EFFECTS OF SOUND WALLS ON URBAN FLOODING.
CASE STUDY: HURRICANE HARVEY

A Thesis

by

JAIMLYN ROSE SYPNIEWSKI

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF MARINE RESOURCES MANAGEMENT

Chair of Committee,	Samuel Brody
Co-Chair of Committee,	Wesley Highfield
Committee Members,	David Retchless
	Ashley Ross
Head of Department,	Kyeong Park

August 2019

Major Subject: Marine Resources Management

ABSTRACT

Flooding has historically occurred within coastal areas of Texas due to hurricanes and other catastrophic weather events and continues to be a frequent and costly hazard. One community where flood vulnerability has intensified due to development is Friendswood, Texas. As residential areas are being developed near major roadways, the Texas Department of Transportation often undertakes noise abatement measures to reduce the impact of noise from highway traffic on housing areas. These structures may act as mini 'dams' impeding the flow of floodwaters and increasing flood depths upstream of such structures. No studies have investigated the relationship between sound walls or noise barriers to flood damage. Given climate trends that point to increased future hazards, it is critical to understand how development practices, including the use of sound walls or noise barriers, contribute to flooding in urban areas. This paper seeks to answer: Do sound walls impact floodwater depths? More specially, is the floodwater depth significantly higher on the upstream side of the sound wall as compared to the downstream side? Multiple statistical tests were performed including; T-Tests, ANOVA and Regression analysis. The results of this study indicate that the location of a sound wall, especially upstream of a sound wall that has few drainage openings, is an important predictor of flood damage to residential properties. Using projected future storm and climate streams in these models would further identify adaptations that could improve community resilience into the future.

DEDICATION

This paper is dedicated to all of those impacted by Hurricane Harvey. It was thanks to the kindness of strangers and the warmth of friends during this devastating event that I can pursue this study.

I hope that this paper contributes to flood mitigation research around the country helping to create a safer, drier future.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Highfield of the Department of Marine Sciences and Dr. Brody, Dr. Ross and Dr. Retchless of the Marine Resources Management Department.

The data analyzed was provided by Professor Highfield and the City of Friendswood. All other work conducted for the thesis was completed by the student independently.

Funding Sources

This paper is based on research supported by the U.S. National Science Foundation (grant no. 1545837.)

NOMENCLATURE

DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
GIS	Geographic Information Systems
IPCC	International Panel on Climate Change
LiDAR	Light Detection and Ranging
LULC	Land Use Land Cover
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
TNRIS	Texas Natural Resources Information System
TxDOT	Texas Department of Transportation
USA	United States of America
USACE	United States Army Corps of Engineers

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Problem Statement

Flooding has historically occurred within coastal areas of Texas due to hurricanes and other catastrophic weather events, continuing to be a frequent and costly hazard. The National Flood Insurance Program (NFIP) reported losses of US $19 billion in Texas alone (Brody et al., 2012). The majority of these losses have occurred along the Gulf of Mexico coast where over $52 billion was accrued in flood damage from 200-2005; increased development in flood-prone areas has exacerbated the vulnerability of these local communities (Michel-Kerjan et al., 2012).

One community where flood vulnerability has intensified due to development is Friendswood, Texas. Friendswood is located 7.5 miles from Galveston Bay and has historically flooded during severe rainfall events. Several studies have explored the nexus between flooding and correlated factors such as urban sprawl (Faccini et al., 2018; Franci et al, 2015; Lambert et al., 2015; Burchell et al., 1998), urbanization (Leopold, 1994; Burges et al, 1998; Brezonik and Stadelmann, 2002; Burns et al., 2005), wetlands (Brody et al., 2007a and 2007b; Highfield et al., 2018), open space (Brody and Highfield, 2013), and the addition of impervious surfaces (e.g. pavement, roads, rooftops, etc.) due to infrastructure or the built environment (Brody et al, 2018; Brody et al, 2015, Brody et al, 2015). However, no studies have investigated the relationship between sound walls or noise barriers and flood damage.

As residential areas are being developed near major roadways, the Texas Department of Transportation (TxDOT) often undertakes noise abatement measures to reduce the impact of noise from highway traffic on housing areas. The traffic noise abatement measure used most often is the construction of noise barriers, usually built of concrete or masonry (Texas DOT, 2011). These structures may act as mini ‘dams’ impeding the flow of floodwaters and increasing flood depths upstream of such structures (Figure 1-1).

Figure 1-1: Sound Wall off FM 528 Friendswood Texas

Damages due to flooding are likely to only increase into the future as hurricanes, tropical storms, and extreme precipitation events are expected to grow in intensity and frequency. Maurer and others (2017) reported that the 100-year event of the late twentieth century is currently projected to be approximately a 40-year event, representing a 2.5-fold increase in occurrence probability. Balaguru and others (2016) found a median increase in storm surge ranging between 25% to 47%, with changes in hurricane intensity increasing future storm surge by about 10% relative to the increase that may result from sea level rise alone. Climate extremes are becoming more common in the United States and elsewhere (IPCC, 2012). The US Climate Extremes Index (NOAA, 2013) shows that the three most extreme years of the past century occurred within the last 15 years.

Consequently, flooding and other damages associated with extreme climate events are also increasing. For example, Friendswood has flooded multiple times since the 1970s, with extensive property damage occurring in 1973, 1979, 1989, 1994, 2001, 2006, and 2009 (USACE, 2012). Most recently, Friendswood suffered extreme damage during Hurricane Harvey in 2017. Given climate trends that point to increased hazards into the future, it is critical to understand how development practices, including the use of sound walls or noise barriers, contribute to flooding in urban areas.

2. RESEARCH QUESTIONS AND OBJECTIVES

The importance of maintaining the integrity of hydrological systems, both for mitigating flood damage and for preserving healthy ecosystems, is well understood (e.g., Brody & Highfield, 2013; Brody, S.D.; Highfield, W.E.; Kang, J.E., 2011). There are also several studies that link proximity variables, such as streams or coastlines, wetlands, forests, agriculture, open space, and grasslands, to flood damage (Brody & Highfield, 2013; Burns D., J., Hassett J., & C., 2005; Highfield, Brody, & Shepard, 2018). However, research on the impacts of the built environment on flood damage tends to be limited to imperviousness or other structures built to mitigate flood damage, such as dams or levees (Brody S. D., Zahran, Highfield, Grover, & Vedlit, 2007; Haddad, Ashofteh, & and Mariño, 2015; Wenger, 2015). Sound walls are part of the built environment, and their indirect impacts may be included in the studies quantifying the percentage of the impervious surface; however, no studies explicitly investigate the link between sound walls and flood water depth. Therefore, the research question addressed in this study is:

> *Do sound walls impact floodwater depths? More specially, is the floodwater depth significantly higher on the upstream side of the sound wall as compared to the downstream side?*

No study to date has explored the impact of sound walls on urban flooding while controlling for an array of characteristics (e.g., precipitation, flood zone designation, soil drainage, and elevation). This study examines the relationship between sound walls and the flood depth from Hurricane Harvey within the city of Friendswood TX., USA.

Friendswood is an ideal study area since: 1) it has consistently experienced flood damage, 2) contains two sound walls within proximity to a major stream, Clear Creek, and 3) was one of the most impacted cities following Hurricane Harvey. Furthermore, it has experienced rapid urban development in the past decades with many of the homes flooded by Harvey located outside the historically established 100-year floodplain. This allows for additional analyses in this study to explore if sound wall placement increased flooding. In other words, did flooding occur in areas that would not have otherwise flooded had the sound walls not been present?

Results from this study provide valuable information for flood managers and environmental planners on how the development and placement of sound walls, relative to streams and neighborhoods, can adversely affect flood mitigation measures. Such information is critical, given the continued development of Friendswood and other similar communities, which have an increased vulnerability to riverine and overland flooding. The findings also provide guidelines for building more flood-safe sound walls, resulting in increased long-term flood resilience within the surrounding communities.

3. LITERATURE REVIEW

Rapid urban development, such as in the region of Friendswood, has substantially increased the extent of impervious cover and reduced the watershed's natural water retention capacity resulting in higher and more-frequent stormwater flows (Michel-Kerjan *et al.,* 2012). Therefore, overbank flows have become more common, even with moderate rainfall events. In addition, continued development within the floodplain has compounded the problem of addressing flood risk management not only by introducing additional flood-prone structures but also by narrowing flood risk management options (USACE, 2012). Although local authorities have regulations in place to reduce the effects of new development, these regulations are not in effect for the entire watershed and are not designed to reduce the current flood risk. Flood vulnerability is increasing due to continued urban expansion (Faccini *et al.,* 2018) and urban sprawl, generally characterized as low-density, haphazard development spiraling outward from urban centers (Burchell *et al.,*1998). Urban sprawl, in particular, has been linked to the severity of natural disaster impacts, especially with regards to post-disaster spending (Lambert *et al.,* 2015).

Regardless of the frequency of policy and engineering measures to reduce the adverse impacts of floods, they remain one of the costliest events within Friendswood (Brody *et al.,* 2007). The losses are worsened by increased residential and commercial development, particularly around Clear Creek. Rising population density along the stream is accompanied by the alteration of hydrological systems (e.g., watersheds and wetlands) and higher amounts of impervious surfaces (e.g., pavement and buildings); both factors lessen the capacity for these systems to store and hold surface water run-off naturally (USACE, 2012). As a result, neighborhoods are increasingly vulnerable to repetitive flood damage.

Several studies have demonstrated that urbanization increases not only run-off volume but also peak discharges and associated flood magnitudes (Leopold, 1994; Burges, Wigmosta and Meena, 1998; Brezonik and Stadelmann, 2002; Burns *et al.,*2005). Brody and others (2007) provided evidence that flood damage is not solely a function of rainfall but also is driven by the scale and type of human development. For example, proximity to wetlands was found to reduce flood losses in some cases (Highfield *et al.,* 2018). Brody and Highfield, (2012) found that open space can also mitigate the adverse impact of flooding.

Studies have also shown a correlation between flooding losses and the built environment, particularly regarding the increase in impervious surfaces, such as roads and rooftops, concerning vegetated areas (Brody *et al.,* 2015). However, adverse impacts from floods do not stem solely from the percentage of impervious surfaces present within the landscape; flood damages are also tied to the intensity with which impervious surfaces are clustered (Brody *et al.,* 2013) and the type of development pattern within communities (Brody *et al.,*2011). Generally, the higher the ratio of impervious surface to vegetation, the higher the increased flood loss (Brody *et al.,* 2015). Nevertheless, a recent study indicated that previous surface land covers did not make a significant difference in reducing flood losses in the Clear Creek watershed (Brody *et al.,* 2018). This implies, as suggested by Brody and others (2013), that local land should be coupled with regional structural mitigation strategies, such as dikes and levees. Land Use/Land Cover patterns should also be considered in conjunction with the construction of dikes, levees, gates, and other structural mitigation projects; the type of land use pattern behind barriers may be as crucial to reducing flood risk as the barriers themselves (Brody *et al.,* 2015).

Noise barriers, or sound walls, are not built with the purpose of flood mitigation but rather with the intent to reduce the impact of noise from highway traffic, usually within a residential area (Texas DOT, 2011) (Figure 3-1). When determining the feasibility of a sound wall, federal regulation requires that topography and drainage factors need to be considered before construction (23 C.F.R. §772.13). However, to maintain noise reduction standards, any potential drainage cannot reduce the surface area of the wall by more than 3%. Nevertheless, as sound barriers tend to be solid wall-like concrete structures between 10-15 feet in height, the flow of water will most likely be impeded, particularly as most do not include methods for draining or moving floodwaters (Klingner *et al.,* 2003). Sound walls bear a resemblance to levees and damns used in flood mitigation, but even their efficacy is questionable.

The use of impermeable barriers, such as levees or dams for flood mitigation, has recently been criticized. While the construction of protective levees has been shown to reduce the rate of flood damages up to 99% in comparison with a non-construction of levees scenario (Haddad *et al.,* 2015), Wenger (2015) found levees should only be used as a temporary solution in flood-prone areas because they can lead to additional flooding over time. For example, stream engineering, which includes the use levees, was found to elevate flood hazards on the lower Mississippi to levels that are unprecedented within the past five centuries (Munoz *et al.,* 2018). The use of levees, in this case, only added to a growing list of externalized costs associated with conventional flood mitigation and navigation projects, including a reduction in a stream's ability to convey flood flows (Munoz *et al.,* 2018).

In an urban development context research is needed to determine if sound walls exacerbate flooding by hindering the ability of the flood water to move past the barrier. Floodplain management, planning, and assessments are routinely completed, but none of these have viewed sound walls in a similar context as levees. As a result, development controls continue to be inadequate; and future floods may fuel demand for increased drainage controls in sound wall construction. An increase in extreme storms will cause greater flooding damage if sound walls continue to act as a choke point on streams, preventing or hindering overland water flow. Adjustments need to be planned and funded to place appropriate structures in place that will both block noise and allow flood waters to drain.

4. CONCEPTUAL MODEL

There are two dependent variables in this study. The main one is Flood Depth, which will be analyzed while controlling for proximity and environmental variables. The second is damage categories, which will be examined relative to proximity and location, either upstream or downstream. The unit of analysis for the study is a residential parcel.

4.1. Hypothesis

It is hypothesized that:

1. **Sound Wall Proximity:** The closer to a sound wall a parcel is located, the higher the increase recorded flood depths.
2. **Upstream vs. Downstream:** A parcel located upstream of a sound wall will experience greater flood depth than similar parcels located equidistant downstream.

Hypothesis (1) and **(2)** are combined to form the Null Hypothesis:

3. **Null Hypothesis:** The proximity to the sound wall, either upstream or downstream will have no significant effect ($\rho = 0.05$) on the measured flood depth layer, or

$$\mathbf{H_o: \mu_a = \mu_b} \qquad \textbf{(1)}$$

where, μ is the mean flood depth at proximity a or b, or any distance either upstream or downstream from the sound wall.

The alternate hypothesis is:

$$\mathbf{H_1: \mu_a \neq \mu_b} \qquad \textbf{(2)}$$

5. RESEARCH METHODS

Flood depth data was collected from the aftermath of Hurricane Harvey at the parcel level by the City of Friendswood. A multiple regression analysis was used to control for the impact of several environmental and locational measures, including:

1) Elevation,
2) Soil drainage as a function of soil texture,
3) Stream and Sound wall proximity, and
4) Flood zone designations on reported flood depth.

This data was used to determine whether the proximity to sound walls has a direct effect on flood inundation.

5.1. Study Area

The City of Friendswood is the study area; it is located on the border of Harris and Galveston counties just 19 miles south of Houston, Texas. The City of Friendswood covers approximately 13,351.4 acres and is located entirely within the Clear Creek watershed, which is drained primarily by Clear Creek and its associated tributaries (Figure 5-1). The city itself has very little topographic change; as a result, much of the area is located within a floodplain (Figure 6-4). Friendswood frequently experiences severe storm events resulting in multiple small-scale floods as well as major flood events. It has also experienced significant growth over the last few decades with residential development in vulnerable areas resulting in higher amounts of property damage during flooding.

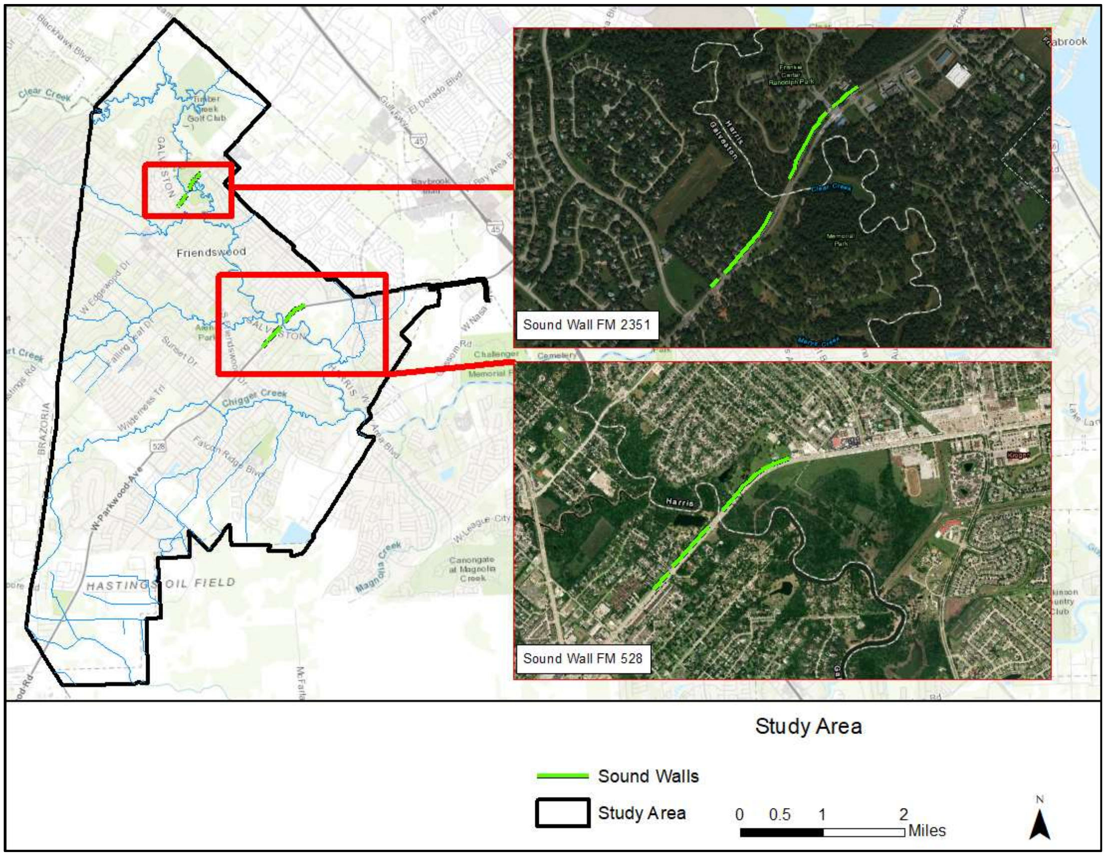

Figure 5-1 Study Area and Sound Wall Locations

The most recent flood was a result of Hurricane Harvey. Between August 25 and 31, 2017, Friendswood experienced record rainfall, causing the overflow of Clear Creek which resulted in extensive damage to the local communities. Based on the National Weather Service precipitation data, parts of Friendswood experienced more than 45 inches of rainfall over three days during Hurricane Harvey, which was classified as a 1,000-year flood event. As a result of this unprecedented rainfall, over 2,450 houses experienced flooding within the City of Friendswood. Flood depths for each of the flooded houses were selected for analysis and compared to the flood depths of downstream homes equidistant from a sound wall. Flooding during this event may have been increased due to the sound walls creating “choke points” on the stream.

There are two sound walls located within the city limits that may have contributed to increased flooding, one each in the northern and southern parts of the city. The sound walls are located on FM 528 on the southern end of Friendswood and FM 2351 located on the northeast city boundary (see Figure 5-1).

5.2. Sound Walls

There are two sound walls in Friendswood; both were examined. They are approximately 12 feet high and 0.5 foot wide. Both are of the same general construction with small drainage openings measuring 2 feet x 6 inches every 20 feet. However, most of the drainage openings were blocked by debris either prior to, or during, Hurricane Harvey.

5.2.1. Location FM 2351

Figure 5-2 Sound Wall FM 2351 Location

The northernmost sound wall examined in this study is located on FM Highway 2351on either side of Clear Creek, as shown in Figure 5-2. The wall is 2,070 feet long and is broken into four different sections, allowing for egress of traffic into residential areas. The four sections range from 331 to 813 feet long. Two of the three gaps are 85 feet to allow for a road, and the third gap is 386 feet to accommodate the stream. The wall has parks on both the north and south side. Just north of the sound wall is Frankie Carter Randolph Park; to the is south Memorial Park. There is a small residential area to the far east side of the wall.

5.2.2. Location FM 528

Figure 5-3 Sound Wall 528 Location

Figure 5-3 shows the second sound wall, located in south Friendswood along FM Highway 528, crossing Clear Creek. It is a total of 3292 feet long and is broken into three sections, ranging in size from 461 feet at the east end to 1750 feet at the southwest end. The residential egress gap is 145 feet while the gap over Clear Creek is 450 feet. North of the sound wall is a single-family residential area, called Forest Bend. South of the wall and east of the stream is an expanse of open land. On the west side, there is another small residential area.

5.3. Hurricane Harvey

Hurricane Harvey made landfall near Rockport, Texas as a Category 4 hurricane. The storm had maximum sustained wind speeds of 200km/hour. Harvey moved across southeast Texas, dumping unprecedented amounts of rain. Rainfall totals during the seven days between August 25 and 31, 2017 were amongst the highest ever recorded, peaking at 51.88 inches (Sebastian et al., 2017). Due to this extreme precipitation, Harvey caused flooding at a record scale. More than 100,000 residential properties are estimated to have been affected in southeast Texas; over 2,450 homes located in Friendswood flooded (Figure 5-2). All the major creeks within Friendswood exceeded their channel capacities, reaching water levels not previously recorded (Sebastian et al., 2017). Rainfall totals exceeded the 1,000-year return period with a high of 36.2 inches (TCEQ, 2017).

5.4. Unit of Measurement

A parcel-level analysis of flood depth was used to identify the influence of sound walls on flood depth and damage categories after Hurricane Harvey. The flood depth was collected by the City of Friendswood and then log-transformed to better approximate a normal distribution. The study sample includes all parcels within Friendswood that were affected by the flooding caused by Hurricane Harvey. Some of the data points collected included houses that were within partially flooded residential areas that had a water level of zero. However, no data were collected on the parcels that were located outside of flooded areas. As a result, only the surveyed data were used to avoid the assumption that a parcel did not flood because it was not documented. All data are based on the Hurricane Harvey precipitation event to ensure similar storm and time conditions throughout the model. Figure 5-4 shows the location of the data points used in the analysis.

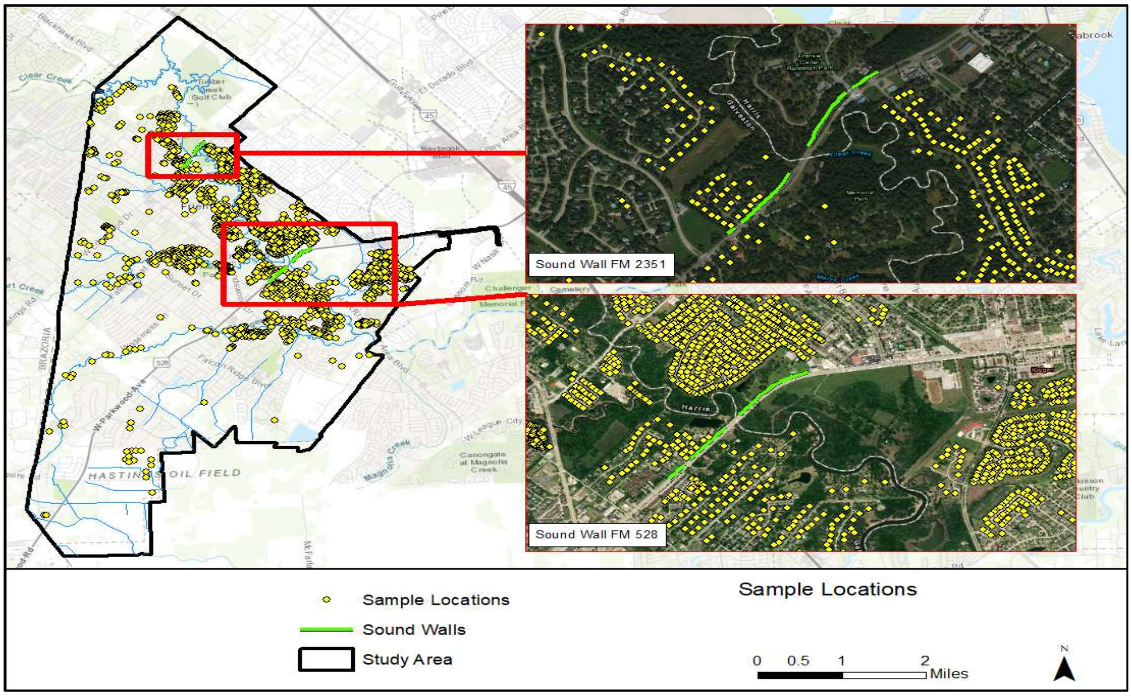

Figure 5-4 Sound Wall Locations

6. CONCEPT MEASUREMENT

For the study, a total of 2,450 data points were collected: 2,444 points corresponding to a residential structure flooded during Hurricane Harvey and six points taken along the sound wall corresponding with the high-water line. A regression model was used to determine the effect of sound walls on urban flooding. In the model, location is one of the most critical factors in determining the effect of sound walls on flood depth. Distance to waterbodies, distance to sound walls, and whether a parcel is located upstream or downstream from the nearest sound wall was examined in this study. The proximity to waterbodies is a factor in predicting flood depth, as parcels located near waterbodies will be the first affected in the event of stream overflow. When a stream exceeds flood state due to large amounts of precipitation, the surrounding structures are directly exposed to flood damage from increased flood inundation. The parcels located near waterbodies are also more likely located within the 100-year floodplain. Accordingly, the dependent variables are flood depth (logged) and damage categories. The independent variables of interest are sound wall proximity and parcel upstream/downstream location in relation to the sound wall. Control variables included stream proximity, elevation, flood zones, soil drainage, and damage categories.

Table 6-1 Variable Measurement and Expected Effect on Flood Loss

DEPENDENT VARIABLE			
Variable Name	*Variable Operation*		*Data Source*
Flood Depth (log)	Total floodwater depth following Hurricane Harvey; log transformed for non-normality		City of Friendswood
Damage Categories	Damage incurred as a result of Hurricane Harvey: Affected, Minor, Major and Destroyed	+/-	City of Friendswood
INDEPENDENT/CONTROL VARIABLES			
Variable Name	*Variable Operation*	*Sign*	*Data Source*
Sound Wall Proximity	Proximity to nearest sound wall in meters	-	GIS
Upstream of Sound Wall FM 2351	Point located upstream of sound wall, located on FM 2351	+	GIS
Upstream of Sound Wall FM 528	Point located upstream of sound wall, located on FM 528	+	GIS
River Proximity	Proximity to nearest river in feet	-	TNRIS
Precipitation	Average precipitation for 7 days during Hurricane Harvey in millimeters	+	National Weather Service
Elevation	Elevation of residential parcels in feet	-	TNRIS
Flood Zone A	High risk flood zones	+	FEMA
Flood Zone B	Moderate to low risk areas	-	FEMA
Drainage	Soil drainage classes: Moderately well drained, Somewhat poorly drained, Poorly drained	+/-	NRCS

6.1. Dependent Variables

6.1.1. Flood Depth

Flood depth is measured as the total recorded inundation from Hurricane Harvey. The inundation was collected in the field by City of Friendswood workers during the Harvey aftermath to document areas with the highest flooding as part of a flood mitigation study conducted by the City itself. The extent of the inundation is assumed to be equal to the area of the parcel for this assessment. As there were several parks near the sound walls, the high-water mark on the sound wall was used to determine flood water depth in these areas. The flood depth collected ranged from 0 to 3.1 meters, as shown in Figure 6-1.

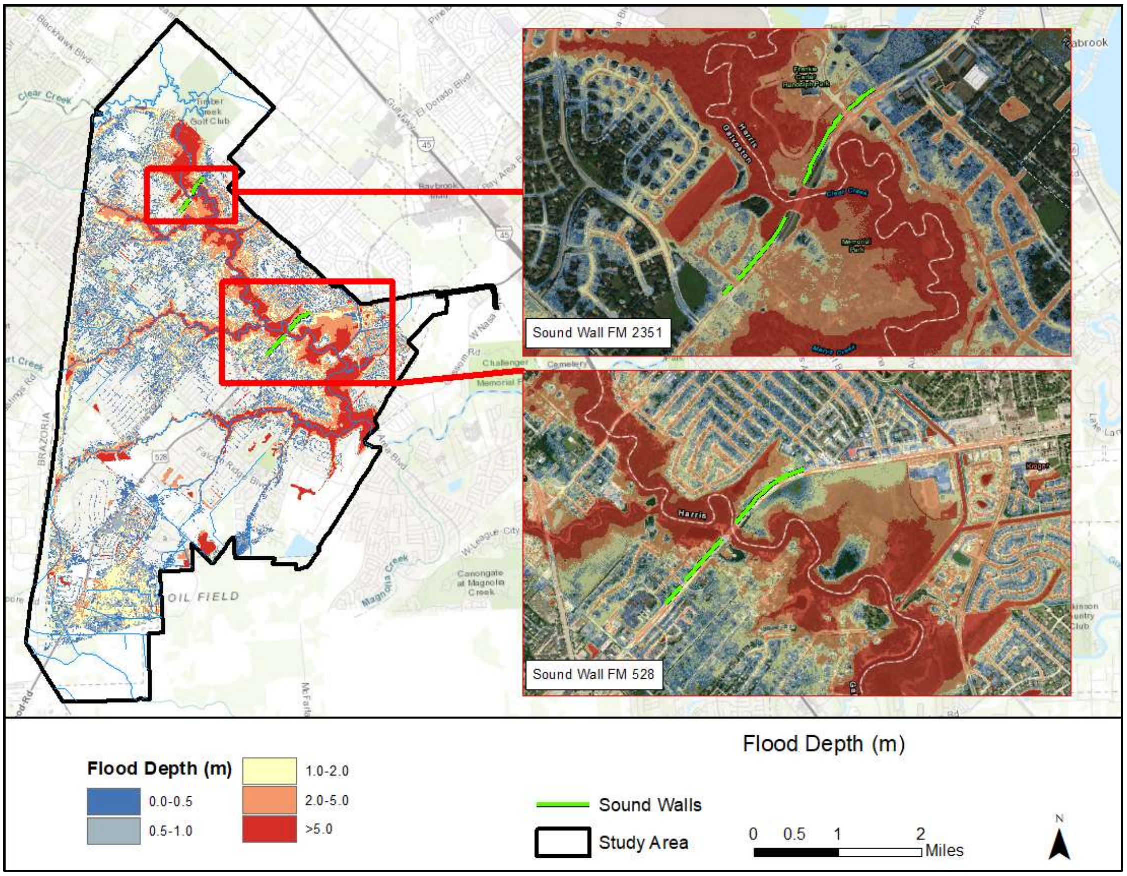

Figure 6-1 Flood Depth in Friendswood (m)

6.1.2. Damage Categories

The City of Friendswood collected damage from the flooding and classified into four groups: Destroyed (n = 276), Major (n =1,050), Affected (n=216) and Minor (n = 902). These classifications recorded damages as follows:

1) Destroyed – The structure is permanently uninhabitable and cannot be repaired. Damage includes the complete removal of the structure with only the foundation remaining or more than 4 feet of water.

2) Major – The structure is currently uninhabitable, and extensive repair is needed; includes cracked walls, penetration of structure and 2-4 feet of water damage.
3) Minor – The structure is habitable with minor repairs. The structure has broken windows or doors, damaged siding or 6 inches to 2 feet of water.
4) Affected – The structure is habitable with some minor damage such as; damage to cars or air conditioning and less than 6 inches of water.

These variables were converted to integers and used as a dependent variable for various statistical tests, including a T-test and ANOVA.

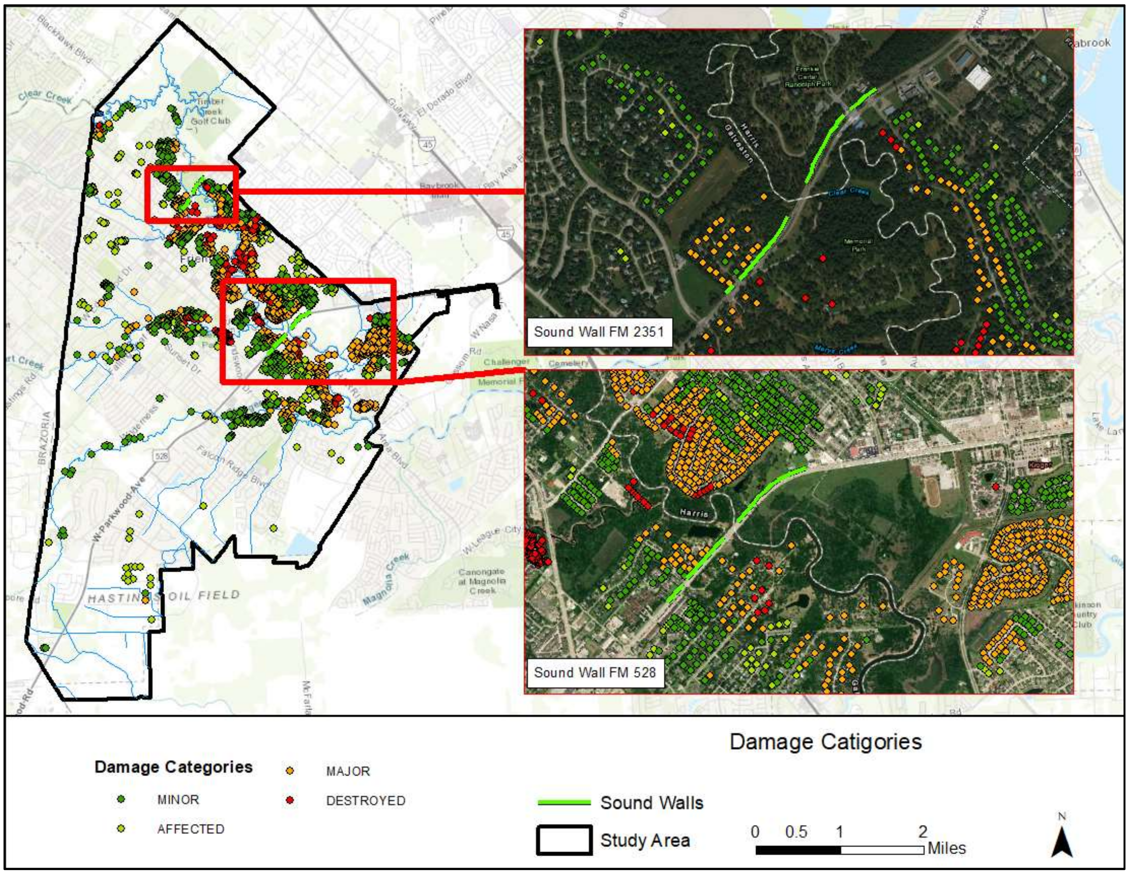

Figure 6-2 Damage Categories

6.2. Location Variables

6.2.1. Sound Walls

The sound walls were digitized using Google Earth and a combination of street view and aerial view to ensure accuracy at the endpoints. A drive-by was also conducted to determine the height, width, and any potential drainage holes in the sound walls.

6.2.2. Sound Wall and River Proximity

The distance to streams and sound walls was measured as a straight-line distance calculated from the centroid of the parcel to the nearest waterbody and nearest sound wall respectively.

6.2.3. Upstream / Downstream

The upstream or downstream location of the parcels relative to the sound walls was also calculated using GIS software. The delineation between upstream and downstream was determined using digital elevation models (DEMs) and converted contour maps to split the water flow of the surrounding areas accurately.

6.3. Control Variables

6.3.1. Precipitation

Precipitation is generally considered the most significant predictor of flooding and flood damages. Precipitation is measured as the average surface precipitation in millimeters (mm) recorded over the 7-day Hurricane Harvey storm event; this data was collected by the National Weather Service, and Iowa State University adjusted the gauge data. The precipitation ranged from 765 mm to 1131.5 mm within the study area.

6.3.2. Elevation

Elevation is also a key factor as a structure that is at a higher elevation or has been elevated above the base flood level should experience less flood inundation than one located at a lower elevation. The elevation within Friendswood averages around 30 feet, with an elevation range of -2 to 59 feet above sea level. This data was determined using a LiDAR dataset created by the Texas Natural Resources Information System (TNRIS).

6.3.3. Flood Zone

The Flood zone of the parcel was recorded. For example, a house located within a 100-year floodplain has a 1% probability of flooding each year; houses within a flood zone have a higher probability of flooding than houses located outside of a flood zone. There are four flood zone designations found within the study area: A, AE, B, and X and defined as follows:

1) Zones A and AE are considered high-risk areas with a 1% annual chance of flooding, shown in Figure 6-2 as the 100-year floodplain.
2) Zones B and X are considered to be moderate to low risk areas generally located in the areas between the limits of 100-year and 500-year floods.

The flood zones of Friendswood are shown in Figure 6-2. The floodplain data was provided by FEMA and coded into the dataset as a dummy variable where a parcel was either located in a high-risk flood area, a moderate risk flood area or outside of the floodplain.

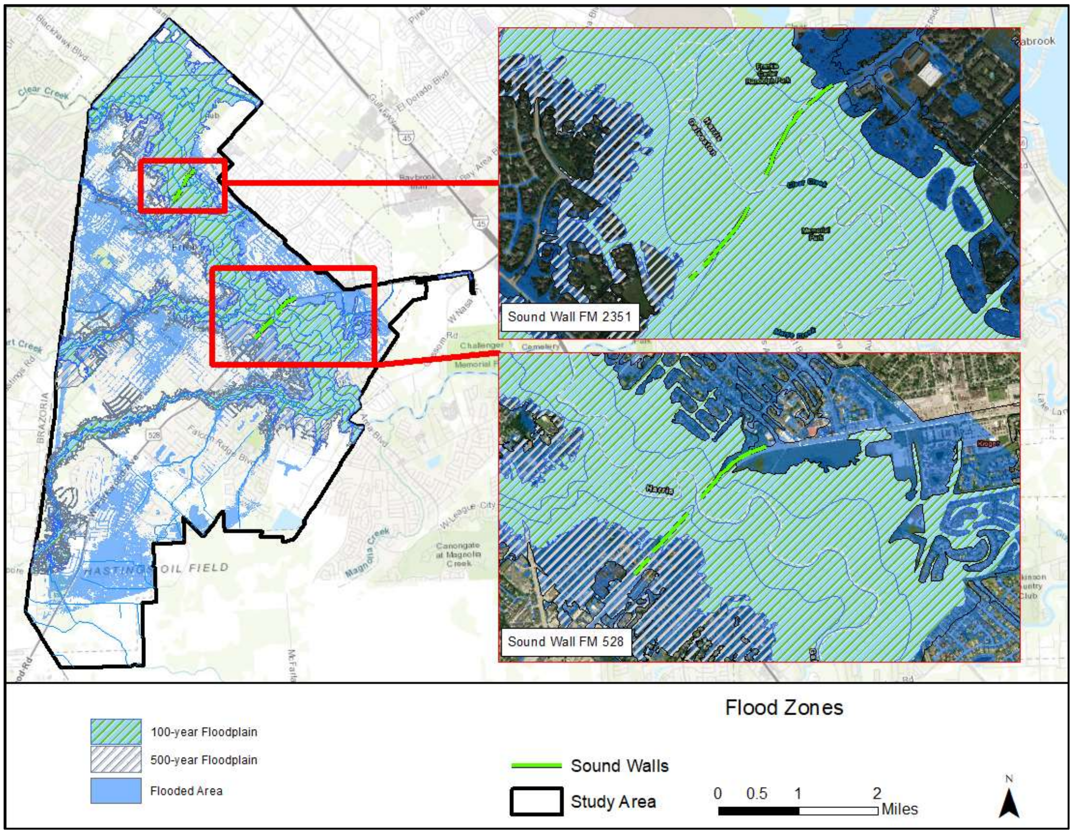

Figure 6-3 Flood Zones

6.3.4. Soil Drainage

The soil drainage class needs to be considered when accounting for flood depth as soil carrying capacity can reduce or improve overland runoff within residential areas. The Drainage Class of the soil refers to the frequency and duration of wet periods when the soil formed. The Natural Resources Conservation Service (NRCS) describes the three types of drainage classes found in Friendswood as:

1) Moderately well drained - water is removed from the soil in a somewhat slow manner with moderately low or lower saturated hydraulic conductivity.

2) Somewhat poorly drained - soils exhibit low or very low saturated hydraulic conductivity and have a high-water table from additional seepage or continuous rainfall.
3) Poorly drained - drained soils have water that moves so slowly the soil is wet at shallow depths throughout the year. There is free water commonly at or near the surface, and free water is usually present. The water table is commonly a result of low or very low saturated hydraulic conductivity of nearly continuous rainfall or a combination of these factors.

This dataset was then coded as a dummy variable where the soil was either classified poorly/somewhat poorly drained, or as moderately well drained.

6.4. Descriptive Statistics

The summary descriptive statistics for all variables in the model are shown in Table 6-2.

Table 6-2 Descriptive Characteristics of Variables

CONTINUOUS MEASURES				
Variable	Mean	Std. Dev	Min	Max
Flood Depth (log)	2.93	0.91	0.00	4.79
Precipitation	864.71	25.74	795.40	920.00
Elevation	23.19	3.40	4.29	35.94
River Proximity (ft)	773.15	563.88	10.80	3256.53
Sound Wall Proximity (m)	1088.22	716.45	9.74	7147.79
BINARY MEASURES				
Variable	Category		Freq	Percent
Flood Zone A	Out		1496	60.80
	In		958	39.20
Flood Zone B	Out		2013	82.36
	In		431	17.64
Drainage	Moderately well drained		1575	64.44
	Poorly Drained		53	2.17
	Somewhat poorly drained		816	33.39
Upstream FM 2351	Upstream		193	7.90
	Downstream		2251	92.10
Upstream FM 528	Upstream		1553	63.54
	Downstream		891	36.46
Damage Categories	Affected		216	8.84
	Minor		902	36.91
	Major		1,050	42.96
	Destroyed		276	11.29

Total Observations: 2,450

7. DATA ANALYSIS

Prior to any regression analysis, a flood depth layer was created from LIDAR data and the water depth data collected from the City of Friendswood. This provided a visual representation of high-water flooding within the study area (Figure 6.1). To directly test Hypotheses 1 and 2, the dependent variable means for proximity to the sound wall, and upstream/downstream location concerning the sound wall was examined. A one-way analysis of variance (ANOVA) was used to determine whether the mean of the flood damage categories was significantly different based on the proximity to sound walls. Additionally, paired t-tests were calculated to determine if there was a significant difference in the means of the upstream flood depths compared to the downstream flood depths for both sound wall FM 528 and sound wall FM 2351.

The data was then analyzed using a linear regression model to identify if proximity to sound walls and upstream/downstream location in relation to sound walls are significant predictors of flooding while controlling for other factors. The model estimated was:

$$\begin{aligned} Y(flood\ depth) \\ &= \beta_0 + \beta_1(sound\ wall\ proximity) \\ &+ \beta_2(upstream\ sound\ wall\ FM\ 2351) \\ &+ \beta_3\ (upstream\ sound\ wall\ FM\ 528) + \beta_4(river\ proximity) \\ &+ \beta_5(elevation) + \beta_6(Flood\ Zone\ A) + \beta_7(Flood\ Zone\ B) \\ &+ \beta_8(soil\ drainage) \end{aligned}$$

Significant spatial autocorrelation was detected using Moran's I on the original OLS residuals. To correct for this bias, diagnostics for spatial lag and spatial error models were estimated using Robust LaGrange Multiplier tests (Anselin *et al*., 1996) using an Inverse Distance spatial weights matrix. Diagnostics indicated that a spatial error regression model was the most appropriate to isolate the effect of sound walls on flood depth. No other statistical biases were found. Precipitation was excluded from the final model as it was highly uniform throughout the study area, which was not surprising given the small area analyzed.

8. RESULTS

Within the City of Friendswood, 2,444 residences had documented flooding associated with Hurricane Harvey; flooding depths ranged up to 120 inches or 10 feet. Flooding damage to the residences was sorted into four categories: minor, affected, major, and destroyed. Within Friendswood, 42.96% of residences received Major damage, while 276 residences were considered destroyed. Over 60% of the residences that were flooded occurred outside of the 100-year floodplain, despite the large amount of floodplain area within Friendswood.

8.1. Paired T-Tests

8.1.1. Differences in Flood Depth & Damage Means for Sound Wall Proximity & Upstream/Downstream Location

A paired t-test was completed on all flooded residences to determine whether there was a statistically significant mean difference between the flood depth upstream of the sound walls compared to the downstream residences. For sound wall FM 528, flood depth was greater upstream of the sound wall (mean = 28.89 ± 20.31 in) as opposed to the residences located downstream of sound wall FM 528 (mean = 21.43 ± 16.9). This difference was statistically significant (Table 8-1).

Table 8-1 T-test Sound Wall FM 528

T-test Sound wall FM 528				
Group	Obs	Mean (m)	Std. Err	Std. Dev
0 - Downstream FM 528	891	21.43	0.56	16.9
1 - Upstream FM 528	1559	28.89	0.51	20.31
Combined	2450	26.18	0.39	
Diff		-7.46	0.80	
diff = mean(0) - mean(1)				t = **-9.2760**
Ho: diff = 0			degrees of freedom = **2448**	
Ha: diff < 0		Ha: diff != 0	Ha: diff > 0	
Pr(T < t) = 0.0000		Pr(|T| > |t|) = 0.0000	Pr(T > t) = 1.0000	

Similarly, a paired t-test was calculated on the residences upstream and downstream of sound wall FM 2351. Interestingly, the test showed significance, but in the opposite direction. Flood depth was greater downstream of sound wall FM 2351 (mean = 27.03 ± 19.63) as opposed to the residences located upstream of sound wall FM 2351 (mean = 16.23 ± 14.181 in). The difference between the two groups was statistically significant (Table 8-2).

Table 8-2 T-test Sound Wall FM 2351

T-test Sound wall FM 2351				
Group	Obs	Mean (Units)	Std. Err	Std. Dev
0 - Downstream FM 2351	2257	27.02	0.41	19.62
1 - Upstream FM 2351	193	16.22	1.02	14.18
Combined	2450	26.18	0.39	
Diff		10.80	1.44	
diff = mean(0) - mean(1)				t = **7.4766**
Ho: diff = 0			degrees of freedom = **2448**	
Ha: diff < 0		Ha: diff != 0	Ha: diff > 0	
Pr(T < t) = 1.0000		Pr(|T| > |t|) = 0.0000	Pr(T > t) = 0.0000	

The paired t-test between the damage categories and the distance to sound walls revealed that there was a statistically significant difference between the different damage categories as determined by one-way ANOVA (F (3,2440) = 26.68, p = .000). A Tukey post-hoc test revealed that distance to sound walls were statistically significantly higher in the affected group compared to the destroyed group (442.78 ± 64.08 meters to sound wall, p = .000), between affected compared to minor (471.5 ± 53.43), and affected compared to major (412.20 ± 52.70).

Table 8-3 Summary of the Distance to Sound Wall (m)

Summary of the Distance to Sound Wall(m)					
Damage Category		Mean		Std.Dev	Freq.
Destroyed		1046.5532		416.81041	276
Major		1077.1308		584.60081	1,050
Minor		1017.8353		768.45357	902
Affected		1489.332		1132.6396	216
Total		1088.2239		716.44801	2,444
Analysis of Variance					
Source	SS	df	MS	F	Prob > F
Between groups	39829227	3	13276409	26.68	0
Within groups	1.21E+09	2440	497605.4		
Total	1.25E+09	2443	513297.8		
Bartlett's test for equal variances: chi2(3) = 325.2721 Prob>chi2 = 0.000					

These results suggest that the closer a parcel is to a sound wall, the higher the flood damage in the affected category. Conversely, the further a residence is from a sound wall; the more likely the damage will be classified as minor, this can be seen in Figure 6-2.

8.2. Regression Analysis

8.2.1. Testing Sound Wall Proximity & Upstream/Downstream Location while Controlling for Other Factors

As shown in Table 8-4 regression results, proximity variables play a critical role in predicting the amount of flood depth to residential properties after Hurricane Harvey. Three of the four proximity factors included in the model are statistically significant ($p < 0.05$): proximity to streams, proximately to sound walls, and whether the parcel was upstream of Sound Wall FM 528. Parcels located upstream of sound wall FM 528, but not sound wall FM 2351 were associated with statistically significant (where $p < 0.01$) increases in the flood depth. The further away from a sound wall, a parcel is located, the less likely it flooded.

Table 8-4 Flood Depth Regression Results

Error Model Regression Results				
Variable	Coef.	Std. Err.	Z	P>|z|
Elevation	-0.055***	0.007	-8.340	0.000
Flood Zone A	0.4069***	0.044	9.150	0.000
Flood Zone B	0.6832	0.047	1.460	0.145
Soil Drainage	-0.088**	0.035	-2.480	0.013
River Proximity	-0.0006***	0.000	-18.840	0.000
Sound Wall Proximity	-0.0002***	0.000	-5.340	0.000
Upstream of Sound wall FM 2351	-0.1098	0.116	-0.950	0.344
Upstream of Sound wall FM 528	0.2587***	0.047	5.520	0.000
Constant	4.4407***	0.148	30.070	0.000
W - e.LnDepth	5.2378***	0.030	176.820	0.000
W - var(eLnDepth)	0.3145	0.009		

Wald test of spatial terms: chi2(1) = 18,991.60 Prob > chi2 = 0.000

_*p<0.1;** p<0.05; *** p<0.01_

Total Observations: 2,450

Proximity to streams was also a strong predictor of flood depth. As expected, residences closer to a waterbody experienced significantly higher ($p < 0.000$) water depth. Residences within the 100-year floodplain incurred significantly higher amounts of flooding ($p < 0.01$) than those located outside of the floodplain. On the other hand, elevation was found statistically significant ($p < 0.01$) in reducing flood depth; the higher the elevation, the less likely the parcel was to be flooded.

9. DISCUSSION AND POLICY IMPLICATIONS

While much of Friendswood is in the historical FEMA-defined 100-year floodplain, over 60% of all flooded residences, occurred outside of the floodplain. This finding demonstrates a need for flood risk management to be emphasized for properties, not just inside the floodplain but outside of it as well. This study indicates that such risk management should consider the impacts of sound walls on flood risk.

9.1. Study Results

The results of this study indicate that residential proximity to a sound wall is a central factor when considering adverse impacts from storms resulting in overland flooding. Proximity variables were among the most reliable predictors for flood depth examined within the study area. The importance of sound wall location in predicting property damage has not been previously illustrated because sound walls have been generally overlooked as a contributing factor to flood damage.

Flooding upstream of sound wall FM 528 had a significant impact on residential flooding. One reason for this could be the lack of egress points, creating an impermeable barrier which caused a choke point on the flow of water resulting water accumulation. Interestingly, there was also an area of increased flood depth directly below the egress points on sound wall FM 528. If the sound wall had created a choke point, then all the water would be filtered into one area accounting for a more significant impact downstream. It can be surmised that sound walls cause a notable increase in residential flooding within its immediate vicinity; both upstream and down.

Surprisingly, being located upstream of sound wall FM 2351 did not make a significant difference in flood damages, while sound wall FM 528 had a significant impact on upstream flooding. There are a few possible reasons for this difference. First, there were more egress areas (e.g., openings in the sound wall for roads) in sound wall FM 2351; the wall was broken into four sections, allowing for a higher, more efficient discharge of water during the flood event. Sound wall FM 528 only had two, smaller, egress points. Additionally, the area located directly upstream of the sound wall FM 2351 is an open-area park, as such, no flood depth or damage was recorded, potentially skewing the regression results. The northern location of sound wall FM 2351 should be noted as well; only 7.88% of the analyzed residences were located upstream of sound wall FM 2351.

9.2. Policy Implications

Flood risk management helps reduce the impact of flood events. The degree of that risk could be a function of a property's flood vulnerability determined by factors such as its elevation, proximity to the stream or sound walls, flood zone designation, etc. Flood risk management requires the identification of all flood risks, as well as policies that address those risks and implements effective risk reduction measures. Potential adaptations to the sound walls need to be addressed against multiple criteria including egress, stream proximity and drainage openings, and under different flooding scenarios, and then integrated into flood mitigation policy.

Updating sound wall drainage could be implemented as a method to reduce residential flooding. Sound walls keep the floodwaters trapped upstream from the area behind the sound wall, similar to a levee, until the point at which area behind the sound walls is significantly more inundated and the people and property are affected. The risk to those behind sound walls is potentially a function of the characteristics of the sound wall (i.e., egress frequency, length, drainage openings), and their location (i.e., upstream or down). Sound walls impound the hydrologic flow of overland floodwater and can increase the probability of adjacent flooding.

Construction standards and building codes have been developed at the government level for sound walls, but there is no national standard for drainage requirements. This lack of standards fails to address the impacts of the floodwater that gets trapped upstream of a sound wall. However, additional measures can be added and enforced at the local level. New codes would provide for public safety while prescribing drainage practices and measures that directly reduce sound wall impact on flood damages – damages that could be significantly reduced by attention to modern drainage standards.

A few examples of implementing flood reduction requirements could be:

1) Requiring a full break in the sound wall every 500 feet or increasing drainage points based on proximity to a waterbody.
2) Establishing specific parameters for drainage, potentially based on base flood elevation.

3) Increasing the frequency of egress points in a sound wall that will let floodwaters flow freely.

These changes may be simple to implement but could significantly reduce the impact sound walls have on flooding. Furthermore, all built and impermeable structures should be assumed to have a direct effect on the flow of water. Policies should recognize how sound walls can affect potential flood depth. Understanding this and incorporating proper mitigation techniques, especially in residential areas that have high proximity to streams and flood zones, could help plan for flood resilient neighborhoods.

Precise mapping of risks provides the information necessary to make rational decisions in developing community-based flood risk management strategies. Planning and development efforts must extend beyond typical flooding measures, such as drainage measures and land use, as well as extending outside of floodplains to better capture flood hazards. Furthermore, these risks would be communicated to communities and residences so they may better prepare for potential flooding events. Some possible ways for risks to be mitigated would be for homeowners to purchase flood insurance even if located out of historical flood plain maps or to update to the floodplain maps, so they more accurately depict areas currently prone to flooding or may become prone to future flooding.

9.3. Validity Limitations

Validity and reliability threats are an unavoidable part of any study design. There are two main types of validity threats: internal and external (Campbell and Stanley 1963; Cook and Campbell 1979; Shadish, Cook, and Campbell, 2002). Internal validity refers to whether there is a strong relationship between the dependent and independent variables, while external validity is the confidence that the study results apply to other groups.

The main internal threat to this study is whether flood depth is related to the proximity to sound walls or if the flood depth may have risen due to other factors, such as debris build up or an unaccounted choke point on the stream. There is also the possibility that the independent variables were influenced by other ecological or regional factors that were not accounted for or cannot be realistically captured in a regression model. However, all practical measures have been taken to reduce the internal validity threats by attempting to control for factors that are known to influence flood inundation.

A main external validity threat is also present within this paper; flood depth is based on data collected during an unprecedented storm event. As a result, the findings of this study may be skewed based solely on the rarity of the event in which they were collected. In addition, this study was conducted on a small scale; some of the methods involved may become too time restrictive to apply to a more extensive study area. Furthermore, only two sound walls were tested, sound walls with different designs may affect floodwaters differently.

10. CONCLUSION

The results of this study indicate that the location of a parcel relative to a sound wall, especially upstream of a sound wall that has few drainage openings, is a critical predictor of flood depth in residential properties. While a targeted city-level analysis represents a proof of concept in understanding how sound walls can increase flood losses, it also lays the groundwork for additional research. First, this study only examines approximately 2,450 parcels within one city over a 13,351.4-acre section; the area affected by Hurricane Harvey was over 1.3 million acres. Future work should take an expanded approach, analyzing a whole watershed with various types and locations of sound walls. This approach would increase not only the sample size but also allow comparisons across different design tactics.

Additional measures of land use and development would add greater insight into the importance of residential proximity to sound walls on flood vulnerability. Characterizing the land use (e.g., open spaces, impervious surfaces, developed areas) may yield valuable information on the effect of sound walls in the development of flood-resilient communities. Finally, this study did not utilize in-depth modeling techniques, that could detail the effect of flooding with or without sound walls in place. For example, XP-Stormwater and Wastewater Management Model (XP-SWMM) (Guo, 2001; Sharifana, Roshan, Aflatoni, A.Jahedia, & Zolghadr, 2010) as well as the U.S. Army Corps Hydrologic Engineering Center (HEC) programs—Hydrologic Modeling System (HEC-HMS) and Stream Analysis System (HEC-RAS) (Knebl, Yang, Hutchison, & Mainment, 2005; Ostad-Ali-Askari & Shayannejad, 2015; Yang, Townsend, & Daneshfar, 2006) have been shown to effectively model detailed flooding. Measuring sound wall mitigation techniques and statistically testing their efficacy in decreasing observed flood depth could provide critical information to community planners for reducing the impacts of floods within their city. Using projected future storm and climate streams in these models would further identify adaptations that could improve community resilience into the future.

REFERENCES

Anselin, L., Bera, A., Florax, R., & Yoon, M. (1996). Simple diagnostic tests for spatial dependence. *Regional Science and Urban Economics*, 26:77–104.

Balaguru, K., Judi, D. R., & Leung, L. (2016). Future hurricane storm surge risk for the U.S. gulf and Florida coasts based on projections of thermodynamic potential intensity. *Climatic Change*, 138: 99–110.

Bilskie, M. V., Hagen, S. C., Alizad, K., Medeiros, S. C., Passeri, D. L., Needham, H. F., & Cox, A. (2016). Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern Gulf of Mexico. *AGU Publications*, 4: 177–193.

Brezonik, P., & Stadelman, T. (2002). Analysis and predictive models of stormwater runoff volumes, loads and pollutant concentrations from watersheds in the twin cities metropolitan area, Minnesota, USA. *Journal of the American Water Resources Association (JAWRA)*, 36: 1743–1757.

Brody, S. D., & Highfield, W. (2013). Open Space Protection and Flood Losses: A National Study. *Land Use Policy*, 32: 89-95.

Brody, S. D., Blessing, R., Sebastian, A., & and Bedient, P. (2013). Delineating the Reality of Flood Risk and Loss in Southeast Texas. *Natural Hazards Review*, 14: 89-97.

Brody, S. D., Blessing, R., Sebastian, A., & Bedient, P. (2018). Case study results from southeast Houston, Texas: Identifying the impacts of residential location on flood risk and loss. *Journal of Flood Risk Management*, 21: 5110-5120.

Brody, S. D., Highfield, W., & and Blessing, R. (2015). An empirical analysis of the effects of landuse/landcover on flood losses along the Gulf of Mexico coast from 1999 to 2009. *Journal of the American Water Resources Association (JAWRA)*, 51: 1-12.

Brody, S. D., Peacock, W., & Gunn, J. (2012). Ecological indicators of resiliency and flooding along the Gulf of Mexico. *Ecological Indicicators*, 18: 493–500.

Brody, S. D., Zahran, S., Highfield, W. E., Grover, H., & Vedlit, A. (2007). *Identifying the impact of the built environment on flood damage in Texas.* Oxford, UK: Blackwell Publishing.

Brody, S., Blessing, R., Sebastian, A., & Bedient, P. a. (2013b). Examining the impact of land use/land cover characteristics on flood losses. *Journal Of Environmental Management*, 57: 1252–1265.

Brody, S., Highfield, W. E., Blessing, R., Makinoc, T., & and Shepardd, C. C. (2017). Evaluating the effects of open space configurations in reducing flood damage along the Gulf of Mexico coast. *Landscape and Urban Planning*, 167: 225-231.

Brody, S., Highfield, W., Ryu, H., & Spanel-Weber, L. a. (2007a). Examining the relationship between wetland alteration and watershed flooding in Texas and Florida. *Natural Hazards*, 40: 413–428.

Brody, S., Sebastian, A., Blessing, R., & Bedient, P. (2018). Case study results from southeast Houston, Texas: identifying the impacts of residential location on flood risk and loss. *Journal of Flood Risk Management*(11), 11: 110-120.

Brody, S., Zahran, S., Highfield, W., Grover, H., & Vedlitz, A. (2007b). Identifying the impact of the built environment on flood damage in Texas. *Natural Disasters*, 32: 3661-3666.

Brody, S.D.; Highfield, W.E.; Kang, J.E. (2011). *Rising waters: causes and consequences of flooding in the United States.* Cambridge, UK: Cambridge University Press.

Burchell, R., Shad, N., Listokin, D., Phillips, H., Down, A., Seskin, S., . . . and Gall, M. (1998). *The Costs of Sprawl—Revisited.* Washington, D.C: National Academy Press.

Burges, S. J., Wigmosta, M. S., & Meena, J. M. (1998). Hydrological Effects of Land-Use Change in a Zero-Order Catchment. *Journal of Hydrological Engineering*, 3: 86–97.

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., & Kendall, C. (2005). Effects of suburban development on runoff generation in the croton river basin. *Journal of Hydrology*, 311: 266-281.

Campbell, D., & Stanley, J. (1963). *Experimental and quasi-experimental designs for research.* Chicago, IL: Rand-McNally.

Cook, T. D., & Campbell, D. T. (1979). *Quasi-experimentation: Design and analysis issues for field settings.* Boston, MA: Houghton Mifflin Company.

Faccini, F., Luino, F., Paliaga, G., Sacchini, A., Turconi, L., & de Jong, C. (2018). Role of rainfall intensity and urban sprawl in the 2014 flash flood in Genoa City, Bisagno catchment (Liguria, Italy). *Applied Geography 98*, 98: 224–241.

Franci, F., Mandanic, E., & Bitelli, G. (2015). Remote sensing analysis for flood risk management in urban sprawl contexts. *Geomatics, Natural Hazards and Risk*, 06: 583-599.

Franci, F., Mandanici, E., & and Bitelli, G. (2015). Remote sensing analysis for flood risk management in urban sprawl contexts. *Geomatics, Natural Hazards and Risk*, 6: 583-599.

Guo, Y. (2001). Hydrologic design of urban flood control detention ponds. *Journal of Hydrologic Engineering*, 6: 1061-1084.

Haddad, B. O., Ashofteh, P., & and Mariño, M. (2015). Levee Layouts and Design Optimization in Protection of Flood Areas. *Journal of Irrigation and Drainage Engineering*, 10: 141-152.

Highfield, Norman, & Brody. (2012). Examining the 100-Year Floodplain as a Metric of Risk, Loss, and Household Adjustment. *Risk Analysis*, 33: 186-191.

Highfield, W. E., Brody, S. D., & Shepard, C. (2018). The effects of estuarine wetlands on flood losses associated with storm surge. *Ocean and Coastal Management*, 157: 50–55.

IPPC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change.* Cambridge: Cambridge University Press.

Klingner, R. E., Mcnerney, M. T., & Busch-Vishniac, I. (2003). *Design Guide for Highway Noise Barriers.* Austin: Texas Dept of Transportation.

Knebl, M., Yang, Z., Hutchison, K., & Mainment, D. (2005). Regional scale flood modeling using NEXRAD rainfall, FIS and HEC-HMS/RAS: a case study for the San Antonie River Basin Summer 2002 storm event. *Journal of Envrionmental Management*, 75(4): 325-336.

Lambert, T. E., Catchen, J., & and Vogelgesang, V. (2015). *The Impact of Urban Sprawl on Disaster Relief Spending: An Exploratory Study.* Available at SSRN: https://ssrn.com/abstract=2738396 or http://dx.doi.org/10.2139/ssrn.27383.

Leopold, L. (1994). *A View of the River.* Cambridge, MA: Harvard University Press.

Maurer, E. P., Kayser, G., Doyle, L., & and Wood, A. W. (2018). Adjusting Flood Peak Frequency Changes to Account for Climate Change Impacts in the Western United States. *Journal of Water Resources Planning and Management*, doi: 10.1061/(ASCE)WR.1943-5452.0000903.

Michel-Kerjan, E., Lemoyne de Forges, S., & and Kunreuther, H. (2012). Policy tenure under the US National Flood Insurance Program (NFIP). *Risk Analysis*, 32: 644–658.

Munoz, S. E., Giosan, L., Therrell, M. D., Remo, J. W., Shen, Z., Sullivan, R. M., . . . and Donnelly, J. P. (2018). Climatic control of Mississippi River flood hazard amplified by river engineering. *Nature*, 556: 95–98.

NOAA. (2013). *US climate extremes index.* Retrieved from National Oceanic and Atmospheric Administration: http://www.ncdc.noaa.gov/extremes/cei/

Ostad-Ali-Askari, K., & Shayannejad, M. (2015). Usage of Rockfill Dams in the HEC-RAS Software for the Purpose of Controlling Floods. *American Journal of Fluid Dynamics*, 5(1): 23-29.

Pistrika, A., Tsakiris, G., & Nalbantis, I. (2014). Flood Depth-Damage Functions for Built Environment. *Springer International Publishing Switzerland*, 1(4): 553–572.

Sebastian, A., Lendering, K., Kothuis, B., Brand, N., Jonkman, S. N., GelderPieter, v., . . . Lhermitte, S. (2017). *Hurricane Harvey Report. A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region.* Houston : TUDelft University.

Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). *Experimental and quasi-experimental designs for generalized causal inference.* Boston, MA: Houghton Mifflin.

Sharifana, R. A., Roshan, A., Aflatoni, M., A.Jahedia, & Zolghadr, M. (2010). Uncertainty and Sensitivity Analysis of SWMM Model in Computation of Manhole Water Depth and Subcatchment Peak Flood. *Science Direct*, 2: 7739-7740.

TCEQ. (2017, Oct. 2). *EPA/TCEQ: updated status of systems affected by Harvey.* Retrieved from Texas Commission on Environmental Quality: https://www.tceq.texas.gov/news/releases/epa-tceq-updated-status-of-systems-affected-by-harvey-2

Texas Department of Transportation . (2011). Building Barriers to Traffic Noise. *Environmental Affairs Division*.

TxDOT. (2011). *23 CFR Part 772 - Prodecures for abatement of highway traffic noise and construction noise*. Retrieved from Legal Information Institute: https://www.law.cornell.edu/cfr/text/23/part-772#

USACE. (2012). *Final. Supplemental Environmental Impact Statement for the Clear Creek General Reevaluation Study Brazoria, Fort Bend, Galveston, and Harris Counties, Texas.* Galveston: U.S. Army Corps of Engineers.

Wenger, C. (2015). Building Walls Around Flood Problems: The Place of Levees in Australian Flood Management. *Australasian Journal of Water Resources*, 19: 3-30.

Yang, J., Townsend, R. D., & Daneshfar, B. (2006). *Applying the HEC-RAS model and GIS techniques in river network floodplain delineation.* Ottawa: NRC Research Press.