Stage hydrographs comparison upstream and downstream of I-610

Comparison of the unsteady HEC-RAS stage hydrographs at varying locations confirm that flooding has decreased upstream of I-610 and increased downstream of I-610 due to Project Brays. We have selected four locations in total near main roads (Figure 5.b): 2 upstream of I-610 in Meyerland (Hilcroft Avenue and Chimney Rock Road) and 2 downstream of I-610 in Braeswood (Stella Link Road and Buffalo Speedway). In short, result confirm our earlier observation that flood depths have decreased in Meyerland (Figure 5.c and Figure 5.d) but have increased in Braeswood (Figure 5.e and Figure 5.f).

Figure 5.b: Locations of the four hydrographs selected
Figure 5.c: Hydrographs for an Atlas 14 100-year storm near Hilcroft Avenue in Meyerland

Figure 5.d: Hydrographs for an Atlas 14 100-year storm near Chimney Rock Road in Meyerland
Figure 5.e: Hydrographs for an Atlas 14 100-year storm near Stella Link Road in Braeswood

Figure 5.f: Hydrographs for an Atlas 14 100-year storm near Buffalo Speedway in Braeswood
We conclude that both the decrease of flooding on the upstream and increase of flooding on the downstream are caused by the widening of the upper part of the channel. The widening creates improved conveyance in the Brays Bayou channel, which transports flood water more quickly to the downstream, alleviating flooding in places upstream of I-610 including Meyerland (blue area in Figure 18). However, this also delivers an extra amount of flood water downstream of I-610, creating more flooding in neighborhoods such as Braeswood (red area in Figure 18).

5.1.3. Extent of Flooded Area Difference for Project Brays’ Channel

Widening

To have a grasp of the level of flood mitigation effect by Project Brays’ channel widening, we calculated the extent of flooded area in ArcGIS. Our results show that the channel widening work of Project Brays has decreased the extent of flooded area for all four frequency storms tested, but only in limited terms. Table 5.b shows that the channel work of Project Brays has reduced the extent of flooded area of all design storms tested by 0.68~1.5 square miles. Percentagewise, the overall areas decreased by 2.6%~5.8% compared to those before Project Brays’ channel widening.
<table>
<thead>
<tr>
<th>Frequency Storm</th>
<th>Extent of Flooded Area Before Project Brays (mi²)</th>
<th>Extent of Flooded Area After Project Brays’ Completion (mi²)</th>
<th>Extent of Flooded Area Reduction (mi²)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old 100-year</td>
<td>17.05</td>
<td>16.06</td>
<td>0.99</td>
<td>5.8%</td>
</tr>
<tr>
<td>Old 500-year</td>
<td>26.27</td>
<td>25.59</td>
<td>0.68</td>
<td>2.6%</td>
</tr>
<tr>
<td>Atlas 14 100-year</td>
<td>23.61</td>
<td>22.79</td>
<td>0.82</td>
<td>3.5%</td>
</tr>
<tr>
<td>Atlas 14 500-year</td>
<td>35.41</td>
<td>33.91</td>
<td>1.5</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

Table 5.b: Comparison Extent of Flooded Area Before and After Project Brays’ Channel Widening in Four Frequency Storms Tested

5.2. Golf Course Detention Modeling Results

5.2.1. Number of Houses Flooded Difference for Golf Course Detention

Driven by the less-than-satisfying results of Project Brays’ channel widening, we proposed to convert two golf course locations upstream of Meyerland to detention (see 1.3). We created four additional runs (old 100-year, old 500-year, Atlas 14 100-year, and Atlas 14 500-year) for detention, and compared them with the ones before Project Brays. Modeling results of the two extra detention basins show that converting the two golf courses to detention basins can produce better flood mitigation in Meyerland compared to Project Brays’ channels widening in a flood event.

As shown before when we evaluated the channel widening effects, we performed a raster calculator analysis in ArcGIS to display the net changes of...
flooding across the watershed. The result map shows an overall reduction of extent of flooded area and peak flood depths across the Brays Bayou watershed (Figure 5.g).

Figure 5.g: Change in flood depth before and after the installation of detention in an Atlas 14 100-year flood. (Blue: Decrease due to detention; Red: Increase)

From the map in Figure 5.g, the addition of detention basins at the two golf course locations has a watershed-wide flood mitigation effect. Same as we did for channel widening, we calculated the difference in number of houses flooded during design storms (Table 5.c). As a result, golf course detention not only has much better effect watershed-wide, but also has great effects in both Meyerland and Braeswood. In Table 5.c, there is a significant contrast between channel widening’s increased flooding in Braeswood and golf course detention’s decreased flooding there.
TABLE 5. Number of Houses Flooded Difference. (Blue: Decrease due to channel widening / detention; Red: Increase)

<table>
<thead>
<tr>
<th></th>
<th>Old 100-yr</th>
<th>Atlas 14 100-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brays</td>
<td>Meyerland</td>
</tr>
<tr>
<td>Channel Widening</td>
<td>-1477</td>
<td>-584</td>
</tr>
<tr>
<td>Golf Course Detention</td>
<td>-3879</td>
<td>-658</td>
</tr>
</tbody>
</table>

Besides number of houses flooded, we also compared the maximum flood depth difference before and after the golf course detention. In Figure 5.g, flood depth decreases by as much as 1.4 ft in dark blue areas with Meyerland in its center, and only increases by as slightly as 0.13 ft at locations the farthest upstream and downstream. We can visually see that Meyerland will be the largest beneficiary of the installation of the two detention basins, given its location in the dark blue area where flooding is reduced the most.

5.2.2. Stage hydrographs comparison upstream and downstream of I-610

It is also important to monitor the stage differences as a function of time at fixed locations. We took the Atlas 14 100-year hydrographs (Figure 5.h and Figure 5.i) in HEC-RAS on Hilcroft Avenue in Meyerland and Buffalo Speedway in Braeswood (Locations 1 and 4 in Figure 5.b), the same ones we used for modeling results of the channel widening. The stage hydrographs show that detention has better effects in Meyerland, and much better effects in Braeswood.
The peak stage on Hilcroft Avenue is reduced by 0.83 ft, which is 0.19 ft more than the effects of channel widening. The peak stage on Buffalo Speedway is reduced by 0.25 ft, which is 0.82 ft more than channel widening, which exacerbated flooding in Braeswood. We also performed the same simulation for an old 100-year storm. To summarize the result, we show the flood mitigation effect presented as peak stage reduction comparison in Table 5.d. In short, the golf course detention basins have better peak stage reduction effect than Project Brays’ channel widening.

<table>
<thead>
<tr>
<th>Location</th>
<th>Hilcroft Ave</th>
<th>Buffalo Speedway</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Storm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlas 14 100-yr</td>
<td>-0.64</td>
<td>-0.25</td>
</tr>
<tr>
<td>Old 100-yr</td>
<td>-0.61</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

Table 5.d: Peak stage reduction comparison between Project Brays’ channel widening and golf course detention. (Blue: Decrease due to channel widening / detention; Red: Increase)
Figure 5.h: Stage Hydrograph for an Atlas 14 100-year storm near Hilcroft Avenue in Meyerland

Figure 5.i: Stage Hydrograph for an Atlas 14 100-year storm near Buffalo Speedway in Braeswood
5.3. Other Uses for the Updated Floodplain Maps of the Brays Bayou Watershed from This Study

In previous result sections we evaluated changes in the floodplain response brought by the channel widening work of Project Brays and compared it with that of our detention proposal. In this section, we explore another important way that this study can contribute to the understanding of the Brays Bayou Watershed, through the updated floodplain maps.

There are two fields that the updated floodplain maps can significantly contribute in: flood warning and city planning. First, as reviewed in the introduction and literature review sections, the Flood Alert System (FAS) on Brays Bayou utilizes the most recent floodplain maps to make real-time predictions before a flood event occurs. Floodplain maps from this study are the most updated both channel geometry-wise (HEC-RAS) and rainfall-wise (Atlas 14) and are therefore ideal for FAS. With more accurate and up-to-date floodplain maps like these, FAS can make accurate predictions and alert the emergency personnel before flooding.

Second, the new floodplain from this study will serve as a source for planners, developers, and homeowners to consider where to build and how high to build to avoid flooding. Floodplain map results from this study shows that the extent of flooded area has increased significantly with the Atlas 14 rainfall. For example, the Brays Bayou 100-year floodplain has grown by 6.56 mi$^2$, an astounding 38% of the original size. (Figure 5.j) displays the difference between the old and new 100-
year floodplain where orange indicates newly flooded area. Therefore, due to increased rainfall shown in Atlas 14, places that used to be safe from riverine flooding now have a higher chance to flood.

Figure 5.j: Floodplain Growth from the Old 100-year Floodplain to the New Atlas 14 100-year Floodplain (orange)
Chapter 6

Conclusion and Future Work

6.1. Conclusion

Houston, repetitively flooded with substantial loss of lives and properties, is in dire need of a flood mitigation solution that protects it when the next major flooding occurs. The Meyerland neighborhood is right in the center of the repetitively flooded Brays Bayou watershed, making it one of the most flooded neighborhoods in the United States. Project Brays, a $480 million regional flood mitigation project, is a massive effort to alleviate flooding in Brays Bayou neighborhoods such as Meyerland, with little studies that quantified or modeled its effects using actual design and construction drawings.

In this thesis we used 1D unsteady HEC-RAS to model the flood mitigation effects of Project Brays’ channel widening work, with manual inputs of HCFCD’s
Project Brays design and construction drawings into the HEC-RAS model.

Interestingly channel widening has reduced flooding in Meyerland but has increased flooding in neighborhoods such as Braeswood. This pattern of result is seen in the number of houses flooded difference, depth-difference map and stage hydrographs. Furthermore, similar patterns were observed among all four storms that were simulated.

A large regional structural flood mitigation project to create higher conveyance in the channel is not the perfect solution for the Brays Bayou Watershed. Without appropriate downstream flood mitigation to navigate the excessive amount of water, flooding can be exacerbated in the downstream area. As reviewed in the literature review section, Juan et al. (2020) have also observed that the increased conveyance in the Brays Bayou channel caused the watershed to have faster and higher peak response towards a storm event and makes a highly developed watershed prone to more flooding.

The side effects of channel widening drove us to propose the alternative option: to add two extra detention basins at golf course locations that are immediately upstream of Meyerland, making the most effective stormwater detention for Meyerland possible. Our results show that building stormwater detention basins can provide better flood mitigation effects in Meyerland than channel widening does, as well as watershed-wide flood mitigation effects. Given that the cost for detention basins in Project Brays was much lower than the channel widening cost, there is great opportunity to convert the golf courses to detention
basins to reduce flooding in Meyerland. Still, to fully evaluate whether adding these detention basins is entirely beneficial, it is important to account for the buyout costs, the aesthetics, and the community’s opinion of the golf courses, which are outside the scope of this study.

The question this study sheds some light on is to whether use channel widening to speed up the movement of water in a watershed, or to use detention to hold water past the peak of a flooding event. Though we concluded that detention is a better mitigation strategy, both strategies are only remedies to overdevelopment. Houston has been rapidly developing and expanding since the middle of the last century. The urban area sprawled outside with low levels of regulations, contributing to both the vibrant growth of the city and yet, the little preparedness against natural hazards, which in this case, are increased repetitive flooding in neighborhoods like Meyerland. Development of watersheds were so quick that we might have used more lands than we should.

At this point, Houston ended up using channel widening to compensate for the watershed’s increased conveyance of that cause flooding, and in the process, increased the conveyance again. If there is a takeaway of this thesis, it would be that increasing the conveyance will only be a temporary solution to increased levels of rain and flooding and can create flooding somewhere else. The more permanent solution to repetitive flooding lies inside foresightful watershed management, the one that engineers based on the watershed’s natural characteristics, and that leaves
a safety room for increased future natural hazards like the extreme rainfall displayed by Atlas 14.

### 6.2. Future Work

One of the elements of Project Brays that this thesis did not cover is the bridge modification work. It is not modeled in this study since modeling it requires excessive amount of time and effort to make changes manually to 32 bridges in HEC-RAS. In addition, the final construction drawings are not available to this study for accurate modeling of the bridge modifications. There is still a possibility that by increasing the conveyance at bridge crossings, the backwater effect that caused the increased flooding in areas downstream of I-610 can be reduced. However, typically, as long as a bridge is not removed completely, the reduction of backwater effect is limited. Still, if future researchers want to evaluate the comprehensive effects of Project Brays, the effects of bridge modifications cannot be missed.

Another important future work is to use a depth-damage curve to determine the economic value that Project Brays has created in Meyerland. Using design storm floodplain raster data from this study, future researchers will be able to model flood loss prevented by Project Brays and compare that to the cost of Project Brays to have a complete economic analysis. On the other hand, given the large number of elevated houses in Meyerland, future researchers can also estimate how much flood loss that homeowners prevented by elevating their houses in Meyerland with depth-damage curves.
Finally, the effect of our newly proposed detention basins at the two golf course locations (Braeburn and Westwood) need to be further investigated by reservoir modeling in HEC-HMS. Our peak-shaving method, though adequate for the purpose of this study, is only a preliminary estimate for flow volume reduction effects that the new detention can create. To fully model the operation of the golf course detention with inflow and outflow during a storm, the complete dimensions of the detention basins are needed. Only then can the elevation-volume-outflow relationship for the detention operation be calculated in HEC-HMS.
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Chapter 7: Appendix

Figure 7.a: Atlas 14 100-year Floodplain Before Project Brays’ Channel Widening

Figure 7.b: Atlas 14 100-year Floodplain After Project Brays’ Channel Widening
Figure 7.c: Old 100-year Floodplain Before Project Brays’ Channel Widening

Figure 7.d: Old 100-year Floodplain After Project Brays’ Channel Widening