Rice University

Addressing Uncertainty in Residential Damage Estimates from Tropical Cyclone Storm Surge, with a Focus on Variability in Structure Elevations

by

John Nicholas Irza

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree

Master of Science

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Houston, Texas
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Accurate surge damage estimates are essential to coastal risk analyses. This study aims to improve damage modeling practices for residential structures by assessing how different elevation assumptions affect modeled damages and how such uncertainty can be addressed. Inaccuracies associated with applying riverine methodologies to surge damages are also explored. A residential damage model was developed for Galveston County, Texas. Model results showed high sensitivity to elevation assumptions in damage totals and spatial distribution of damage. Discrepancy in estimates produced under different assumptions approached $2 billion. A survey of home elevations in the county was conducted to correct the elevation estimates, reducing uncertainty substantially. Additional uncertain parameters were incorporated into the damage model and uncertainty (UA) and global sensitivity (GSA) analyses were performed with respect to different independence assumptions. UA results suggested that the status quo in uncertainty analyses may over-predict model variability. GSA results showed high sensitivity to independence assumptions.
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## Abstract

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In 2005, roughly 1,100 people perished because of Hurricane Katrina (Rappaport, 2014).\(^1\) The deadliest storm to strike the United States since the 1928 Okeechobee Hurricane, Katrina accounted for 40% of tropical cyclone fatalities observed in the United States between 1963 and 2012 (Rappaport, 2014).

As a historical outlier in terms of death and destruction, Katrina shared similarities with the 1953 North Sea Flood that claimed the lives of 1,836 people in Netherlands (Gerritsen, 2005). The North Sea Flood occurred when a slow-moving low-pressure system brought high winds and storm surge to a wide expanse of North Sea coastline, affecting England, Germany, Belgium and the Netherlands. The Netherlands were subjected to the worst of the storm, where a 13.1 ft (4 m) storm tide\(^2\) ruptured some 150 dykes, many of which were poorly designed and inadequately maintained (Gerritsen, 2005). The resulting inundation caused extensive structural damage, the evacuation of some 100,000 people and the aforementioned loss of life (Gerritsen, 2005).

\(^1\)The exact number of deaths directly attributable to Katrina remains uncertain. Previous publications have cited values between 1,200 and 1,500 (Blake and Gibney, 2011), while reports immediately following the disaster estimated a death toll as high as 1,833 (Graumann et al., 2006). The 1,100 value is the most up-to-date estimate available (Rappaport, 2014).

\(^2\)Storm tide is the combined water surface elevation from storm surge and astronomical tides.
Less than three weeks into the aftermath of the North Sea Flood, the Delta Committee convened to conceive a strategy to ensure that such a disaster would never occur again. One year later, the Committee presented its initial report and the beginning of what would become the Delta Works: a clean-sheet design of a stratified system of flood control structures that would ultimately offer protection up to the 10,000-year storm in the most at-risk areas (Gerritsen, 2005; Wesselink, 2007).

Like the North Sea Flood, much of Hurricane Katrina’s destruction was attributed to inadequacies in existing flood protection systems. After Hurricane Betsy struck New Orleans in 1965, the United States Congress authorized the construction of the Greater New Orleans Hurricane Protection System. Construction of the network of levees, pumps and other flood control structures was initially estimated to take 13 years at a cost of $90 million, but ultimately required 40 years and $700 million (van Heerden, 2007). Nevertheless, because of the use of outmoded standards in the design of the system—as built—the Greater New Orleans Protection System was under-sized for the 100-year storm. Further compromising the function of the system was the fact that its levee foundations were improperly designed to resist foundation scour when over-topped (van Heerden, 2007). Thus, when Hurricane Katrina made landfall, over half of New Orleans’ levees experienced full or partial failure, with the resulting widespread inundation greatly exacerbating damage and loss of life (Graumann et al., 2006; van Heerden, 2007).

After Katrina and the failure of the Greater New Orleans Hurricane Protection System, approximately $15 billion has been spent to repair and renovate the system, resulting in what is now known as the Greater New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS) (Coastal Protection and Restoration Authority of Louisiana, 2012). The updated system is designed to provide 100-year protection and to resist scour when over-topped, ensuring some degree of protection will
remain in the event that the capacity of the system is exceeded (Sills et al., 2008). Currently, the HSDRRS’s level of protection is significantly less than what is offered by the Delta Works, although Louisiana’s coastal master plan does call for the system to eventually achieve a 500-yr level of service (Coastal Protection and Restoration Authority of Louisiana, 2012).

While billions of dollars were invested after Katrina to improve protection for the greater New Orleans region, the Dutch emphasis of disaster avoidance over disaster response remains antithetical to the predominant school of thought in other coastal areas of the United States. Today, coastal developments continue to grow, even when the true risk of such construction remains uncertain and often under-communicated to the public. Even after the destruction caused by Hurricane Ike (2008) and Hurricane Sandy (2012), thousands of miles of U.S. coastline remain vulnerable. And adding to this vulnerability is the looming threat of climate change; rising sea levels and changing weather patterns have the potential to dramatically increase coastal flood risk on a worldwide scale (Knutson et al., 2010; Peduzzi et al., 2012; Walsh et al., 2016).

This is not to discount the importance of disaster response. No protection system is invulnerable—the Delta Works included. In fact, after Katrina, concerns arose that the Dutch population had become overly-confident in their level of flood protection, potentially leading to ill-advised development in the floodplain and reducing public responsiveness in the rare case of a disaster (Wesselink, 2007).

Nonetheless, disaster response alone is inadequate for regions with dense coastal development and/or infrastructure. In these regions, the unmitigated consequences of a storm are—quite simply—too significant. Within the United States, the cities of New Orleans, Miami and New York and the petrochemical facilities of the Houston-
Galveston region are examples of areas where a substantial level (≥500-yr) of tropical cyclone protection should be seriously considered.

So, while the next major storm to make landfall in the United States may be the watershed event that results in a national reevaluation of flood risk reduction policy—the United States’ equivalent of the 1953 North Sea Flood, a more palatable option would be to see if such a change could be introduced gradually, avoiding the necessary consequences of such a disaster (If Katrina, Ike and Sandy were not enough to get our attention, what storm will be sufficient?).

The research community can serve a key role in transforming the United States’ approach to flood risk management. In the years since Hurricane Katrina, an extensive body of literature has evolved around improving the process of hurricane risk assessment. And as our ability to accurately characterize tropical cyclone risk on the large-scale becomes increasingly robust, the resulting conclusions may present a reality too poignant to ignore. Hopefully, this revelation will be the watershed moment that induces a widespread transition from a reactionary to a proactive approach to coastal risk management within the United States.

This thesis represents a small contribution to this effort and will focus on addressing some of the challenges and uncertainties associated with estimating damage to single family residential structures from tropical cyclone storm surge. With this context in mind, this chapter will serve as an introduction to the hazards presented by such storms, the need to develop strategies to mitigate their threat and the prerequisite need for accurate hazard assessment. At the conclusion of the chapter, the study area for this thesis will be introduced—and with it—much of the motivation behind this study’s specific research objectives.
1.1 The Tropical Cyclone Hazard

The tropical cyclone (TC) hazard consists of the joint threat of strong winds, heavy rainfall, storm surge and waves that can devastate a coastal community when a storm makes landfall. While these components collectively represent a TC’s potential hazard, if a particular storm presents all or a subset of these threats depends on the characteristics of the storm and the vulnerabilities of the region it impacts.

1.1.1 The Tropical Cyclone Hazard in the United States

In the United States, tropical cyclones can make landfall essentially anywhere along the Gulf and Atlantic coasts—from South Texas to Maine. On average, the U.S. receives 17.8 hurricanes per decade. Of these storms, 6.0 are major hurricanes, which are classified as Category 3 or greater on the Saffir-Simpson Hurricane Scale (SSHS) (Blake and Gibney, 2011). TCs have accounted for nine out of the top fifteen costliest weather disasters in the United States since 1980, with hurricanes Katrina (2005), Sandy (2012) and Andrew (1992) occupying the top three positions with respective damage totals of $153.5, $67.6 and $45.9 billion (in 2015 dollars) (NOAA). As will be outlined in the subsequent sections, each of these storms produced these considerable damage totals, despite having decidedly different characteristics.

1.1.1.1 Hurricane Andrew

In 1992, Hurricane Andrew made landfall in southeast Florida, destroying 25,000 homes and damaging 125,000 (Rappaport, 1993). At its initial landfall, the storm had sustained winds of approximately 167 mph (75 m/s), classifying it as a Category 5 on the SSHS (Landsea et al., 2004). Wind damage from the storm was extensive; Andrew’s winds decimated entire subdivisions, especially those comprised primarily
of mobile homes. In the hardest-hit areas, 99% of mobile homes were destroyed by the storm (Rappaport, 1993).

While Andrew had a storm tide as high as 16.9 ft (5.2 m), damage due to storm surge was not as widespread as that from its high winds (Rappaport, 1993). In their post-storm damage assessment, Fronstin and Holtmann (1994) determined that only three homes were destroyed from storm surge out of those in 420 subdivisions—high winds destroyed the rest. Surge damage was likely decreased by Andrew’s small size, which despite its high wind intensity, limited the magnitude and the extent of its surge impacts (Powell and Reinhold, 2007; Irish et al., 2008; Bass et al., 2016).\textsuperscript{1}

Fronstin and Holtmann (1994) also observed in their assessment that newer structures, those built after the 1970s, were more likely to have been destroyed by winds. The increase in vulnerability in newer construction was attributed by Fronstin and Holtmann (1994) to an “erosion of the building code”, which was the product of market pressures for cheaper housing and regulatory lapses to meet the demand.

\subsection{1.1.1.2 Hurricane Sandy}

When Hurricane Sandy made landfall near Brigantine, New Jersey, its sustained winds were just 81 mph (36 m/s), making it “only a Category 1” on the SSHS (Blake et al., 2013). Therefore, unlike Andrew, the storm was not a significant threat in terms of wind damage. However, Sandy’s huge size, partially due to a concurrent extra-tropical transition, produced a substantial, widespread storm tide in highly populated regions of New York and New Jersey, killing 72 people and causing extensive damage (Blake et al., 2013). The highest storm tide observed during Sandy was 16.9 ft (5.2 m), but most areas affected by the storm reported values greater than 7.2 ft (2.2 m) (Schubert et al., 2015). In many areas, the observed storm tide was greater than FEMA flood

\textsuperscript{1}See Section 3.2 for more detail regarding storm size vs. intensity as indicators of a TC’s potential to generate storm surge.
elevations corresponding to the 1% annual exceedance probability (Schubert et al.,
2015).

In total, Hurricane Sandy damaged or destroyed an estimated 650,000 homes in
the Northeast (305,000 were destroyed in New York, alone). Most of the damage
was attributed to Sandy’s surge and waves (Blake et al., 2013; Hatzikyriakou et al.,
2015). Damage to infrastructure were also substantial. New Jersey reported roughly
$2.9 billion in damage to transportation infrastructure, and New York City suffered
$5 billion in damage to its subway system when eight tunnels and two stations were
inundated by the storm. $2.5 billion in additional damage was done to New York’s
infrastructure (Blake et al., 2013).

1.1.1.3 Hurricane Katrina

As mentioned in the introduction, at landfall as a large, Category 3 hurricane (SSHS)
at the Louisiana-Mississippi border, Hurricane Katrina wielded the dual threats of
intense winds and extreme storm surge (in a sense, the union of the hazards of Andrew
and Sandy). While the wind damage from the TC was significant, the damage due
to storm surge was extraordinary. Storm tides in the range of 24-28 ft (7.3-8.5 m)
were recorded along long swaths of the Mississippi coastline, and storm tides between
10-17 ft (3.0-5.2 m) overwhelmed the New Orleans levee system (Graumann et al.,
2006). Inundation resulting from the levee failure was responsible for an estimated
two-thirds of the fatalities in the New Orleans area and extensive property damage
(Jonkman et al., 2009).

Katrina’s death toll makes it the third deadliest tropical cyclone to make land-
fall in the United States since 1851 (Blake and Gibney, 2011). Although, it should
be noted that the first and second positions are respectively occupied by the 1900
Galveston Hurricane (~8,000 deaths) and the 1928 Florida/Lake Okeechobee Hurri-
cane (∼2,500 deaths). Unlike Katrina, both storms struck prior the advent of modern forecasting, communication and protection systems (Blake and Gibney, 2011). In 2005, the tragedy that was Hurricane Katrina clearly demonstrated that, despite modernization, tropical cyclones can still result in catastrophic loss of life.

1.1.1.4 Tropical Storm Allison

While a smaller disaster when compared to Andrew, Sandy and Katrina, Tropical Storm Allison (2001) is an instance when rainfall was the primary hazard presented by a TC. After the storm made landfall at Galveston Island, Texas, it dropped up to 37 inches (95 cm) of rain on the City of Houston and surrounding Harris County (Kelly, 2001). Since the storm did not have high winds and did not generate a significant storm tide, Allison’s damage toll was almost exclusively due to rainfall-induced flooding: 45,000 homes and businesses were inundated by the storm. The widespread flooding resulted in approximately $6.7 billion (CPI-adjusted, 2015) in damage, forty percent of which was done to the Texas Medical Center (Kelly, 2001).

While Allison is the most destructive tropical storm on record, the fact that the total damage caused by the storm is lower than the prior examples should not diminish consideration of the rainfall hazard. In fact, if the U.S. moves towards a preventative approach for coastal risk, future protection systems will have to address the fact that TC rainfall has been shown to potentially complicate the design and function of structural mitigation strategies (Torres et al., 2015).

1.1.2 The Tropical Cyclone Hazard Globally

Figure 1.1 shows the tracks and SSHS categories of documented TCs over a 150-year period (1856-2006). The figure demonstrates the prevalence of the TC hazard and shows that the North Atlantic Hurricane basin is not the most active worldwide.
However, the magnitude of TC activity does not alone dictate the regional threat posed by tropical cyclones. In fact, the deadliest TC ever recorded made landfall in Bangladesh in 1970, a region of the globe with relatively subdued TC activity. The 20 ft (6.1 m) storm tide produced by the Bangladesh Cyclone killed approximately 300,000 people, making it the deadliest such storm on record (Frank and Husain, 1971). The Bangladesh disaster reflects essentially the worst-case scenario in that it occurred at the intersection of a dangerous storm, a dense, poorly-protected population and little advanced warning. Nevertheless, the event does illustrate the upper bounds of the potential for damage from tropical cyclones.

More recently, Typhoon Haiyan (2013) made landfall in the central Philippines with sustained winds of 196 mph (88 m/s), which is well over the Category 5 threshold (SSHS). The high winds and the large storm tide generated by the TC resulted in the deaths 6,300 people, even with advance warning of the storm’s landfall (Lagmay et al., 2015).
1.1.3 Damage Taxonomy

So far, discussion of previous storms has quantified disaster using two metrics: monetary damage and loss of life. However, damage taxonomy is more nuanced. Following the classification guide outlined by Jonkman et al. (2008),\textsuperscript{1} TC damage is first categorized as either direct or indirect. Direct damage is that is an immediate consequence of the hazard, and is often further classified as tangible or intangible. Tangible, direct damage is that can be easily assigned a dollar value; it includes damage to buildings, infrastructure and farmland as well as costs associated with interruption to business, emergency response and immediate environmental cleanup. Direct, intangible damage—on the other hand—is an immediate consequence of the hazard that cannot be easily assigned a dollar value. Direct, intangible damage includes loss of life as well as environmental/ecosystem damage beyond the immediate cost of cleanup.

Indirect damage does not share an immediately apparent nexus with the disaster. Like direct damage, it can be further classified as tangible and intangible, depending on how easily it is assigned a monetary value. Tangible, indirect damage includes cascading regional or national economic impacts originating from the initial disaster as well as demographic shifts in the immediately affected (and surrounding) areas due to redevelopment or evacuation. Intangible, indirect damage includes psychological trauma and loss of public trust in government authorities.

This thesis will primarily focus on direct damage assessment. However, it should be understood that—to fully characterize the hazard presented by TCs—all types of damage should be taken into consideration. For more information on indirect and intangible damage assessment for tropical cyclones and riverine floods, the reader is referred to the review provided by Merz et al. (2010). Additionally, Jonkman et al.

\textsuperscript{1}While Jonkman et al. (2008) were primarily focused on the consequences of flooding, their classification framework can be extended to the consequences of any disaster.
(2008) outline how direct and indirect damage assessment can be incorporated into a single modeling framework.

1.1.4 The Persistence of the Tropical Cyclone Hazard

One of the primary reasons why tropical cyclones have presented a continual hazard in the United States, despite modernization, is that coastal communities in the United States have experienced rapid population growth throughout the twentieth and twenty-first centuries. The sustained growth has resulted in burgeoning populations in the areas most vulnerable to tropical cyclones (Perry et al., 2001; Mackun et al., 2011). Botts et al. (2015) estimated that, across these coastal communities, over 6.6 million single family homes are at risk from damage due to storm surge alone. In total, the assets at-risk constitute an estimated reconstruction value of over $1.4 trillion dollars.

Unfortunately, this problem has been exacerbated by a poor regulatory framework that has ensured that when development does occur in at-risk areas, the cost of such construction does not adequately factor in the associated increase in risk. Citing many failures, Burby (2006) outlined how regulatory shortcomings contributed to the disaster that was Hurricane Katrina, including the role the National Flood Insurance Program (NFIP) had in subsidizing development in hazardous areas and the general disconnect between federal studies of coastal flood risk and local zoning and development policies. Dolan and Wallace (2012) observed similar phenomena along the Upper Texas Coast. Because most of flood risk regulation in the United States takes place at the federal level, such problems are likely endemic to much of the developed U.S. coastline.

Excluding shortcomings in local regulation, climate change will likely be a significant factor in ensuring the persistence of the TC hazard globally and throughout the
twenty-first century. While uncertainty remains in our understanding of how climate change will ultimately alter coastal TC risk, research has suggested that while the overall frequency of TCs generated worldwide will decrease, the average intensity of such storms is likely to be higher (Emanuel et al., 2008; Knutson et al., 2010). This trend in TC frequency in intensity on a global scale has been generally supported by more recent studies (Walsh et al., 2016). However, assessments of individual tropical cyclone basins are subject of considerable uncertainty. This is especially the case in the North Atlantic basin (Walsh et al., 2016).

A century from now, changes in TC frequency and intensity due to climate change and a one meter (3.28 ft) increase in mean sea level could cause New York City’s 100-year surge depths to occur every 3-20 years and the 500-year surge depths to occur every 25-240 years (Lin et al., 2012). Similar trends are likely to be observed on a global scale. Even with improved governance and development strategies, over the next 20 years, climate change will still result in a substantial increase in the number of people exposed to the TC hazard worldwide (Peduzzi et al., 2012). Hanson et al. (2011) estimated, by the 2070s, Miami and New York will be, respectively, the first and third most vulnerable cities worldwide in terms of assets exposed to coastal flooding. In areas susceptible to coastal erosion and/or subsidence, the increase in TC risk over the next century will likely be more substantial than with climate change alone (Hanson et al., 2011).

1.2 Hazard Assessment: A prerequisite to Risk-Based Design

Having established the severity and the persistence of the tropical cyclone hazard, it becomes clear that eventually some action must be taken to mitigate the threat.
The first step in the mitigation process is to identify the most vulnerable regions so resources can be prioritized for their protection. Once these areas have been determined, mitigation alternatives—structural and non-structural—can be developed, evaluated and implemented to reduce coastal risk.

It follows that a key component of the mitigation process is to be able to quantify the regional TC hazard. This is essential to both initial investigations of at-risk areas and evaluations of the economics of different mitigation approaches; i.e., the value of the alternative’s risk reduction, relative to annualized costs of the project. This process, known as risk-based design, was pioneered by the United States’ aerospace industry in the 1960s, when Boeing utilized it in the design of the Minuteman missile and 747 aircraft (Keller and Modarres, 2005). Risk-based design procedures were further refined by the nuclear industry in the late 1960s and early 1970s, when risk-based design was used to characterize and mitigate the low-probability, high-consequence failure modes endemic to reactor design (Keller and Modarres, 2005). In flood protection, risk-based design was first adopted in the U.S. by the USACE in the mid-1990s (USACE, 1996). Subsequently, it has found widespread use in Europe (Apel et al., 2009).

Because accurate quantification of the hazard is essential to the risk-based design progress, a significant amount of research has been invested into improving such estimates for coastal and riverine flood risk mitigation projects as well as quantifying their uncertainty. This thesis is focused on direct storm surge damage to single family residences, but an overview of the current state of TC risk assessment is provided by Lin et al. (2014). In addition to surge damage modeling, the review summarizes current practices in TC climatology, hydrodynamic modeling and wind damage modeling—all of which will not be addressed in this document.
Outlined in the preceding sections, the magnitude of the TC hazard, its persistence and the consequential need for its accurate assessment constitute the overarching motivation for this study. The motivation behind the specific focus of this thesis—damage estimates for single family residences—is best understood in the context of its Study Area.

1.3 The Study Area

This thesis will focus on the Houston-Galveston region of the Upper Texas Coast, specifically, Galveston County. Figure 1.2 is a map of this region, with the Study Area outlined in dark red. The Houston-Galveston region encompasses Galveston Bay, a shallow, wind-driven estuarine system with an average depth of approximately 7 ft (2.1 m). Galveston County can be divided into three principle regions: the mainland, Galveston Island and the Bolivar Peninsula. Galveston Island and the Bolivar Peninsula border the county to the southwest and southeast, respectively, and partition Galveston Bay from the Gulf of Mexico. The primary nexus between Galveston Bay and the Gulf of Mexico is the inlet at Bolivar Roads, which is located in between Galveston Island and the Bolivar Peninsula. San Luis Pass, to the southwest of Bolivar Roads, and Rollover Pass, to the northwest, are the two other points of access to Galveston Bay.

The Houston Ship Channel (HSC) runs through Bolivar Roads and up the length of Galveston Bay to the Port of Houston, which is the second largest port in the United States in terms of overall tonnage (American Association of Port Authorities). The port generates $264.9 billion in total statewide economic impact and is home to a $15

\(^1\)The Port of South Louisiana is the largest by this metric (American Association of Port Authorities).
Figure 1.2: Map showing the Houston-Galveston region with the boundaries of this thesis’ study area, Galveston County, outlined in dark red. Highways are depicted in yellow, significant roads in gray and heavily developed areas in shaded gray. Inset depicts county location relative to the rest of the state of Texas.
billion petrochemical complex—the second largest in the world (The Port Authority of Houston).

Located on the east end of Galveston Island is downtown Galveston City. This area is the most densely populated area on Galveston Island and the Bolivar Peninsula, and is considered the region’s cultural and historical center. The western portion of Galveston Island (known as the West End) and much of the Bolivar Peninsula are also developed, but sparsely so, especially when compared downtown Galveston. In terms of the mainland, major population centers include the communities of Texas City, League City, Kemah, San Leon, La Marque and Tiki Island. These population centers tend to be distributed in the northern, eastern and central portions of the county. The Tiki Island region is the exception to the south. Figure 1.2 depicts the communities’ locations.

1.3.1 Historical Storms in the Houston-Galveston Region and Existing Surge Protection

The Houston-Galveston region has historically been one of the most hurricane-prone areas in the United States. Since 1850, sixteen storm surges of 16.4 ft (5 m) or greater have been recorded in the region (Sebastian et al., 2014). The most infamous of these events was the 1900 Galveston Hurricane, which having killed roughly 8,000 people is still the deadliest natural disaster on record in the United States. In response to the 1900 disaster, between 1902 and 1904, a 17 ft (5.18 m) seawall was constructed along the seaward side of downtown Galveston. The seawall proved effective during the 1915 hurricane, as the storm only resulted in the deaths of 11 people in downtown Galveston. Further north in Galveston Bay, between 1962 and 1987, a 20 ft (6.1 m) tall levee was constructed around Texas City, which is home to one of the largest
industrial centers in the Houston-Galveston region. Figure 1.2 shows the locations of these two structures.

1.3.2 Hurricane Ike

On September 13, 2008, at 0100 CDT, Hurricane Ike made landfall at the north end of Galveston Island as a strong Category 2 storm (SSHS) with 110 mph (49 m/s) winds and a minimum central pressure of 950 mb (Berg, 2009). Despite its relatively low intensity, Ike produced substantial storm surge because of its immense size. At Hurricane Ike’s peak strength, 40 hours before landfall, tropical storm force winds extended 400 km from the center of the storm and hurricane force winds extended 140 km (Berg, 2009). As a comparison, despite having a much higher sustained intensity, Hurricane Andrew’s tropical storm force winds extended 190 km from the storm’s center; its hurricane force winds only extended 77 km (Powell and Reinhold, 2007).

In Galveston County, the highest storm tide observed during Ike was on the Bolivar Peninsula, where water surface elevations were estimated to vary between 15–20 ft (4.6–6.1 m) above mean sea level (MSL). On Galveston Island, Ike’s storm tide was lower, approximately 10–15 ft (3.0–4.6 m) above MSL (Berg, 2009). The storm resulted in approximately $33.3 billion (CPI-Adjusted, 2015) in damage, making Ike the fourth costliest storm to hit the U.S. since 1981 (NOAA).

While Hurricane Ike caused extensive damage to the Houston-Galveston region, the disaster was far from the worst-case scenario. Had Ike made landfall 22 miles (35 km) to the southwest of its original landfall location, a significantly higher storm tide would have been observed not only in Galveston County, but—more critically—in the Houston Ship Channel (Bedient, 2012; Sebastian et al., 2014). Such a substantial storm surge in the HSC could have been catastrophic, potentially causing extensive
damage to petrochemical facilities and resulting in a long-term production outage, which could have consequences for the entire U.S. economy. Such a disaster could also result in the large-scale release of hazardous chemicals into the Houston Ship Channel and Galveston Bay, producing widespread environmental damage (Bedient, 2012; Burleson et al., 2015; SSPEED Center, 2015).

1.4 Protection Proposals for the Houston-Galveston Region

Hurricane Ike exposed many vulnerabilities to TC storm surge in the Houston-Galveston region. In response, in the years following the storm, several different mitigation strategies have been proposed for the region. Examples of such proposals include a continuous barrier spanning the entire Galveston Bay coastline (the Ike Dike or the Coastal-Spine) (Merrell et al., 2010) and a localized surge gate for the Houston Ship Channel (the Centennial Gate) (Bedient et al., 2011; Christian et al., 2014). Figure 1.3 shows a rendering of the proposed HSC surge gate. Non-structural mitigation approaches have been proposed as well, including the Texas Coastal Exchange and the Lonestar Coastal National Recreation Area (Blackburn et al., 2014).

More recently, Rice University’s Severe Storm Prediction Education and Evacuation from Disasters Center (SSPEED Center) has been evaluating several different protection alternatives known as the Houston-Galveston Area Protection System, or HGAPS (SSPEED Center, 2015). The HGAPS alternatives contain many elements from previous proposals, including a HSC surge gate and a coastal barrier design. In addition to these features, the HGAPS also includes a novel approach to surge suppression: a gate structure located in the middle of Galveston Bay known as the Mid-Bay Strategy (SSPEED Center, 2015; Torres et al., 2016). Figure 1.4 presents
the different levee and gate alignments under consideration as a part of the HGAPS initiative. The Mid-Bay Strategy would augment existing surge protection with features G, H, F, E, and M, as shown in Figure 1.4. Two additional strategies under consideration by the SSPEED center, the Lower-Bay Strategy and the Upper-Bay Strategy, shift the location of the proposed gate structure in the Mid Bay Strategy to the locations indicated by features L and U in Figure 1.4, respectively.\footnote{These two approaches draw heavily from previous proposals. The Lower-Bay Strategy is similar to the Coastal Spine or Ike Dike proposal, and the Upper-Bay strategy is a variation on the Centennial Gate concept.}

In the process of evaluating different HGAPS configurations, preliminary assessments of the damage reduction offered by each of these mitigation strategies have been conducted (SSPEED Center, 2015). As mentioned previously, such benefit analyses are an essential procedure in risk-based design. To perform these analyses, researchers have developed novel surge damage modeling methodologies, including a modeling
Figure 1.4: Map showing the various surge protection alternatives under consideration as a part of the SSPEED Center’s Houston-Galveston Area Protection System (SSPEED Center).
framework to estimate industrial damage to the petro-chemical facilities in the Houston Ship Channel (Burleson et al., 2015) as well as procedures to estimate potential damage to petro-chemical storage tanks (Kameshwar and Padgett, 2015) and bridges (Kameshwar and Padgett, 2014).

In addition to these efforts, a damage model was developed for single family residences (SFRs) in Galveston, Chambers and Harris counties (SSPEED Center, 2015). While the model was only designed to perform a preliminary damage assessment, the development process raised several concerns about standard approaches to residential surge damage modeling. Such concerns would eventually evolve into the research objectives that are the focus of this thesis.

1.5 Chapter Conclusion and Research Overview

This chapter provided an overview of the tropical cyclone hazard, which consists of the threat presented by high winds, extreme rainfall, waves and storm surge. As shown through historical storm events, any storm may present all or a subset of these hazards. Additionally, the TC threat was shown exist on a global scale; climate change, coastal development, subsidence and sea-level rise all have the potential to exacerbate this global issue in the coming decades. Focus was then shifted towards methods to mitigate the surge hazard, specifically the process of risk-based design and the requisite need for accurate damage assessments. The Houston-Galveston region was then introduced as the Study Area for this thesis, and an overview of surge protection initiatives developed by the local research community in the aftermath of Hurricane Ike was provided. Challenges associated with quantifying the damage reduction provided by these alternatives was the primary motivation behind this thesis’ work.
The following chapters will outline research that is focused on advancing current practices in storm surge damage assessment for single family residential structures from simple, low-resolution models that are heavily dependent on assumptions, to more detailed, data-rich analyses. This thesis will largely focus on building elevation estimates for coastal residences, which, despite appearing insignificant at a first glance, will be shown to serve a key role in the damage modeling process. Analysis will also be focused in drawing distinctions between modeling riverine flood damage, which is solely inundation-driven, and surge damage modeling, which requires consideration of potential damage from high waves and water velocities in addition to inundation. Current modeling practices will be shown to not adequately account for this distinction. Finally, uncertainty and sensitivity analysis will show that even with the improvements in residential damage modeling presented by this body of work, significant uncertainty remains. Therefore, this work should be contextualized as a small component of a larger “push” towards improved damage assessment—indirect and direct, intangible and tangible, and not just for single family residences. In this spirit, recommendations for further investigation will be provided in the conclusion of this document.
2.1 Why Single Family Residential Structures?

As stated in Chapter 1, this thesis will focus on modeling storm surge damage to single family residential structures. The primary justification behind choosing this scope is that single family residences (SFRs) constitute the clear majority of at-risk assets in Galveston County. Within the Study Area, SFRs constitute 95.9% of the total number of residential parcels and 95.2% of total residential parcel value (see Table 2.1).\footnote{Parcel data were obtained from the Galveston Central Appraisal District.} Figure 2.1 illustrates this point by visualizing the prevalence of SFRs relative to other residential parcel classes. The same assessment in adjacent Harris County resulted in a similar conclusion: SFRs accounted for 96.8% of residential parcels and 85.4% of their total appraised value.\footnote{Average multi-use property values increased from 365,932 in Galveston County to 2,029,910 in Harris County, resulting in a relative decrease in total SFR value. Parcel data were obtained from the Harris County Appraisal District.}

With this knowledge, it is clear that—at least in the Houston-Galveston region—damage analysis of SFRs should be prioritized over other residential asset classes.
In other areas of the U.S., the proportion of SFRs relative to other residential asset classes may be lower; however, it is unlikely that SFRs will become negligible in all but the most densely populated areas. Moreover, with respect to intangible damage assessment, impacts to SFRs, despite sometimes constituting a smaller proportion of a region’s potential direct tangible damage, can proxy for the social impact of a storm, thereby increasing their relative importance. This is because, unlike commercial, industrial or environmental damage, damage to SFRs imparts a direct burden on the region’s population.

Another area where SFR hazard assessment plays an outsize role is in evacuation management. Dueñas-Osorio et al. (2012) developed a framework to estimate hurricane risk in Harris County, Texas to compare assessed risk with the risk perceived by residents surveyed after Hurricane Ike. Dueñas-Osorio et al. (2012) were able to show a mismatch between perceived and actual risk and demonstrated that this mismatch.
Table 2.1: Residential parcel counts and values for Galveston County by type: single family, mobile homes, condominiums, small-scale multi-family and large-scale multi-family.

<table>
<thead>
<tr>
<th>Parcel Type</th>
<th>Total No.</th>
<th>Total Val.</th>
<th>% of Total No.</th>
<th>% of Total Val.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Family</td>
<td>103,022</td>
<td>$15,141 M</td>
<td>95.9%</td>
<td>95.2%</td>
</tr>
<tr>
<td>Mobile Homes</td>
<td>2,388</td>
<td>$59 M</td>
<td>2.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Condominiums</td>
<td>150</td>
<td>$35 M</td>
<td>0.1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Multi-Family (Small)</td>
<td>1,291</td>
<td>$108 M</td>
<td>1.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Multi-Family (Large)</td>
<td>526</td>
<td>$556 M</td>
<td>0.5%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

ccontributed to shadow evacuation during the storm.\(^1\) Improvements in coastal hazard assessment for SFRs could aid in communicating disaster risk (and, conversely, lack of risk) more effectively to residents prior to a storm, potentially reducing the number of shadow evacuees as well as those disobeying evacuation orders.

### 2.2 The Standard Method for Flood Damage Assessment

Having established the importance of accurate assessment of coastal risk for single family residences, an overview of the typical methodology for performing such assessments is necessitated. Storm surge damage is effectively an extension of flood damage. In areas with minimal wave action and low water velocities, surge damage is inundation-driven and mirrors damage from riverine flooding. When waves and/or high water velocities are present, the damage paradigm shifts. Increased forces from the water and waves can cause extensive structural damage or complete destruction of buildings. Section 2.3 will explore this distinction in greater detail. This section, however, is concerned with the inundation-driven component of surge damage, which

\(^1\)Shadow evacuation describes instances when residents decide to evacuate from a storm when they are not required to do so. While such behavior might seem at first to be relatively harmless, shadow evacuees can complicate evacuation for those under mandatory evacuation orders.
is typically modeled using the same methodology as flood damage, using what will be referred to in this thesis as the standard method for flood damage assessment (the Standard Method). The Standard Method is as follows (see Figure 2.2):

1. Obtain water surface elevation data by using a hydrodynamic model, a wave model, observed data, or regulatory floodplains.

2. Develop an asset inventory. Data are typically aggregated from land-use/land-cover data, tax assessor databases and parcel datasets.

3. Determine the asset values, i.e., the maximum possible damage.

4. Apply a depth-damage function based on the asset type to estimate the inundation damage from the flood as a percentage of the total asset value. Use the resulting percentage and the asset’s value to compute the estimated damage.

This approach to flood damage assessment is generally seen at the internationally accepted methodology (Vrisou van Eck et al., 2000; Egorova et al., 2008; Jongman et al., 2012). The Standard Method is not a recent development, either; the concept of the depth-damage function has its roots in the United States in the 1960s (White, 1964; Smith, 1994). While some damage models utilize absolute functions, which relate inundation to a monetary sum, relative damage functions, which relate inundation to a damage percentage of the asset’s total value, are more commonly employed because they tend to be more accurate (Merz et al., 2004). This is because absolute functions do not account for variability in asset characteristics that can influence flood damage (Merz et al., 2004). Additionally, absolute damage functions require regular re-calibration from observed flood damage to maintain accuracy, whereas relative functions usually only require updates to asset values (although this need for up-to-date asset values could also be weakness in areas where such data are not readily available) (Merz et al., 2010).
In addition to functions for a SFR’s structure and contents, damage curves exist for a large variety of other asset types, including commercial structures and contents, vehicles, industrial facilities, hospitals and infrastructure (see Penning-Rowsell et al. (2005) and FEMA (2012) for example functions). However, damage functions can vary substantially by source or region (see Figure 5.1, for example). And, even though most damage models utilize the Standard Method, different models can produce significantly different damage estimates for a given storm event (e.g., Apel et al. (2009) and Jongman et al. (2012)).

2.3 Surge Damage vs. Flood Damage: Deviations from the Standard Method

Despite being developed for riverine floods, the Standard Method has been widely utilized in coastal risk assessments (e.g., Aerts et al. (2013), Johnson et al. (2013),...
Schubert et al. (2015) and SSPEED Center (2015)). In the United States, this is likely because the most commonly used damage modeling software packages, the Federal Emergency Management Agency’s (FEMA) HAZUS-MH (HAZards U.S. Multi-Hazard) (Scawthorn et al., 2006a,b; FEMA, 2012) and the U.S. Army Corps of Engineers’ HEC-FDA (Flood Damage Assessment) (USACE, 2014), employ this approach. Despite its ubiquity, there are some key issues associated with directly applying the Standard Method to model surge damage.

The major limitation in using the Standard Method to estimate surge damage is that the depth-damage functions assume inundation is the sole driver of damage. For riverine floods, this is not a bad assumption. While it has been suggested that damage models should incorporate water velocity into their analyses, it was shown that velocity has little relation to structural flood damage, with inundation serving as a much better predictor (Kreibich et al., 2009). However, since Kreibich et al. (2009)’s work focused on riverine flooding, where flow velocities are relatively low (<2 m/s (6.6 ft/s), in the study), their conclusions cannot be extrapolated to surge analyses where velocities can be higher.

A study of residential building damage in New Orleans from Hurricane Katrina by Pistrika and Jonkman (2010) showed higher damage in areas subjected to higher flow velocities due to levee failures. Nadal et al. (2010) performed a stochastic, component-based analysis of flood damage to reinforced-concrete frame buildings under a variety of depth and velocity scenarios. Inundation was shown to drive damage at low water velocities. But, at high velocities (>5.5 m/s, 18 ft/s), such as those observed in extreme TC storm surges or tsunamis, Nadal et al. (2010)’s results suggested that velocity can play an increased role in damaging structures. However, Nadal et al. (2010) did note that because wave action played a key role in causing damage, inun-
Inundation remained a relevant parameter to consider as it indicated if waves were able to affect the structure.

Observations of residential damage after Hurricane Ike supported the findings of Nadal et al. (2010) and Pistrika and Jonkman (2010); widespread instances of complete structural failure suggested the presence of damage mechanisms beyond inundation (FEMA, 2009; Kennedy et al., 2011). Kennedy et al. (2011) observed a binary pattern of building destruction from Ike on the Bolivar Peninsula that was dictated by the elevation of the structures relative that of the breaking waves. Sufficiently elevated homes survived, most others did not. Kennedy et al. (2011) also noted that the transition from minimal damage to complete structural collapse occurred within a small range of structure freeboard, approximately 1.6 ft (0.5 m). Figure 2.3 shows images of a community on the Bolivar Peninsula before and after Hurricane Ike to illustrate this phenomenon.

Using damage observations from the Bolivar Peninsula obtained after Hurricane Ike, Tomiczek et al. (2014) developed fragility equations for pile-elevated, wood-framed homes, and found that building freeboard, wave height, water velocity and construction date were relevant factors in predicting building destruction. Tomiczek et al. (2014)’s findings supported the observations made by Kennedy et al. (2011), as their regression analysis showed that building freeboard and wave height showed the highest skill in predicting observed damage. Kennedy et al. (2011)’s findings pointed to wave impact as the principle factor in determining if a structure collapsed from storm surge, and that complete destruction tended to occur once sufficiently high wave heights reached the elevation of the home’s lowest horizontal structural member (LHSM).

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1 The elevation of the structure relative to the elevation of the wave crests.
2 Since Hurricane Ike had relatively low wind velocities (Category 2, SSHS), Tomiczek et al. (2014)’s results were assumed to reflect only the effects of storm surge, since modern building codes likely prevented anything beyond minor wind damage.
Figure 2.3: Images of the Crystal Beach community on the Bolivar Peninsula before/after Hurricane Ike (top/bottom). The yellow arrow indicates the location of the same structure in both photos (U.S. Geological Survey).
While Tomiczek et al. (2014) included velocity and building age in their regression analysis, the results suggested that the two parameters were not nearly as important as building freeboard or significant wave height. However, the observed water velocities used by Tomiczek et al. (2014) to develop the fragility curves were relatively low (<1.6 m/s, 5.2 ft/s).

Similar observations were made of residential damage from Hurricane Sandy. A Bayesian network-based approach was applied by van Verseveld et al. (2015) to assign structures to different classes of damage severity. The authors found that depth of inundation and wave attack showed the highest predictive skill with respect to structural damage. A component-based analysis of residential damage due to Hurricane Sandy was conducted by Hatzikyriakou et al. (2015). The study found that structures located in areas close to the failure zones of coastal dune systems had a higher threat of foundation failure. Hatzikyriakou et al. (2015) also noted that waterfront structures often served as breakwaters for landward buildings. However, in instances where the front line of residences was destroyed, the resulting debris would often extensively inland structures. Hatzikyriakou et al. (2015) also found the elevation of a building’s LHSM above ground was negatively correlated with the observed damage.

Because Hatzikyriakou et al. (2015) did not incorporate any storm surge data from a hydrodynamic model into their analysis, they were not able to assess how Sandy’s storm tide, wave heights, or velocities related to the observed damage. Consequently, many of their results, such as distance from the coast being negatively correlated with damage and ground elevation being positively correlated with damage,\(^1\) were likely proxies for hydraulic conditions during the storm (Hatzikyriakou et al., 2015).\(^2\)

\(^1\)Because of the topography of Hatzikyriakou et al. (2015)’s study area, structures located closest to the ocean were actually constructed on the highest ground.

\(^2\)Like Ike, Hurricane Sandy (Category 1, SSHS) did not have sufficiently high wind velocities to produce significant damage.
Also, most of the structures (365 out of 376) within Hatzikyriakou et al. (2015)’s study area were constructed using closed foundations. This is in direct contrast to the previously mentioned studies of the Bolivar Peninsula, where most structures were elevated on wood piles. However, it appears the built environment in downtown Galveston City is similar to the region assessed by Hatzikyriakou et al. (2015), at least in terms of predominate foundation type and density of development. Future work should further investigate the distinctions in between the behavior of surge damage in different developed environments, so that more nuanced fragility equations can be developed.

From these recent publications, it becomes clear that other factors besides inundation are responsible for storm surge damage to single family residential structures. While work remains in terms of developing/improving models specifically for storm surge, it is likely that utilizing the Standard Method in coastal risk assessments results in an underestimate of damage, since the threshold for complete structural failure is so closely tied to if a structure’s LHSN is inundated and not the depth of inundation (Kennedy et al., 2011; Tomiczek et al., 2014). Therefore, the Standard Method results in elevated coastal structures with a low level of inundation being assessed minor damage via depth-damage functions, when—in reality—the structures were likely to have been completely destroyed by waves.

Of course, the Standard Method could still overestimate damage for a given storm simply due to depth-damage functions providing poor estimates of inundation damage. However, in such a scenario, an entire class of potential surge-specific damage is still omitted. Therefore, in instances where the Standard Method overestimates damage, correctly accounting for surge damage should result in a further increase in the magnitude of overestimation.
Unfortunately, both HAZUS-MH and HEC-FDA do not support incorporating these surge-specific damage pathways into their analyses (FEMA, 2012; USACE, 2014). HAZUS-MH does employ a separate set damage functions for structures located in the FEMA coastal VE zones (FEMA, 2012); however, the functions still rely on depth of inundation as the sole predictor of damage. Additionally, none of the available HAZUS-MH functions incorporate wave height (FEMA, 2012; Tomiczek et al., 2014).

2.4 Residential Structure Elevations and Storm Surge Damage Modeling

In both the standard method for flood damage assessment and in more recent studies of surge-specific damage mechanisms, one of the major predictors of damage is the elevation of the structure relative to that of the water surface or wave crests. Relative depth-damage curves for residential structures and contents typically relate inundation above the first finished floor (FFF) of the home to a percentage damage of the structure or its contents (Davis and Skaggs, 1992; USACE, 2006; FEMA, 2013). Likewise, damage observations by Kennedy et al. (2011) and Tomiczek et al. (2014) after Hurricane Ike suggested structure elevation (in this case, freeboard of the building’s LHSM relative to wave height) was a key indicator of structural failure probability. Similar conclusions were drawn by Hatzikyriakou et al. (2015) in their analysis of Hurricane Sandy’s residential damage.
2.4.1 Regulation of Building Elevations in Coastal Areas and other Sources of Elevation Variability

Because a structure’s elevation dictates so much of its vulnerability to damage from both inundation and storm surge, it is the principle mechanism used to manage riverine and coastal flood risk in the United States. After a community enters the National Flood Insurance Program (NFIP), any new, substantially improved or substantially damaged construction within the boundaries of special flood hazard areas (SFHAs) is required to meet the following minimum elevation requirements:

- Construction in AE zones: sufficiency elevated such that the first finished floor is at or above base flood elevation (BFE) (FEMA, 2002).

- Construction in VE zones: sufficiently elevated on piers or piles such that the lowest horizontal structural member is above BFE (FEMA, 2002).

Within these requirements, SFHAs are the boundaries of the 100-year floodplain and BFEs are the corresponding 100-yr water surface elevations. Structures in the shaded (500-year floodplain) and unshaded portions of Zone X are not subjected to any minimum elevation requirements, nor are those constructed before the community entered the NFIP. BFEs and the boundaries of SFHAs are obtained via the region’s or watershed’s most recent flood insurance study (FIS) (FEMA, 2002).

Beyond satisfying the minimum elevation requirements of the NFIP, coastal municipalities can also require additional freeboard. This additional requirement is typ-

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1 Areas of riverine flooding or coastal flooding inland from the VE zones, without significant wave action.

2 Areas of coastal flooding with high waves and water velocities.

3 It should be noted that floodplain maps within the United States are deterministic, i.e., there is a clearly defined border between flood zones. However, there is uncertainty associated with this delineation and studies have argued that a probabilistic representation of floodplains should be adopted (e.g., Di Baldassarre et al. (2010)). How such uncertainty should be implemented in a regulatory framework remains unclear, especially as probabilistic floodplains may present challenges in their communication to the public.
Figure 2.4: Depiction of the different FEMA flood zones. Note how the post-NFIP structure in zone VE is depicted as elevated, such that its LHSM is above BFE; whereas, the pre-NFIP structure is shown constructed slab-on-grade (FEMA).

Because of the NFIP, regulations concerning elevation of newly-constructed or substantially-improved residences in many coastal communities have changed significantly over the past half-century. While the major transition in construction practices is typically before and after a community enters the NFIP, construction regulations can change substantially over the years, as subsequent FISs produce revised flood-plains and BFEs or as communities implement and change provisions requiring additional freeboard. Also, reconstruction after storms can result in varying building elevations because highly-damaged areas that are rebuilt are required to be elevated at least to BFE. Adjacent areas not subjected to damage can remain at pre-storm elevations.
However, a structure’s elevation is not only dictated by regulation. In areas of historical flood risk, such as Galveston Island and the Bolivar Peninsula, many pre-NFIP structures are elevated substantially above adjacent grade because historical storms prompted conservative building practices. This observation runs contrary to what is depicted by FEMA in Figure 2.4 (i.e., the assumption that pre-NFIP construction is slab-on-grade).

Additionally, some post-NFIP construction may be elevated beyond the regulatory elevation. Possible explanations for this practice could be builders wanting to reduce the flood risk for such structures; or—more likely—homeowners’ desire to have additional space below their residences for storage or vehicle parking. The result of such a wide variety of regulations and construction practices is that residences within U.S. coastal communities often exhibit significant variation in elevation, even on a local scale. Figure 2.5 shows two examples of such variability within the Study Area.

2.4.2 Incorporating Variation of Building Elevations into Damage Modeling

At this juncture, it is evident that adequate knowledge of structures’ elevations is a pre-requisite for accurate damage assessment. Unfortunately, obtaining such data presents a significant challenge, especially on the scale required for coastal risk assessments. Communities participating in the NFIP are required to keep some record of the elevations of the LHSMs and FFFs of all post-NFIP construction (FEMA, 2004).\(^1\) Often, such records take the form of FEMA elevation certificates, because adopting the format earns credit under the CRS (FEMA, 2015).

While some communities within the U.S. make digital copies of elevation certificates available online, most do not. Throughout Galveston County, elevation cer-

\(^1\)Pre-NFIP homeowners can optionally provide elevation information to qualify for lower flood insurance premiums.
Figure 2.5: Examples of variation in the elevation of residences within the Study Area. A.) Adjacent homes in downtown Galveston showing pre- vs. post-FIRM construction practices. The houses to the left and center were built in 2014 and 2011, respectively. The house on the right was constructed in 1959, prior to the NFIP. B.) Adjacent, post-NFIP homes on the Bolivar Peninsula. Most likely an example of residents electing to add additional freeboard. 
Source of Images: Google Street View.
Certificates are maintained by individual municipalities as paper records and require an Open Records Request to obtain access. This makes obtaining large quantities of elevation certificates extremely time consuming, essentially infeasible on a county-wide basis. And even when such data is readily available, since pre-NFIP residences are not required to submit elevation information under the NFIP, there may be significant gaps in this data in areas with an older building stock—downtown Galveston is an example of such an area.

Consequently, the typical approach to incorporating building elevations into residential damage models is to make assumptions, typically employing one of three approaches:

1. Assign building elevations based on age, foundation type and flood zone. This is what is currently employed by HAZUS-MH (FEMA, 2012).

2. Assume compliance or non-compliance with FEMA BFEs and municipal regulations based on age and flood zone. This was the approach utilized by SSPEED Center (2015).

3. Some combination of the above.

Depending on the region, these three approaches can produce significantly different estimates of building elevation. Assessing uncertainty in storm surge damage assessments due to these different assumptions is one of the primary objectives of this study.
2.5 Uncertainty in Flood and Coastal Risk Assessments

There is a significant body of literature surrounding assessment of uncertainty in flood damage estimates. Apel et al. (2004) showed how uncertainty in levee failure and in extreme value statistics for annual discharge resulted in significant uncertainty in the resulting exceedance probabilities of damage for a polder at Mehrum, along the Rhine River. The study, however, did not place a large emphasis on uncertainty in the damage calculations themselves, but rather focused on uncertainty in the hydraulic conditions and levee failures.

Merz et al. (2004) focused on uncertainty damage functions. The authors assessed roughly 4,000 damage records from German flood events between 1978 and 1994 and showed that absolute depth-damage functions performed poorly in predicting the observed damage. Merz et al. (2004) suggested that the use of relative functions would likely be more accurate, but still raised concerns that cost benefit analyses for flood control projects may be inaccurate when using current practices. In general, all of the uncertainty studies reviewed as a part of this thesis cited depth-damage functions as a major source of uncertainty in damage analyses.

Egorova et al. (2008) presented an approach to assess uncertainty in flood damage functions as well as the in the maximum possible damage that could be done to an asset. The authors’ damage model was applied to different inundation scenarios for a dike ring in the Netherlands, and the model was run under different assumptions of spatial independence and dependence in the behavior of the uncertain parameters. The results showed that variability in damage estimates is highly sensitive to the independence assumptions. Further discussion of Egorova et al. (2008)’s methodology and findings is included in Chapter 5.
Apel et al. (2009) explored how increasing levels of detail in the hydraulic and damage analyses affects the accuracy of damage estimates. Comparing the estimates to recorded damage from a 2002 flood in Germany, the authors found that a compromise in accuracy and level of effort could be reached using a combined 1-D/2-D hydraulic model with a medium-detail damage model. Interestingly, the results suggested much greater variability between different damage models versus using different hydraulic modeling approaches.

A study by Merz and Thieken (2009) investigated how different aspects of the flood damage modeling process contributed to uncertainty in flood risk curves. Three components of the process were considered in the study: flood frequency analysis, inundation estimation and damage estimation. The relative contributions of the different components to uncertainty in the estimated damage was shown to vary with the magnitude of the flood; however, damage modeling was consistently the lowest contributor to overall uncertainty.

Freni et al. (2010) further investigated uncertainty in depth-damage functions and showed that because of the magnitude of uncertainty associated with such functions, the marginal benefit in accuracy obtained by using a more detailed hydraulic model was overshadowed by uncertainty in the damage functions. Uncertainty bounds (95% CI) for the depth-damage functions were shown to be 40% to 50% of the mean value. However, it should be noted that the study used absolute damage functions instead of relative functions.

Koivumäki et al. (2010) performed a small-scale analysis of flood damage assessment uncertainty for a 2005 flood in Kittilä, Finland. The authors found that uncertainties in the exposure analysis (whether a building was impacted by flooding) played a more important role at this scale than studies of larger areas; uncertainty was also attributed to damage functions as well. In a similar focus on exposure anal-
ysis, Boettle et al. (2011) found that terrain model uncertainty was more important during more frequent storm events, but diminished in importance with less-probable storms.

A study by de Moel and Aerts (2011) compared the relative importance of uncertainty in inundation depth, land use, asset valuation and damage functions to overall uncertainty in damage estimates. Overall, damage estimates for a dike ring in the Netherlands were shown to vary by a factor of 5-6.\(^1\) Depth-damage functions and asset values were shown to contribute the greatest to the overall uncertainty.

Jongman et al. (2012) compared the damage estimates provided by seven off-the-shelf flood damage models for two European floods. Substantial variability was observed in the damage estimates produced by the different models. Much of this variability was attributed to discrepancies in the damage functions used by different models. The authors also noted the need for improved infrastructure damage modeling, as none of the models properly captured infrastructure damage observed during the flood events.

A study by de Moel et al. (2012) evaluated uncertainty in coastal flood risk assessments in the western Netherlands. A Monte Carlo framework to efficiently assess different scenarios of a levee breach was applied, with the results demonstrating that depth-damage functions were the largest contributor of uncertainty in the damage modeling process. The authors also found that uncertainty in damage modeling was approximately commensurate that associated with modeling the surge hazard and levee failure.

Saint-Geours et al. (2013) evaluated how uncertainty propagated through the entire risk-based design process. Sensitivity analysis was performed on the net present value (NPV) of a flood control project on the Orb river, which is in France. Uncertain

\(^1\) The highest estimate was 5-6 times the lowest estimate.
parameters included flood frequency statistics, damage functions, land-use, water depths and project cost. While each of these components were shown to contribute equally to the overall uncertainty in the NPV calculations, depth-damage functions accounted for—by far—the largest amount of uncertainty in the estimates of annual avoided damage for residential structures.

Expanding on the work performed by de Moel et al. (2012), de Moel et al. (2014) assessed uncertainty in expected annual damage (EAD) estimates for the failure of a dike ring in the Netherlands. Uncertainty in dike failure and breach growth was incorporated at 13 different locations along the levee ring. Sensitivity analysis, performed by the authors, showed that uncertainty in depth-damage functions contributed the most to uncertainty in EAD estimates; however, uncertainty in the duration of the flood wave and its associated probability were of a similar magnitude. Regardless, de Moel et al. (2014)’s findings suggest that uncertainty in the damage analysis be given equal weight to that of the surge hazard in coastal risk assessment.

Finally, Tate et al. (2014) conducted one of the few studies on uncertainty in flood damage assessment in the United States. Tate et al. (2014) performed a sensitivity analysis of the HAZUS-MH model, finding that modeling the flood hazard, building stock and damage functions were all important contributors to uncertainty.

A common conclusion can be synthesized from this body of work: flood and coastal risk assessment is fraught with uncertainty. Uncertainty/sensitivity analysis should therefore be an essential part of any risk assessment, especially because it appears that the relative importance of different uncertain parameters may vary on a case-by-case basis, as shown by the varying conclusions of the previously mentioned studies. Nonetheless, depth-damage functions were singled out as a major source of uncertainty in almost all reviewed publications.
Variability in structural elevation relative to adjacent grade was not given major consideration in most of the uncertainty studies reviewed for this thesis; it was mentioned in only two of the reviewed studies. Koivumäki et al. (2010) commented that a lack of building elevation data likely hindered the accuracy of their damage assessment. Saint-Geours et al. (2013) incorporated variability in home elevations in their assessment. However, variation in residential elevation within Saint-Geours et al. (2013)’s study area was slight and their analysis did not independently assess how the variation contributed to uncertainty in the NPV estimates.

The lack of research regarding the effect that uncertainty in building elevations has on flood damage analyses is likely due to the following reasons. First, most uncertainty studies have focused on Europe, where variability between residential structure elevations is much less than in coastal communities of the United States. Therefore, the potential contribution to uncertainty from structure elevation is minor relative to other less-certain parameters. Furthermore, much of the European work utilized raster land-use, land-cover data to develop asset inventories instead of individual parcel datasets. It is likely that there is much more uncertainty associated with land use classifications and their associated values compared to structure elevation, which existing European studies focused on these parameters. Finally, within coastal areas of the United States, a lack of existing structure elevation data as well as the high cost of obtaining such data are large obstacles to assessment. To the author’s knowledge, there is no comprehensive study of the effect of uncertainty in structure elevations on uncertainty in residential storm surge damage modeling.

¹Similar conclusions can be made regarding inland areas in the United States, where there is also little variability in structure elevations (e.g., Tate et al. (2014)).
2.6 Research Objectives

Acknowledging such shortcomings in the existing literature and typical residential damage modeling practices, the research objectives of this thesis can be divided into two phases. The first seeks to investigate uncertainty in surge damage estimates due to different initial assumptions about structure elevations as well as applying the Standard Method to model storm surge. The specific objectives are as follows:

- Develop a baseline single family residential surge damage model (BDM) per the Standard Method and use it to investigate how different initial assumptions about residential structure elevations affect damage estimates across a diverse storm set (Chapter 3).

- Improve the BDM’s capability to model storm surge damage by accounting for the potential for structural collapse (SC) in the model (BDM+SC). Evaluate how this update to the Standard Method affects damage model performance relative to the BDM (BDM vs. BDM+SC) and under the different initial elevation assumptions (Chapter 3).

- Develop and validate a low-cost methodology to estimate the FFF and LHSM elevations of residential structures on a large-scale basis. Apply this tool to survey elevations within the Study Area to evaluate the accuracy of the different initial elevation assumptions (Chapter 4).

- Update the BDM+SC to correct the initial elevation assumptions using the elevation data obtained from the survey of the Study Area (BDM+SC+EC). Compare the corrected model results under the different initial elevation assumptions (Chapter 4).
After addressing some of the systemic issues with current coastal residential damage modeling practices, the second phase of this thesis’ work is focused on extending the analyses of uncertainty in flood damage assessment mentioned in Section 2.5. Specifically, the second component of objectives seek to perform a preliminary investigation of how uncertainty in damage estimates propagates through the BDM+SC+EC. The specific objectives are as follows:

- Incorporate additional aspects of damage model uncertainty commonly mentioned in the Literature into the BDM+SC+EC.

- Investigate the sensitivity of the updated model to different assumptions of independence and dependence between uncertain model parameters.

- Perform a sensitivity analysis of the updated model to rank each uncertain parameter’s contribution to the overall uncertainty in the model’s damage estimates.

The second phase of work will be discussed in Chapter 5.
Because of limitations in off-the-shelf, publicly available damage modeling software, as well the lack of transparency surrounding their computational procedures and assumptions, all damage models discussed in this thesis were developed from scratch, using MATLAB. The first half of this chapter will discuss the baseline damage model (BDM), which utilizes the Standard Method to estimate storm surge damage to single family residential structures. The second half of the chapter will discuss the BDM+SC, which extends the capabilities of the BDM (and therefore the Standard Method) to better represent storm surge damage, which requires consideration of damage pathways beyond depth of inundation.

3.1 BDM Development

Figure 3.1 presents a flowchart of the baseline damage model. This section will provide an overview of the data requirements of the BDM and elaborate upon the
procedure outlined in Figure 3.1. The four elevation assumption scenarios subject to examination throughout this thesis will also be introduced in this section.

### 3.1.1 Data Requirement Overview

Table 3.1 shows the data requirements of the BDM. The same data were also used in the subsequent updates to the BDM discussed later in this study. Data were obtained from a wide variety of sources and were preprocessed extensively for use in the BDM. Appendix A provides a detailed overview of the preprocessing.

### 3.1.2 Depth-Damage Functions and CSVRs

Many different relative depth-damage functions are available in the United States (see Davis and Skaggs (1992) for examples). For this study, residential damage functions were obtained from two sources: the U.S. Army Corps of Engineers (USACE) New Orleans District (USACE, 2006) and the Federal Emergency Management Agency (FEMA) (FEMA, 2013). The sources were chosen because they were developed relatively recently and were therefore seen as more likely to reflect contemporary construction practices, and—in the case of USACE functions—were developed for the Gulf Coast.

To create the final structural depth-damage functions shown in Figure 3.2, damage ratios from the saltwater, short-duration curves in USACE (2006) were averaged at each depth, across different foundation types and then averaged with the FEMA (2013) functions.\(^1\) The contents curves were used in their unaltered forms from US-

\(^1\)Foundation types were averaged to obtain a single representative damage function for single-family residential structures, which would later be used as a mean value when uncertainty was included in the damage functions in Chapter 5. Because of the well-documented, significant uncertainty associated with the damage functions (see Figure 5.2 and recall Section 2.5) removing this distinction was assumed to have a minor impact on the plausibility of the results.
Figure 3.1: Flowchart of the baseline damage model.
Table 3.1: Damage model data requirements and their respective sources. These data were used in all iterations of the residential surge damage model discussed in this thesis.

<table>
<thead>
<tr>
<th>Data Requirement</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure Characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Structure value</td>
<td>2015 Galveston Central Apprasial District (GCAD) Certified Roll</td>
</tr>
<tr>
<td>Structure age</td>
<td></td>
</tr>
<tr>
<td>Foundation type</td>
<td></td>
</tr>
<tr>
<td>Number of stories</td>
<td></td>
</tr>
<tr>
<td>Structure location</td>
<td>2015 GCAD Parcel Shapefile</td>
</tr>
<tr>
<td>Ground elevation</td>
<td>2006 Houston Galveston Area Council LiDAR Digital Elevation Model (DEM)</td>
</tr>
<tr>
<td><strong>Regulatory Information</strong></td>
<td></td>
</tr>
<tr>
<td>National Flood Insurance Program</td>
<td>2015 NFIP Community Status Book (FEMA)</td>
</tr>
<tr>
<td>(NFIP) adoption date</td>
<td></td>
</tr>
<tr>
<td>Municipal freeboard requirements</td>
<td>City municipal codes (incorporated areas), Flood Plain Management Regulations of Galveston County, Texas (2002) (unincorporated areas)</td>
</tr>
<tr>
<td><strong>Surge Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Still water elevation</td>
<td>ADCIRC + SWAN model</td>
</tr>
<tr>
<td>Significant wave height</td>
<td></td>
</tr>
<tr>
<td>Water velocity</td>
<td></td>
</tr>
<tr>
<td>Hurricane wind fields</td>
<td>FEMA and USACE (2011)</td>
</tr>
<tr>
<td><strong>Depth-Damage Functions</strong></td>
<td></td>
</tr>
<tr>
<td>Structural damage functions</td>
<td>FEMA (2013), USACE (2006)</td>
</tr>
<tr>
<td>Contents damage functions</td>
<td>USACE (2006)</td>
</tr>
</tbody>
</table>
Figure 3.2: Depth-damage functions used in the BDM for structure and contents and for one and two story homes.

ACE (2006) because the functions provided by FEMA (2013) did not extend to a sufficient depth of inundation.

Contents to structure value ratios (CSVRs) were also obtained from USACE (2006). Since three CSVRs—each based on different estimation methodologies—were provided for each structure type in the reference, the CSVRs used in the BDM were taken at the midpoint between the highest and lowest values for both one and two story structures. The resulting CSVRs were 0.65 and 0.55, respectively, for one and two story homes.¹

### 3.1.3 Structure Elevation Calculations

The first step in the BDM computations was to estimate the elevation the residential structures’ first finished floor and lowest horizontal structural member. As discussed

¹One story range: 0.59 - 0.71; Two story range: 0.43 - 0.67. Also, while it may seem unnecessary to average between damage functions and CSVR values when the BDM is to be used as a point of relative comparison between different elevation assumptions, these decisions will allow comparisons to be made to these results when uncertainty in these parameters is incorporated in Chapter 5.
in Section 2.4.2, two methodologies are typically employed for estimation. The first is primarily based on foundation type and the second is based on assumed compliance with NFIP and municipal regulations. Four different scenarios based on the two approaches were implemented in the BDM to assess their effects on the resulting damage estimates. These elevation assumption scenarios are listed in Table 3.2 and will be described in further detail in the following sections.

Table 3.2: The four elevation assumption scenarios, their descriptions and their IDs.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZUS</td>
<td>H</td>
<td>Based on foundation type</td>
</tr>
<tr>
<td>DFIRM</td>
<td>D</td>
<td>Assumed compliance or non compliance with NFIP regulations</td>
</tr>
<tr>
<td>max(HAZUS, DFIRM)</td>
<td>max(H,D)</td>
<td>Maximum of the HAZUS and DFIRM assumptions taken for each structure</td>
</tr>
<tr>
<td>min(HAZUS, DFIRM)</td>
<td>min(H,D)</td>
<td>Minimum of the HAZUS and DFIRM assumptions taken for each structure</td>
</tr>
</tbody>
</table>

3.1.3.1 HAZUS (H)

Elevation scenario H was based on the assumptions used by FEMA’s HAZUS-MH damage modeling software. The estimates are based on the residence’s foundation type, age and flood zone (FEMA, 2012). The approach assigns the elevation of each structure’s first finished floor above adjacent grade per Table 3.3. For post-NFIP structures within FEMA SFHAs, elevation of the FFF above grade is further dictated by if the home is in zone AE or VE. Post-NFIP structures located outside of SFHAs were assumed to follow the pre-NFIP assumption.

Since the elevation values presented in Table 3.3 corresponded to the FFF of the homes, an additional assumption was made about the elevation of the structure’s LHSM relative to its FFF. For this study, this displacement was assumed to be 1.8 ft; this value was obtained by computing the average difference between surveyed
Table 3.3: HAZUS-MH structure elevation assumptions. Values are in terms of FFF elevation above adjacent grade.

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>Pre-NFIP</th>
<th>Post-NFIP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A zone</td>
</tr>
<tr>
<td>Pile (or column)</td>
<td>7 ft</td>
<td>8 ft</td>
</tr>
<tr>
<td>Pier (or post and beam)</td>
<td>5 ft</td>
<td>6 ft</td>
</tr>
<tr>
<td>Solid Wall</td>
<td>7 ft</td>
<td>8 ft</td>
</tr>
<tr>
<td>Basement</td>
<td>4 ft</td>
<td>4 ft</td>
</tr>
<tr>
<td>Crawlspace</td>
<td>3 ft</td>
<td>4 ft</td>
</tr>
<tr>
<td>Fill</td>
<td>2 ft</td>
<td>2 ft</td>
</tr>
<tr>
<td>Slab</td>
<td>1 ft</td>
<td>1 ft</td>
</tr>
</tbody>
</table>

The surveyed elevations were obtained from 49 FEMA elevation certificates. With this information—under the H assumption—the elevation of each structure’s FFF and LHSM above mean sea level (MSL) was computed in the BDM according to the following equations:

\[ E_{FFF} = E_{DEM} + EST_{HAZUS} \]  \hspace{1cm} (3.1)
\[ E_{LHSM} = E_{FFF} - \delta_{LHSM}, \]  \hspace{1cm} (3.2)

where \( E_{FFF} \) and \( E_{LHSM} \) are, respectively, the elevations of the residence’s FFF and LHSM above MSL. \( E_{DEM} \) is the ground elevation obtained from a LiDAR DEM, \( \delta_{LHSM} \) is the assumed distance between the LHSM and the FFF (1.8 ft) and \( EST_{HAZUS} \) is the value obtained from Table 3.3. In the case that Equation 3.2 produced an \( E_{LHSM} \) value that was below \( E_{DEM} \), \( E_{LHSM} \) was adjusted such that \( E_{LHSM} \) equaled \( E_{DEM} \).

3.1.3.2 DFIRM (D)

Elevation scenario D was based on assumed compliance with NFIP and municipal regulations. Pre-NFIP structures and structures outside of SFHAs were assumed
to use slab-on-grade construction, where $E_{\text{LHSM}} = E_{\text{DEM}}$ and $E_{\text{FFF}} = E_{\text{LHSM}} + 1 \text{ ft}$. For post-NFIP structures inside of SFHAs, FFF and LHSM elevations were assumed to comply with NFIP and municipal regulations, and were estimated using the following equations:

- Zone AE:

  $$E_{\text{FFF}} = BFE + \delta_{MREG}$$  \hspace{1cm} (3.3)  
  $$E_{\text{LHSM}} = E_{\text{FFF}} - \delta_{LHSM}$$  \hspace{1cm} (3.4)  

- Zone VE:

  $$E_{\text{LHSM}} = BFE + \delta_{MREG}$$  \hspace{1cm} (3.5)  
  $$E_{\text{FFF}} = E_{\text{LHSM}} + \delta_{LHSM}.$$  \hspace{1cm} (3.6)  

where $BFE$ is base flood elevation above MSL and $\delta_{MREG}$ is any additional freeboard required by municipal regulations. Like scenario H, $E_{\text{LHSM}}$ was set to ground elevation if the estimate fell below grade.

It should be noted that, as discussed in Section 2.4.1, floodplain boundaries and BFEs can change extensively with each subsequent flood insurance study (FIS). Because digital versions of older effective floodplains were not available in the Study Area,\textsuperscript{1} a combination of effective and preliminary digital flood insurance rate map (DFIRM) data were used, and all post-NFIP structures were assumed to be compliant with the available DFIRM data, even if they were subject to earlier regulations at the time of their construction (see Appendix A for more information). Figure 3.3A maps the extent of the preliminary and effective DFIRM data, and Figure 3.3B shows the boundaries of the SFHAs. Approximately 72% of Galveston County falls within the 100-yr floodplain; 80% is within the 500-yr floodplain.

\textsuperscript{1}Q3 data of historical floodplains do not include BFEs.
Figure 3.3: A.) Boundaries of the preliminary (blue) and effective (orange) DFIRMs in the Study Area.
B.) FEMA flood hazard areas in the Study Area obtained from the combined DFIRM dataset. SFHAs—zones AE and VE—are shown in orange and red, respectively.
3.1.3.3 Max(H,D) and Min(H,D)

The final two elevation scenarios evaluated were combinations of assumptions H and D. Max(H,D) selects the maximum elevation value produced by assumptions H and D for each structure. For example, if assumption H yielded an FFF elevation value of 8 ft above adjacent grade and D returned a value of 12 ft, 12 ft is the final assumption under max(H,D). Min(H,D) takes the smaller estimate provided by H and D. In the previous example, 8 ft is assumed for the structure. These two scenarios represent upper and lower bounds for the estimated structure elevations in the Study Area.

3.1.4 Inundation Calculation

Once $E_{FFF}$ had been estimated for all structures, the next step in the BDM computation was to estimate depth of inundation above each structure’s first finished floor (see Figure 3.1). Inundation calculations were performed using the following formula:

$$I_{FFF} = [E_{STW} + 0.7(H_s)] - E_{FFF},$$

(3.7)

where $E_{STW}$ is the still water elevation of the storm surge above MSL and $H_s$ is the significant wave height. The 0.7 coefficient applied to the $H_s$ term is to reflect the assumptions used by FEMA (2011) to estimate the height of the wave crest relative to $E_{STW}$.

3.1.5 Damage Calculations

After depth of inundation was computed for each structure, the associated damage was estimated for the Study Area. Structural damage estimates were computed using
the following formula:

\[ D_{\text{Stot}} = \sum_{i=1}^{N_s} f_s(I_{\text{FFF}[i]})(V_{\text{home}[i]}), \]  

(3.8)

where \( D_{\text{Stot}} \) is the total structural damage in the Study Area, \( N_s \) is the number of structures in the Study Area and \( f_s(x) \) is a structural depth-damage function. Depending on the depth of inundation, \( f_s(x) \) returns a damage ratio, which is multiplied by the total home value (\( V_{\text{home}} \)) to yield a structural damage estimate.

Damage to the contents of the SFRs was estimated similarly to the structural damage:

\[ D_{\text{Ctot}} = \sum_{i=1}^{N_s} f_c(I_{\text{FFF}[i]})(V_{\text{home}[i]})(\text{CSV}) \]  

(3.9)

The differences between equations 3.9 and 3.8 are the use of a depth-damage function specific to residential contents, \( f_c(x) \), and the contents to structure value ratio (CSV). The CSV is multiplied by \( V_{\text{home}} \) to estimate the total value of the residence’s contents. After estimating structural and contents damage, total damage to single family residences in the Study Area (\( D_{\text{tot}} \)) was approximated by:

\[ D_{\text{tot}} = D_{\text{Ctot}} + D_{\text{Stot}} \]  

(3.10)

In addition to monetary damage, another damage metric was computed in the Study Area: the number of affected homes. This metric was designed to serve as a better indicator of the social costs of storm surge damage because it is independent of home value and therefore does not assign a higher weight to more expensive properties. Therefore, the number of affected homes lends insight into the number of residents affected by the event, independent of their affluence.

In this study, a home was classified as “affected” if it was shown to sustain more than 10% structural damage. The 10% threshold was chosen because it was thought
to reflect a degree of damage that would require immediate action by homeowner. However, further investigation is required to better define this threshold. Post-disaster surveys of residents could be a potential resource (e.g., those conducted by Dueñas-Osorio et al. (2012)), or the threshold could be set to a dollar value, such as the amount of a typical flood insurance deductible. To lend perspective to how changes to the 10% threshold may affect this metric, a brief sensitivity analysis to the threshold is included in Section 3.5. The total number of affected homes \( N_{AH} \) was computed using the following formula:

\[
N_{AH} = \sum_{i=1}^{N_s} 1(f_s(I_{FFF[i]})),
\]

where \( 1(x) \) is the indicator function, and was defined as follows:

\[
1(x) = \begin{cases} 
0, & x < 0.1 \\
1, & x \geq 0.1 
\end{cases}
\]

3.2 Storm Selection

For this study, four synthetic tropical cyclones were selected out of the suite used by Bass et al. (2016), which consisted of modified versions of the storms utilized in FEMA’s latest coastal risk assessment of the Gulf Coast (FEMA and USACE, 2011). The FEMA storms were generated using a planetary boundary layer (PBL) model (Thompson and Cardone, 1996) and had their wind intensities and pressure values scaled by Bass et al. (2016) to create a more diverse storm set.

Each of the storm’s integrated kinetic energies were then approximated from the gridded wind field data produced by the PBL. Integrated kinetic energy (IKE) is a metric that was proposed by Powell and Reinhold (2007) to be a better indicator of the storm surge generation potential of a tropical cyclone than the Saffir-Simpson
Hurricane Scale (SSHS). This is because, in addition to the intensity of the storm, IKE also accounts for the size of the storm, which has been shown to be an important indicator of its potential to generate storm surge (Irish et al., 2008). IKE approximates the total energy content of a 1-meter-thick slice of a TC’s wind field using the following equation:

\[ IKE = \int v_1^2 \frac{1}{2} \rho U_{10}^2 dv, \]  

where \( \rho \) is the average density of air at MSL (1.15 kg/m\(^3\)) and \( U_{10} \) is the 1-sec, 10-meter wind velocity in m/s above a specified threshold. Equation 3.13 yields a value in joules, but IKE values are typically expressed in terajoules (TJ). In this study, IKE was calculated using tropical storm-force winds as the selected threshold (18 m/s, 39 mph). This selection results in a version of IKE known as IKE\(_{TS}\), which was suggested by Powell and Reinhold (2007) to be the best predictor of storm’s potential to generate storm surge.

While IKE did not gain a large following after publication, recently, Bass et al. (2016) performed a comparative analysis between the SSHS, IKE, and two other proposed indices: the Hurricane Surge Index (Kantha, 2006) and the Surge Scale (Irish and Resio, 2010). IKE\(_{TS}\) was shown to be the best predictor of the regional surge impacts of a storm.

Using their IKE\(_{TS}\) values as a reference, four storms were selected from Bass et al. (2016)’s storm suite to produce a variety of surge magnitudes. The selected storms are listed in Table 3.4. For perspective, Hurricane Ike’s IKE\(_{TS}\) was approximately 99 TJ, in between storm 2 and storm 3. Therefore, storms 2 and 3 should be interpreted as spanning the range of storms capable of causing a significant, but potentially avoidable disaster. Protection strategies will likely be designed for storms in this range. Storm 4 has an extremely high IKE\(_{TS}\) and therefore represents an extremely rare—likely much greater than 500-yr return interval—storm event. Storm 4 was
Table 3.4: The four selected storms and their characteristics. All values except $IKE_{TS}$ reflect the storm at landfall. $IKE_{TS}$ values were computed 4 hours before landfall to ensure that that each storm’s wind field was entirely contained by the domain of the PBL output.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>1-min Sustained Winds (mph)</th>
<th>Min Pressure (mb)</th>
<th>SS Category</th>
<th>$IKE_{TS}$ (TJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140</td>
<td>932</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>962</td>
<td>2</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>962</td>
<td>2</td>
<td>165</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>900</td>
<td>5</td>
<td>204</td>
</tr>
</tbody>
</table>

selected to illustrate the upper bounds of potential residential storm surge damage in the Study Area.

To provide a wide variety of surge scenarios and to ensure that all regions of the Study Area were exposed to each of the storms, the four TCs were shifted to four different landfall locations, resulting in a total of 16 storm scenarios. Figure 3.4 shows these landfall locations, which are labeled A through D, from west to east. Future references to specific storms in this document will be made by combining the storm ID with its landfall location; for example, storm 3A is storm 3 shifted to landfall location A.

### 3.3 Storm Surge Modeling

Storm surge simulations were performed using the coupled ADCIRC+SWAN model. The 2D version of the Advanced Circulation (ADCIRC) model uses a continuous Galerkin finite element technique to solve the generalized wave continuity equation and the vertically-integrated momentum equations on a triangular mesh (Luettich and Westerink, 2004). The Simulating WAves Nearshore (SWAN) model solves the action balance equation to simulate gravity surface wind generated waves (Booij et al.,
Figure 3.4: Synthetic storm landfall locations and the storm tracks used in this study. Track spacing relative to landfall location B: A, 30 km east; C, 60 km west; D, 120 km west. The Galveston County boundary is outlined in dark red.
1999). Dietrich et al. (2012) tightly coupled the ADCIRC model with an unstructured version of the SWAN model (Zijlema, 2010), so that both run simultaneously on the same computational mesh.

ADCIRC and—more recently—the coupled ADCIRC+SWAN model have been used extensively in hindcast analyses of historical storm events. Such analyses have included Isabel (2003), Katrina (2005), Rita (2005), Gustav (2008) and Ike (2008) (Lin et al., 2010; Bunya et al., 2010; Dietrich et al., 2010, 2011; Hope et al., 2013). The models have been shown to be accurate in capturing the surge and wave responses across these hindcast analyses. For the simulations performed for this study, the computational mesh and model parameters were adopted from the most recent FEMA coastal risk assessment of the Upper Texas coast (FEMA and USACE, 2011).

Simulations of all sixteen storms were performed using the ADCIRC+SWAN model and the Stampede Linux cluster at the Texas Advanced Computing Center at the University of Texas. Using a 1-second time step and a four-day simulation time, each run required approximately 1-hour of wall-clock time when executed on 1024 cores.

### 3.4 Storm Surge Model Results

The ADCIRC+SWAN model produces time-series and maximum output files for a large variety of storm surge and wave parameters. ADCIRC+SWAN output of the maximum still water elevation ($E_{STW}$), water velocity ($V_{H2O}$) and significant wave height ($H_s$) were extracted at every residential structure location within the Study Area. Example plots of the three types of ADCIRC+SWAN output used in this thesis are shown for storm 3C in Figure 3.5.

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1 The four-day simulation time corresponded to the duration of the FEMA wind field data. This duration is required to fully-develop the regional surge response from the synthetic storms.
Figure 3.5: Example ADCIRC+SWAN output for storm 3C. Clockwise from the top left: maximum $E_{Stw}$, $H_s$, and $V_{H2O}$. 
Since the focus of this thesis is on residential damage modeling, storm surge simulation results will not be discussed extensively, as they were solely used as a point of comparison between modeling methodologies. However, a brief overview of general trends in regional storm surge response will be provided to give context to the damage results.

Figure 3.6 shows ADCIRC+SWAN computed maximum $E_{STW}$ for storm 3 at all four landfall locations. From the figure, it is clear that shifting the storm’s landfall location significantly impacts the distribution of storm surge in the Study Area. Across all simulations, however, landfall location C produced the greatest surge values in Galveston County as well as the Houston Ship Channel; this observation is in agreement with the findings of Sebastian et al. (2014).

Figure 3.7 shows ADCIRC+SWAN computed maximum $E_{STW}$ for each of the four storms, with landfall location held constant at C. As expected, with increasing IKE_TS, the regional surge response increased. Due to its landfall location and high IKE_TS, storm 4C produced the highest storm surge within the Study Area out of the entire suite of storms. Maximum $E_{STW}$, $H_s$ and $V_{H2O}$ plots for all sixteen storms are provided in Appendix B.

### 3.5 BDM Results and Elevation Assumption Comparison

The baseline damage model was evaluated for all sixteen storms and under the four elevation assumptions—for a total of 64 model runs. For each storm and under the four initial elevation assumptions, Figure 3.8 shows the BDM total SFR monetary damage estimates for the Study Area as well as the discrepancy between the

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1BDM runtimes were trivial.
Figure 3.6: ADCIRC+SWAN computed maximum $E_{sw}$ for storm 3 at all four landfall locations. Clockwise from the top left: storm 3A, storm 3B, storm 3C and storm 3D.
Figure 3.7: ADCIRC+SWAN computed maximum still water elevations for all four storms at landfall location C. Clockwise from the top left: storm 1C, storm 2C, storm 3C and storm 4C.
highest and lowest damage estimates.¹ Generally, the BDM’s estimated damage increased with increasing IKETS, for a given landfall location. A substantial increase in damage totals was observed between storms 2 and 3, mirroring the similarly significant increase in IKETS between them. It should be noted that both storms 2 and 3 are Category 2 storms under the SSHS; the discrepancy in the hazard presented by each storm—despite similar wind speeds—illuminates the limitations of the SSHS as a stand-alone communicator of a storm’s destructive potential.

Damage estimates were generally the highest for landfall location C, with the exception being storm 1, where landfall location B produced the highest damage totals. This was likely because storm 1B inundated densely populated downtown Galveston, whereas storm 1C did not (see Appendix B for mapped ADCIRC+SWAN model results).

Comparing the different elevation assumptions, the min(H,D) and max(H,D) scenarios resulted in the highest and the lowest total damage estimates, respectively, for a given storm. Such behavior was expected as the max(H,D) and min(H,D) assumptions should result in, respectively, the highest and lowest building elevation estimates across the Study Area. Lower elevation estimates result in an overall higher depth of inundation and increased estimated damage using the Standard Method. Higher elevation estimates have the opposite effect, decreasing estimated damage.

Figure 3.8 plots the discrepancy between the highest and lowest damage estimate produced using the different elevation assumptions. As shown in the figure, the magnitude of difference was substantial. For storm 3D, for example, it approached $1.4 billion. Even for smaller storms, changing elevation assumptions had a large effect. Storm 1D resulted in a total discrepancy of $421 million, which is greater than

¹Discrepancy being defined as the difference between the highest damage estimate and the lowest damage estimate obtained using the different initial elevation assumptions.
the average damage across the four scenarios. In general, storm 3 showed the greatest sensitivity to the different initial elevation assumptions.

Despite its magnitude, storm 4C showed little sensitivity to initial elevation assumptions. This result was likely because the large storm surge generated by storm 4C substantially inundated most of the structures within Galveston County. Thus, the resulting damage estimates exhibited less variability because depth-damage functions were generally evaluated in their asymptotic, high-inundation regions (recall, Figure 3.2), and they were less sensitive to changes in depth of inundation brought about by changes in assumed structure elevation.

Similar trends to the monetary damage estimates were observed when the BDM results were analyzed in terms of the number affected homes. Figure 3.9 shows that the number of affected homes increased with $IKE_{TS}$ for a given landfall location. For a given storm, the highest of number of affected homes occurred at landfall location C. The exception to the previous was storm 1, for which location B resulted in the highest number of affected homes.

Analogous to the estimated dollar damage, significant differences were observed between elevation assumptions in estimates of the number of affected homes. For example, storm 2C exhibited a discrepancy of 9,236 structures across the different assumptions. This observation was especially significant considering the storm’s relatively small estimated monetary damage. Storm 4C showed essentially no variation across elevation assumptions. However, this was expected, as it paralleled the conclusion from the monetary estimates—storm 4C significantly inundated most structures in the Study Area, regardless of their assumed elevations.

A key difference was observed between the monetary damage estimates and estimates of the number of affected homes. Discrepancy in the estimated number of affected homes across elevation assumptions was highest for storm 2; whereas, in
Figure 3.8: Top: BDM estimates of total dollar damage under different elevation assumptions. Bottom: Difference in BDM total dollar damage estimates between the highest and lowest estimates under the different elevation assumptions.
Figure 3.9: Top: BDM estimates of the number of affected homes under different elevation assumptions. Bottom: Discrepancy in BDM estimates of the number of affected homes under the different elevation assumptions.
terms of monetary damage, it peaked with storm 3. The likely explanation for this observation was, because storm 2 produced a lower storm surge than storm 3, SFRs were—on average—subjected to less inundation. Consequently, more structures had lower damage percentages and were therefore more likely to transition across the ten percent threshold with a change in elevation assumption. In this sense, storm 2 was seen as the “sweet spot” in terms of variability in the number of affected homes; i.e., where many structures were inundated, but not to a degree that dulled sensitivity to differences in the elevation assumptions. As a supplement to figures 3.8 and 3.9, tabulated BDM results are included in Appendix C.

3.5.1 BDM Sensitivity to Affected Structure Threshold

As mentioned in Section 3.1.5, future work is required to determine the optimal threshold to classify a structure as “affected”. For this thesis, a 10% structural damage threshold was chosen. To lend more insight into consequences of this assumption, a preliminary sensitivity analysis was performed using the BDM. Five additional structural damage thresholds (1%, 2%, 5%, 15% and 20%) were implemented in the BDM and compared to the 10% assumption. Figure 3.10 shows the results of the sensitivity analysis for the four storms at landfall location C, under the max(H,D) assumption. As expected, the number of affected homes decreased as the threshold increased. Storm 2C and storm 3C appear to be the most sensitive to the choice of threshold. Storm 4C shows little sensitivity to the threshold, which is in line with previous observations that most structures within the Study Area are heavily inundated by the storm.

The relative sensitivities of storm 2C and storm 3C were assessed further, while considering the different initial elevation assumptions. Figure 3.11 presents the results of this analysis. After including the different elevation assumptions, storm 2C exhib-
Figure 3.10: Sensitivity of the estimated total number of affected homes in the BDM to different structural damage thresholds. Comparison is between the different storms at landfall location C.

Ited greater sensitivity to the affected structure threshold than 3C. Likewise, storm 2C showed greater variability between elevation assumptions than 3C. For both storms, variability across elevation assumptions in the number of affected homes changed as the threshold changed. For storm 3C, variability appeared to increase with the threshold; for storm 2C, the opposite occurred.

Overall, the sensitivity analysis results showed that, while the number of affected homes was sensitive to the selected threshold, the relative magnitudes between different storms and initial elevation assumptions were not highly-sensitive to the chosen threshold. Therefore, observations regarding relative behavior of the number of affected homes using different elevation assumption scenarios can be taken with confidence. Until further guidance is provided in terms of an appropriate threshold, magnitudes of the number of affected homes provided using the 10% threshold in this study should be interpreted with the knowledge that they are subject to change.
Figure 3.11: Sensitivity of the estimated total number of affected homes in the BDM to different structural damage thresholds. Comparison is between the storm 2C and storm 3C results under the different initial elevation assumptions. Storm 2C results are depicted in shades of green and storm 3C results are in shades of blue.

3.6 Updating the BDM to Include Complete Structural Failure

As discussed in Section 2.3, observations of residential damage from storm surge suggest the presence of damage mechanisms beyond that of inundation. To investigate the effect of augmenting inundation damage with one of these alternate mechanisms, the BDM was updated to incorporate the threat of structural collapse (SC), which was observed extensively in residential structures on the Bolivar Peninsula after Hurricane Ike (Kennedy et al., 2011). The fragility equations developed by Tomiczek et al. (2014) were chosen to create the updated model—the BDM+SC—because they were developed using ADCIRC+SWAN model output and damage observations from the Study Area. The equations were also the only examples available in the Literature.
The specific function chosen from Tomiczek et al. (2014) is shown below:

\[ P_F(H_s, F_B, age, V_{H2O}) = \]
\[ \Phi(-3.75 + 1.03H_s - 1.79H_sF_B - 0.30F_B^2 - 0.141age^2 + 1.06V_{H2O}^2), \quad F_B \geq -2.98H_s \]
\[ \Phi(-3.75 + 1.03H_s + 2.67H_s^2 - 0.141age^2 + 1.06V_{H2O}^2), \quad F_B < -2.98H_s, \]  
\hspace{1cm} (3.14)

where \( H_s \) is in meters and \( V_{H2O} \) is in meters per second. \( age \) is an integer value that depends upon the structure’s date of construction and is classified accordingly:

\[ age = \begin{cases} 
1, & \text{< 1974} \\
2, & 1974 \leq \& < 1987 \\
3, & 1987 \leq \& < 1995 \\
4, & \geq 1995 
\end{cases} \]

\( F_B \) is the freeboard of the LHSM of the structure relative to the breaking wave height in meters; it is calculated per the following:

\[ F_B = E_{LHSM} - (E_{STW} + 0.7H_s), \]  
\hspace{1cm} (3.15)

where \( F_B \) is in meters. \( \Phi(x) \) is the zero-mean, unit variance, normal cumulative distribution function (CDF), which is:

\[ \Phi(x) = \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{x}{\sqrt{2}} \right), \]  
\hspace{1cm} (3.16)

where \( \text{erf}(x) \) is the error function. Finally, for each of the parameters in Equation 3.14, Tomiczek et al. (2014) provided useful regression limits—they are listed in Table 3.5.
Table 3.5: Useful regression limits for the fragility equation derived by Tomiczek et al. (2014).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Useful Regression Limits</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_s$</td>
<td>(0.8, 2)</td>
<td>m</td>
</tr>
<tr>
<td>$F_B$</td>
<td>(-3, 1)</td>
<td>m</td>
</tr>
<tr>
<td>age</td>
<td>(1, 2, 3, 4)</td>
<td>n/a</td>
</tr>
<tr>
<td>$V_{H2O}$</td>
<td>(0.5, 1.5)</td>
<td>m/s</td>
</tr>
</tbody>
</table>

For each storm, mean failure probabilities could be estimated for each of the residential structures in the Study Area, by using Equation 3.14. Using the failure probabilities, the BDM+SC was developed to estimate the resulting distributions of damage and the number of affected homes, using naive Monte Carlo Simulation (MCS). Figure 3.12 is a flowchart outlining the BDM+SC computation scheme, which was implemented in MATLAB as follows:

1. The elevation of each structure’s LHSM was estimated per one of the elevation assumptions outlined in Section 3.1.3.

2. Each structure’s freeboard was calculated using Equation 3.15.

3. The structure’s and the storm surge’s characteristics were constrained to the useful regression limits in Table 3.5. Each structure’s probability of failure was then estimated using Equation 3.14.

4. The MCS was initialized and the following computations were repeated for each structure in the Study Area, for a sufficient number of trials ($N_{\text{trials}}$) to provide an accurate estimate of the mean damage:

   (a) Generate a uniformly distributed pseudorandom value.

1For storms 3 and 4, the surge parameters were frequently outside of the regression limits because the storms were more intense than Hurricane Ike, which was used for to develop the equations. However, at the regression limits, the failure probabilities approached unity, so constraining the values to these intervals was not expected to have a large effect on the results.
(b) Check if value is less than the structure’s failure probability. If true, proceed to c. If false, proceed to d.

(c) Structure and contents damage are assigned to 100% of their respective appraised and estimated values and the structure is classified as an affected home.

(d) Damage to structure and contents is estimated using the depth-damage methodology of the BDM.

(e) Results from the trial are stored in an array.

5. After the MCS, for each trial, estimates of total damage and the number of affected homes were computed for the Study Area. Like the BDM, affected homes were defined as those that had sustained more than 10% structural damage.

The main loop within the MCS portion of the BDM+SC was implemented using MATLAB’s Parallel Processing Toolbox, with speedup approaching proportionality with the number of processors used. 2,000 simulations were deemed adequate because the 95% confidence intervals for the estimates of the mean dollar damage and the number of affected homes were negligible across all simulations. On a four-core desktop computer, each model run required approximately four minutes to evaluate, resulting in a total runtime of 4.25 hours for all storms and elevation assumptions. Each plot of the of BDM+SC results presented in this thesis is in terms of the estimated mean values of the total dollar damage and the total number of affected homes in the Study Area. Example distributions of the total damage output under the different elevation assumptions are provided for storm 3C in Figure 3.13.

For example, for storm 3C under the min(D,H) assumption, the 95% confidence interval for the mean total damage of $2.5 billion was $667,775. Similarly, small confidence intervals were observed in the number of affected homes and for the other scenarios.
Figure 3.12: Flowchart of the BDM+SC.
Figure 3.13: Example output distributions of total monetary damage from the BDM+SC for storm 3C under different elevation assumptions: A.) D B.) H C.) max(H,D) D.) min(H,D)
3.7 BDM+SC Results and Elevation Assumption Comparison

Figure 3.14 presents the total dollar damage estimates obtained using the BDM+SC, and Figure 3.15 shows the change in these estimates from the BDM to the BDM+SC. As expected, introducing the possibility of structural collapse resulted in increases in estimated damage across all elevation scenarios. This is because, when the BDM+SC was used, structural and contents damage ratios approached unity for residences with a high probability of structural failure. Whereas, with the BDM (the Standard Method), damage ratios were capped well below one because of the asymptotic nature of the depth-damage functions. For the larger storms, this increase was particularly large. Storm 4C, for example, saw a roughly $2 billion increase in damage from the
Figure 3.15: Change in the estimated total dollar damage from BDM to BDM+SC under the different elevation assumptions.

Figure 3.16: Percentage change in the total dollar damage estimates from the BDM to the BDM+SC under different elevation assumptions.
BDM to the BDM+SC. Similarly, large increases were exhibited by storms 3C, 3D, 4B and 4D.

Interestingly, for storm 4C, variation between elevation assumptions in the estimated damage decreased using the BDM+SC, when compared to the BDM. The explanation for such behavior parallels the storm 4C discussion in Section 3.5. With a storm as intense as 4C, most of the structures within the Study Area were well-inundated, regardless of elevation assumption, reducing the assumptions’ influence. Incorporating the chance of structural failure further reduced the influence of the elevation assumptions, because, in areas with high failure probabilities, damage estimates converged to 100% of the total structural and contents value, minimizing the effect of depth of inundation, and—by extension—structure elevation.

In addition to the magnitude of increase in total damage between the BDM and the BDM+SC, the percentage change in the damage estimates between the models was also computed. Figure 3.16 presents these results. Percent increase ranged from 30 to 50 percent across the suite of storms, supporting earlier inference that omission of structural collapse from surge damage assessment (in essence, applying the Standard Method to coastal risk assessments) could dramatically underestimate potential damage to single family residential structures.

Larger storms generally exhibited greater percentage change in estimated dollar damage from the BDM to the BDM+SC than the smaller storms. This was because—in these larger events—more structures were subject to high failure probabilities than the smaller storms. Contrary to this trend, storm 1C showed a similar percentage change in estimated damage as the larger storms. This is because storm 1C drove a highly-localized storm surge into the West End of Galveston Island. Since most structures in the West End that were subjected to damage under the BDM also experienced wave action and strong currents, they also had relatively high probabilities
of failure when assessed using the BDM+SC. Therefore, while the absolute increase in damage from the BDM to the BDM+SC for storm 1C was not substantial relative to the other storms, since a large proportion of the structures experienced individual increases in damage, the proportional change was more significant.

Although Figures 3.15 and 3.16 indicate that failure to include the possibility of structural collapse in residential storm surge damage modeling could drastically underestimate damage, the exact magnitude of underestimation may be subject to change with future improvements to fragility modeling. Tomiczek et al. (2014) voiced concerns regarding the effectiveness of SWAN’s (the wave model’s) ability to capture the decay in $H_s$ across barrier islands. Specifically, Tomiczek et al. (2014) observed that SWAN tended to under-predict the rate of $H_s$ decay, resulting in overestimation of $H_s$ at residences, potentially affecting their regression analysis (Tomiczek et al., 2014).

Another potential issue with the fragility equations developed by Tomiczek et al. (2014) is that they were derived for wood-framed structures on pile foundations. In the BDM+SC, these functions were applied to all homes in Galveston County, regardless of their design. For the West End, the Bolivar Peninsula and immediate coastal areas of the mainland, this assumption was appropriate, as the majority of the homes in these areas were constructed with wood frames and pile foundations. However, in downtown Galveston and inland areas of the mainland, this construction style was not as prevalent. Since $H_s$ and $E_{STW}$ values were generally lower behind the Galveston seawall and in inland areas, the impact of this assumption on the results was likely reduced because failure probabilities were low in these areas. Still, the assumption likely had an impact. Future work should focus on developing a robust library of fragility equations suited for a variety of asset types and development patterns.
Figure 3.17: Range in BDM+SC and BDM total monetary damage between the highest and lowest estimates under the different elevation assumptions.

Despite these potential issues, the results of the comparative analysis between the BDM and the BDM+SC clearly support the argument that consideration of structural collapse is essential to residential storm surge damage modeling. The results also support the corollary that surge damage models should account for more than inundation, as is the case with the Standard Method. Even in instances where inundation-only models produce acceptable damage estimates relative to observed damage, the results are still erroneous as they reflect a case of Type III error—wrong model, right conclusion. In such instances, inundation damage is likely overestimated and compensating for the omission of surge-specific damage pathways. So while adopting Tomiczek et al. (2014)’s fragility equations for the work in this thesis results in some uncertainty in the exact magnitude of damage increase from the BDM to the BDM+SC, the fact that such a change is substantial will hopefully serve as ample motivation for further research.
In addition to changes in estimated damage, the transition between the BDM and the BDM+SC affected variability between damage estimates produced using different elevation assumptions. Figure 3.17 illustrates this change. For most storms, the observed change in variability between the BDM and the BDM+SC was minor. Storms 3C and 3D, however, showed major increases, on the order of $700 million. As previously mentioned, storm 4C exhibited a decrease in variability from the BDM to the BDM+SC and was the only storm to do so in the suite.

While incorporating structural collapse into the model resulted in significant impacts in terms of the estimated dollar damage, it did not have a large effect on the number of affected homes. Such behavior was likely because, to have a threat of structural collapse, a home had to be sufficiently inundated. Therefore, it was likely that the SFR was already classified as affected if it had anything greater than a marginal probability of failure. Across all storms and elevation assumptions, the greatest observed increase in the number of affected homes between the BDM and the BDM+SC was only 91. As an additional reference, tabulated data for all BDM+SC results are included in Appendix C.

3.8 Spatial Distribution of the Damage Estimates

Until this juncture, damage has only been discussed in terms of county-wide aggregates. To lend insight into the spatial distribution of the discrepancy in residential damage estimates between the different elevation assumptions, BDM+SC estimated structural damage percentages for storm 3C were averaged to a 1500 ft (457 m) square grid and are included as figures 3.18 to 3.21. Each figure corresponds to a different initial elevation assumption.

The different elevation assumptions resulted in large discrepancies in the spatial distribution of damage. Comparing the results obtained with assumptions H and
D, immediately behind the seawall in downtown Galveston, essentially no damage is shown in the densely-populated area under assumption H. Assumption D, however, shows damage extending all the way to the seawall.

The reason for the discrepancy between H and D observed behind the seawall is that most of homes in the area were constructed prior to the NFIP. However, despite not being subjected to NFIP regulations, many of these homes were still constructed on wooden piles or piers and elevated above adjacent grade. Under the D assumption, these pre-NFIP structures were assumed to be constructed slab-on-grade, while under the H assumption, these homes were assumed—more accurately—to be elevated (recall, Table 3.3). This difference leads to discrepancy in estimated damage in this region because, under assumption D, the structures have a lower threshold for inundation than H. Similarly, under assumption D, structures have less freeboard above the significant wave height and therefore have higher failure probabilities.¹

On the West End, an opposite trend between D and H was observed. Since much of building stock on this portion of Galveston Island was constructed relatively recently, after the NFIP, D assumes that these structures are fully-compliant with NFIP regulations and are properly elevated above BFE. Because BFEs on the West End are quite high, elevations of structures under assumption D end up being much higher than under H, where FFF elevation is limited to 8-ft above adjacent grade. Therefore, higher damage intensities are observed under assumption H than D. This is because structures under assumption H are more inundated and have higher probabilities of failure.

In terms of the max(H,D) and the min(H,D) assumptions, the spatial distribution of damage behaved as expected. The min(H,D) scenario resulted in the most intense damage across the Study Area compared to the other elevation assumptions;

¹This likely had a marginal impact behind the seawall, where wave action was subdued.
whereas, the max(H,D) scenario resulted in the least intense damage. The similarity between the min(H,D) and H results on the Bolivar Peninsula and the West End are because assumption H typically yielded the lowest elevation estimate on a structure-by-structure basis in these regions. Therefore, H and min(H,D) resulted in similar damage estimates because they produced very similar elevation estimates. This was not necessarily the case in downtown Galveston, where assumption D often yielded the minimum elevation estimate. Therefore, min(H,D)’s spatial results in this area are closer to assumption D than assumption H.

The significant reduction in structural damage observed on both the West End and Bolivar Peninsula under assumption max(H,D), compared to the other elevation assumptions, was likely due to the fact that estimated pre-NFIP structure elevations were higher under H than D and that estimated post-NFIP structure elevations were higher under D than H. Under the max(H,D) assumption, higher elevations were adopted for both pre- and post-NFIP structures, which is why the max(H,D) assumption resulted in such a widespread decrease in damage.

Figures 3.18 to 3.21 clearly demonstrate that different elevation assumptions resulted in dissimilar spatial distributions of damage within the Study Area. This is a key observation because it suggests that in instances where assumptions H and D did not show much variation in total estimated damage, the spatial distribution of said damage could be quite different. This result suggests that—depending on the elevation assumption—coastal risk assessments could highlight different areas as “at-risk”, potentially complicating the design of regional mitigation strategies.

3.9 Chapter Findings

From the work presented in this chapter, it is clear that—using the standard method for flood damage assessment (i.e., the BDM)—different assumptions of structure ele-
vation can produce widely variable estimates of damage to single family residences for a given storm. After incorporating the possibility of structural collapse into the BDM, and thereby improving the Standard Method’s representation storm surge damage, the BDM+SC resulted in large increases in estimated dollar damage relative to the BDM. Similar increases were observed in the variability between damage estimates produced using the different elevation assumptions. However, little change was observed in terms of the number of affected homes with the BDM+SC.

While the observed increase in damage between the BDM and BDM+SC suggests that the Standard Method substantially underestimates storm surge damage to residential structures, because of uncertainties associated with the fragility equations and assumptions used in the BDM+SC, this conclusion should be taken with reservation. With this in mind, the results of the comparative analysis between the BDM and BDM+SC should be interpreted as motivation to further advance fragility modeling, so that the shortcomings of inundation-only surge models can be better characterized.

Finally, an analysis of the spatial distribution of damage showed large variation between elevation assumptions. Such discrepancy presents issues for coastal risk assessments, as different regions may be labeled as “at-risk”, depending on the elevation assumption employed. The next chapter will focus on addressing uncertainty in structure elevations.
Figure 3.18: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption D.

Figure 3.19: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption H.
Figure 3.20: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption max(H,D).

Figure 3.21: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption min(H,D).
Chapter 4

Addressing Elevation Uncertainty

As mentioned in the introductory chapters, one of the major obstacles to assessing uncertainty in residential storm surge damage estimates due to different assumptions of residences’ elevations is the lack of available data of the actual elevations of homes. To address this data shortage, for this study, a novel methodology was developed to estimate structure elevations using GIS and Google Street View (GSV). The first half of this chapter will focus on outlining this methodology, its application to estimate home elevations in the Study Area and the application of the resulting data to evaluate the initial elevation assumptions introduced in Chapter 3. The second half of the chapter will focus on using the elevation data obtained from the survey to produce an elevation-corrected version of the BDM+SC—the BDM+SC+EC. The BDM+SC+EC will be utilized to provide further insight into the accuracy of the initial elevation assumptions.
4.1 Overview of the Street View Elevation Estimation Methodology

Following the overview presented in Figure 4.1, the Street View elevation estimation methodology is outlined below:

1. The coordinates, in latitude and longitude, of the front of structure were determined using aerial imagery. The front of the building was assumed to be either at the edge of the roof or the front deck, whatever was closer to the adjacent street. The ground elevation \( (E_{DEM}) \) at this location was obtained from the 2006 HGAC LiDAR DEM.

2. The structure was located in Google Street View using a web browser. After orienting the Street View panorama such that the target structure filled the browser window, the corresponding URL was copied and tabulated along with the data obtained in the previous steps.

3. The tabulated data were then loaded into MATLAB, where each structure’s URL was parsed to obtain several important parameters: the approximate coordinates—in latitude and longitude—of where the Street View panorama was made; the ID corresponding to the Street View panorama; the field of view \( (fov) \) of the image, in degrees; the orientation of the image relative to the horizon, in degrees; and the heading of camera, in degrees.

4. Using the data from the parsed URL, Google’s Street View Image API was called to download and open the GSV image in MATLAB.

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\(^1\)The availability of this parameter greatly simplified calculations. Determining the field of view of the Street View image without this data, or additional information about the sensor and lens focal length used by the cameras on the Street View vehicle would have likely been impossible.
5. Using a mouse and MATLAB’s Image Processing Toolbox, the locations of the home’s FFF, LHSM and the adjacent ground were selected to obtain their pixel coordinates. The vertical distances in pixels ($\delta_{vpix}$) from the FFF and LHSM to the ground were then computed.

6. The horizontal distance ($D_h$) between the Street View vehicle and the front the structure was estimated from their coordinates (in latitude and longitude) using Vincenty’s algorithm (Vincenty, 1975; Kleder). The image height ($I_{dv}$), in pixels, was calculated from the downloaded image.

7. The elevations of the structure’s FFF and LHSM were estimated using the following equation:

$$Elevation\ Estimate = 2\left(\frac{D_h\delta_{vpix}}{I_{dv}}\right)\tan\left(\frac{fov}{2}\right) + E_{DEM} \quad (4.1)$$

### 4.2 Validation of the Elevation Estimation Methodology

To validate the Google Street View elevation estimation methodology, 49 FEMA elevation certificates were obtained from recently-constructed residences in Galveston County. Surveyed FFF elevations for the homes were recorded from the elevation certificate data. The Street View elevation estimation tool was then used to estimate the FFF elevations of the 49 structures. The elevation of the adjacent grade was then subtracted from the estimated and elevation certificate elevations to minimize any potential error from the DEM. Finally, the elevation certificate data were then plotted versus the values obtained using the GSV tool, resulting in Figure 4.2.
Figure 4.1: Overview of Google Street View elevation estimation methodology. Figure numbering corresponds to that of text.
Figure 4.2: Results of the validation of the Google Street View elevation estimation methodology.
A straight line was fitted through the data, with its y-intercept fixed at the origin. The regression resulted in an R-squared value of 0.93, showing that the function was an excellent approximation of the data. Additionally, the resulting function had a slope close to one, which indicated that elevation estimation tool did not require calibration. Root mean square error (RMSE) between the estimated and elevation certificate data was calculated to be 1.04 ft (0.32 m), which was considered adequate for this study. For comparison, Kennedy et al. (2011) estimated building elevations on the Bolivar Peninsula from Google Street View using expert judgment and managed to achieve a RMSE of 0.85 ft (0.26 m). Because of the efficiency of the Street View tool, this small trade-off in accuracy was deemed acceptable.

While the validation results were favorable, some concerns still remained terms of the accuracy of the tool. Inspection of the validation results (Figure 4.2) suggested that as the estimated elevation increased, so did the error in the estimation. However, because the elevation certificate data lacked many structures at these elevations, it was unclear as to what extent—if any—the error increased.

It is likely that the accuracy of the tool could be significantly improved with better aerial imagery, more accurate information about the location of the Google Street View vehicles and the application of more advanced image processing techniques. Until these improvements have been made and the tool is extensively validated against a wider set of surveyed elevations, the GSV tool should be used only in applications where approximate structure elevations are appropriate.

### 4.3 Structure Elevation Survey and Analysis

After validation, the GSV elevation estimation tool was utilized to conduct a survey of structure elevations throughout the Study Area. Since most of the structures within Galveston County were located outside of SFHAs or areas inundated by the storm
set, conducting a purely random sample would oversample structures that have little effect on storm surge damage estimates. So in lieu of a random sample, a stratified sample was collected to ensure that each SFHA, construction period and portion of the Study Area was adequately assessed. The chosen strata are listed below:

- Flood zone: AE, VE, X
- Structure age: Pre-NFIP; Post-NFIP, Before 2002; Post-2002
- Location: 11 different sample regions (see Figure 4.3)

These characteristics were chosen because they were seen as the most likely factors responsible for trends in building elevation. Flood zones dictate building elevation regulations under the NFIP, and structure age distinguishes between structures that were constructed prior to the NFIP (and its associated elevation requirements) and those that were constructed afterwards. 2002 was chosen as an additional age bracket because it was the year the most recent floodplain maps became effective for the Study Area.

Additionally, the Study Area was divided into 11 subregions (Figure 4.3). The divisions were chosen via visual inspection and were delineated based on natural divides between urban areas as well as any significant changes in development density. The purpose of the spatial classification was to try to capture the effect of any building elevation regulations or variations in perceived flood risk, which could potentially have a localized effect on structure elevations.

Each structure in the Study Area was assigned to its respective stratum. Strata with zero residences were discarded, and strata with less than 50 residences were reassigned to a similar, adjacent stratum. Initially, fifteen residences were sampled, without replacement, from each stratum. Then an additional five to ten samples were

\[1\text{Reassigned structures were not sampled; they were assumed to share their assigned strata's characteristics.}\]
Figure 4.3: Boundaries of the sample stratification regions. Eleventh area includes all homes not located in regions one through ten.

obtained for strata that showed particularly high variability in building elevation. In total, 1,168 homes’ elevations were estimated in the Study Area.

RMSE between the elevations produced by the assumptions and the elevations estimated using the GSV tool was computed for all four elevation assumption scenarios. At 2.48 ft (0.76 m), the max(H,D) scenario was shown to have the lowest RMSE. In a close second, scenario H’s RMSE was only 2.51 ft (0.77 m). D and min(H,D) were further behind, at 3.12 ft (0.95 m) and 3.15 ft (0.96 m), respectively.

While RMSE suggested that the H and the max(H,D) assumptions were comparable, it was recognized that these values were computed over the entire Study Area, and that the performance of the assumptions might differ substantially in surge-prone areas. Further inspection of the data confirmed such speculation, with the results presented in Table 4.1. While all assumptions produced relatively low error totals when aggregated over the entire county, when broken down by flood zone, the results were quite different. Both the H and the min(H,D) assumptions greatly under-predicted
Table 4.1: Average error in feet estimated for different building characteristics under the max(H,D) elevation assumption scenario. Positive values indicate over-prediction by the assumption; negative values indicate under-prediction.

<table>
<thead>
<tr>
<th>Elevation Assumption</th>
<th>All Residences</th>
<th>Zone AE</th>
<th>Zone VE</th>
<th>Zone X</th>
<th>Pre-NFIP</th>
<th>Post-NFIP, Pre-2002</th>
<th>Post-2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>-0.43</td>
<td>-0.90</td>
<td>-0.70</td>
<td>-0.21</td>
<td>-1.75</td>
<td>0.12</td>
<td>-0.27</td>
</tr>
<tr>
<td>H</td>
<td>-0.12</td>
<td>-0.32</td>
<td><strong>-4.00</strong></td>
<td>0.38</td>
<td>0.76</td>
<td>-0.17</td>
<td>-0.79</td>
</tr>
<tr>
<td>max(H,D)</td>
<td>0.39</td>
<td>0.60</td>
<td>0.31</td>
<td>0.38</td>
<td>0.76</td>
<td>0.50</td>
<td>-0.11</td>
</tr>
<tr>
<td>min(H,D)</td>
<td>-0.94</td>
<td>-1.81</td>
<td><strong>-4.40</strong></td>
<td>-0.21</td>
<td>-1.75</td>
<td>-0.54</td>
<td>-0.94</td>
</tr>
</tbody>
</table>

The results in Table 4.1 show that assumption D generally underestimated pre-NFIP structure elevations. This is because the scenario assumed that all pre-NFIP structures were constructed slab-on-grade. In reality—and especially on Galveston Island and the Bolivar Peninsula—many pre-NFIP residences were elevated because residents already perceived flood risk; assumption D faltered in these instances. Because these structures were assumed to be constructed slab-on-grade, inundation and—by convention—damage to such homes was likely grossly over-predicted using assumption D. It should also be noted that while the error for pre-NFIP structures with assumption D was only -1.75 ft (0.53 m), since the error is averaged over the entire
Table 4.2: Average error in feet estimated for different building characteristics under the different elevation assumption scenarios for each region used for the stratified sample. Positive values indicate over-prediction by the assumption, negative values: under-prediction.

<table>
<thead>
<tr>
<th>Region</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>-0.77</td>
<td>-2.81</td>
<td>-2.32</td>
<td>-0.17</td>
<td>-1.65</td>
<td>-0.11</td>
<td>-0.55</td>
<td>0.74</td>
<td>0.18</td>
<td>0.09</td>
<td>-0.11</td>
</tr>
<tr>
<td>H</td>
<td>-2.83</td>
<td>0.24</td>
<td>-4.21</td>
<td>1.17</td>
<td>-2.55</td>
<td>0.22</td>
<td>0.61</td>
<td>0.36</td>
<td>0.03</td>
<td>0.02</td>
<td>0.51</td>
</tr>
<tr>
<td>max(H,D)</td>
<td>-0.15</td>
<td>0.38</td>
<td>-1.51</td>
<td>1.17</td>
<td>-0.84</td>
<td>0.28</td>
<td>0.93</td>
<td>1.23</td>
<td>0.35</td>
<td>0.11</td>
<td>0.53</td>
</tr>
<tr>
<td>min(H,D)</td>
<td>-3.45</td>
<td>-2.95</td>
<td>-5.01</td>
<td>-0.17</td>
<td>-3.35</td>
<td>-0.17</td>
<td>-0.87</td>
<td>-0.13</td>
<td>-0.13</td>
<td>0.00</td>
<td>-0.13</td>
</tr>
</tbody>
</table>

Study Area (where many inland, pre-NIFP structures are constructed slab-on-grade), this value likely under-represents the actual error in surge-prone areas.

Table 4.1 lends insight into why the max(H,D) scenario resulted in the lowest RMSE. By assuming the maximum estimate provided by assumptions D and H, the max(H,D) scenario addressed the major source of error in surge-prone areas for both assumptions. For post-NFIP homes in zone VE, H’s underestimation was overridden by the more accurate results of D, which reflected BFE. Conversely, for pre-NFIP structures in areas with perceived flood risk, the erroneous slab-on-grade assumption in D was replaced by the assumption of H, which bases estimated elevation on foundation type and better reflects the elevations of such structures.

Finally, the results in Table 4.1 demonstrate that while the max(H,D) assumption did not provide the most accurate estimates across all categories, it was—by far—the most consistently accurate. However, the values in Table 4.1 are still aggregated over the entire Study Area. Breaking down the error values by sample region, as shown in Table 4.2, it becomes evident that there is still substantial spatial variability in the error associated with the elevation estimates. When these regions are broken down even further, into individual sample strata, the discrepancy becomes even more pronounced.
4.4 Incorporating Elevation Correction into the BDM+SC

The second half of this chapter will focus on using the elevation data sampled in the Study Area to mitigate the uncertainty in the damage estimates associated with the different elevation assumptions. While the corrected results should be, in a sense, more accurate in that they better reflect the actual elevations of structures in the Study Area, because substantial uncertainty remains in other components of the surge modeling process (see Chapter 5 for further investigation), the corrected results may still do a poor job representing actual surge damage. Therefore, the following work should be viewed as another incremental step in advancing surge damage modeling to more robust representation of reality.

The first step in incorporating elevation correction into the surge damage model was to associate a probability distribution to the error between the estimated and observed structure elevations. Because of the regional variability in the elevation error observed in the previous section, it was decided that building elevations should be corrected by their corresponding sample stratum instead of performing any aggregation. Histograms of the elevation error (estimated - surveyed) were computed and plotted for each of the strata and for each elevation assumption. After examining the plots, the following observations were made:

- The data tended to have a single, most common value.
- The distributions exhibited varying degrees of skewness.
- There appeared to be limits to the extremes of the distribution, e.g., ground elevation serving as a lower bound for underestimates.
- Outliers were frequent, with little intermediate data in some cases.

Because of these observations, it was decided that the triangle distribution best approximated the data because it accommodates skewness, and it is well-suited to sit-
uations were data are limited, but their upper and lower bounds can be approximated. With additional elevation data, a more robust analysis of the distribution of the elevation error could be conducted using a “goodness-of-fit-test”, such as the Kolmogorov-Smirnov test. However, because of the limited sample performed in this study, a subjective distribution like the triangle distribution was deemed more appropriate. The equation for the probability density function (PDF) of the triangle distribution is as follows:

\[
f_X(x) = \begin{cases} 
0, & x < a \\
\frac{2(x-a)}{(b-a)(c-a)}, & a \leq x < c \\
\frac{2(b-x)}{(b-a)(b-c)}, & c < x \leq b \\
0, & b < x,
\end{cases}
\]  

(4.2)

where \(a\) and \(c\) represent the estimated upper and lower bounds of the data, respectively, and \(b\) is an estimate of the central, or modal, value. It was decided that \(b\) would be assigned to the median value of the data and that \(a\) and \(c\) would be assigned to the second highest and the second lowest values. The justification behind this decision for the extreme values was that when the first extremes were used, the triangle distribution tended to over-estimate the spread of the probability distribution in strata with many points clustered around a central value, but with one or two outliers. Figure 4.4 shows four examples of fitted triangular distributions to the elevation error data for four sample strata. The upper-left distribution is an effective illustration of why the second extremes were utilized.

After computing the triangular distribution parameters for all sample strata and under all four elevation assumptions, the BDM+SC was updated to incorporate elevation correction (EC) for the assumed elevations, resulting in the BDM+SC+EC.
Figure 4.4: Four examples of the triangle distributions fitted to the elevation estimate error data. A.) Region 3, zone AE, pre-NFIP, assumption D B.) Region 5, zone AE, post-2002, assumption H C.) Region 2, zone VE, pre-NFIP, assumption max(H,D) D.) Region 1, zone AE, pre-NFIP, assumption min(H,D)
As shown by the flowchart in Figure 4.5, the implementation of the BDM+SC+EC was quite simple. For each trial of the MCS, a random error value was sampled from the triangular distribution corresponding to the structure. The value was then subtracted from estimated FFF and LHSM elevations provided by the initial elevation assumption to “correct” the initial estimate. The corrected elevation values were then used as input to the BDM+SC, which computed the estimated damage for that trial of the MCS. After sufficient trials, BDM+SC+EC resulted in distributions of estimated total dollar damage and the number of affected homes in the Study Area.

Like the BDM+SC, the MCS routine of the BDM+SE+EC was implemented using MATLAB’s Parallel Processing Toolbox. Almost linear performance scaling was observed running the simulation on a four-core, desktop computer. Computing the 95% confidence intervals for the mean damage estimates confirmed that 2,000 trials were sufficient. The intervals were similarly narrow as those obtained under the BDM+SC. Each BDM+SC+EC run required approximately forty minutes to complete on the four-core system, resulting in a total runtime of approximately 43 hours for all 16 storms and four elevation assumptions. All subsequent plots and tables of the BDM+SC+EC results are in terms of the estimated mean values of the total dollar damage and the number of affected homes in the Study Area. Example distributions of the total damage output under the different elevation assumptions are provided for storm 3C in Figure 4.6.

4.5 BDM+SC+EC Results

Figure 4.7 shows the total monetary damage estimates obtained using the BDM+SC+EC. Compared to the BDM+SC results (see Figure 3.14), it was immediately apparent that incorporating elevation correction into the model resulted in a significant reduction in variability between damage estimates produced using the different elevation
Figure 4.5: Flowchart of the BDM+SC+EC.
Figure 4.6: Example output distributions of total monetary damage from the BDM+SC+EC for storm 3C under different elevation assumptions: A.) D B.) H C.) max(H,D) D.) min(H,D)
assumptions. This initial observation was further substantiated by the results presented in Figure 4.8, which shows the observed variation in total dollar damage between the different elevation assumptions across all three damage models: the BDM, the BDM+SC and the BDM+SC+EC. Apart from storms 1D and 4C, incorporating elevation correction dramatically reduced the variability in the damage estimates relative to the BDM and BDM+SC. For example, in the case of storm 3D, variability between the different elevation assumptions was reduced from $2.1 billion to $140 million.

Figure 4.9 plots the change in estimated damage from the BDM+SC to the BDM+SC+EC, providing additional insight as to how each storm’s model results

As discussed previously, storms 1D and 4C are unique cases. Storm 1D did not produce significant damage in the region, therefore the resulting magnitude of variability after elevation correction was small. Conversely, 4C was so large, that all homes in surge-prone areas experienced significant damage regardless of elevation assumption, reducing sensitivity to the elevation assumptions and therefore the impact of the elevation correction.
Figure 4.8: Range in total monetary damage between the highest and lowest estimates under the four different elevation assumptions for the BDM, the BDM+SC and the BDM+SC+EC.

were affected by incorporating elevation correction, under the different elevation assumptions. Across the entire suite of storms, Figure 4.9 shows that the max(H,D) assumption experienced the smallest change in estimated damage after elevation correction, further substantiating the previous claim that it provided the most accurate estimate of building elevations in the Study Area.

What was more intriguing, was that the results shown in Figure 4.9 suggested that applying the elevation correction to assumption H resulted in significant changes in the estimated total damage, despite H having an almost equivalent RMSE to max(H,D). This observation confirmed some of the speculation in Section 4.3; that, while RMSE suggested that the max(H,D) and the H assumptions were commensurate, this was only the case in the aggregate sense, or over the entire Study Area. In surge-prone regions (i.e., those where damage was modeled), the accuracy of assumption H was shown to be much lower than max(H,D).
Figure 4.9 shows that the min(H,D) assumption was consistently subject to the most correction across the storm suite, although assumptions H and D did not perform much better. Since assumptions H and D varied in their relative performance depending on the storm, no clear inferences could be drawn as to which was more accurate. Regardless, like the results discussed above, this behavior was not predicted by the conclusions of the RMSE analysis. Assumption H’s RMSE was much lower than D’s, yet in terms of actual performance, the two assumptions were on par with one another. This observation illustrates the importance of considering the spatial distribution of the error between the different elevation assumptions. Aggregating the error of the estimates to a countrywide or some intermediate level can average out the local variability in the accuracy of the estimates. Therefore, error was sampled from each sample stratum in the BDM+SC+EC to preserve this variability.
Similar results to monetary damage were obtained for the number of affected homes. Figure 4.10 shows the BDM+SC+EC estimates for the mean number of affected homes for each storm, under all four initial elevation assumptions. The results paralleled those shown in Figure 4.7; discrepancy in the number of affected homes estimated using the different initial elevation assumptions was substantially reduced after elevation correction.

Figure 4.11 shows the variability in the estimates of the number of affected homes obtained under the different elevation assumptions, using the BDM, the BDM+SC and the BDM+SC+EC. From the results presented in the figure, it is clear that—as was the case with the total dollar damage—a large reduction in the variation in the estimates of the number of affected homes was observed after elevation correction.\textsuperscript{1} Interestingly, the results diverged from the total dollar damage estimates in that they showed a larger residual variation for the smaller storms than storm 3. In fact, the largest residual discrepancy was observed for storm 2C. This is likely because storm 2C fell in the “sweet spot” for variability in the number of affected homes (recall, Section 3.5).

Finally, Figure 4.12 plots the change in the mean number of affected homes before and after elevation correction. The results, for the most part, paralleled those of the monetary damage—the max(H,D) assumption experienced by far the smallest change after the introduction of elevation correction. Furthermore, assumptions H and D were very similar in terms of their overall performance, with H performing much more poorly than max(H,D) when compared to what was suggested by their relative RMSEs. As an additional reference, tabulated results from the BDM+SC+EC are included in Appendix D.

\textsuperscript{1}The reason why there was such little change in variability between the BDM and the BDM+SC was discussed in Section 3.7.
Figure 4.10: BDM+SC+EC mean estimates of the number of affected homes in the Study Area under different elevation assumptions.

Figure 4.11: Range in the total number of affected homes between the highest and lowest estimates under the four different elevation assumptions for the BDM, the BDM+SC and the BDM+SC+EC.
4.6 Spatial Distribution of the Damage Estimates

After Elevation Correction

The spatial distribution of the structural damage intensity estimated by the BDM+SC+EC was plotted for storm 3C and for all four elevation assumptions, using the methodology described in Section 3.8. Figures 4.13 to 4.16 present these results. Comparing the spatial data obtained from the BDM+SC+EC to that of the BDM+SC (recall, figures 3.18 to 3.21), it is readily evident that elevation correction had a considerable impact on the distribution of damage. The spatial results from the different elevation assumptions were almost identical after elevation correction, whereas substantial variability was observed using the BDM+SC. While some slight discrepancies between elevation assumptions remain in the eastern portion of the Bolivar Peninsula, incorporating the elevation adjustment not only resulted in a convergence in the aggregate...
damage totals produced using different elevation assumptions, but convergence in their spatial distribution as well.

4.7 Chapter Findings

The first part of this chapter evaluated the performance of the different elevation assumptions by comparing estimates of building elevation produced by the assumptions to a sample of actual building elevations in the Study Area. To address the challenges associated with obtaining building elevation data, a novel methodology was introduced to estimate these elevations using GIS and Google Street View. A stratified sample of the structures in the Study Area performed using the tool suggested that the max(H,D) assumption was most accurate, but also uncovered substantial variability in the performance of the estimates in different regions of the Study Area and across different flood zones and construction dates.

The second portion of the chapter was focused on using the elevation survey results to produce a damage model that would correct the initial elevation assumptions; this resulted in the creation of the BDM+SC+EC. Applying the BDM+SC+EC, convergence was observed in the estimates of dollar damage, number of affected homes and the spatial distribution of damage yielded using the different elevation assumptions. The BDM+SC+EC results further indicated that the max(H,D) assumption was the most accurate in the Study Area.

It is promising that the elevation correction methodology resulted in convergence between the damage estimates obtained using the different elevation assumptions. This observation indicates that if data shortages in a region preclude the use of a particular elevation assumption,\(^1\) a lesser approximation can be used instead and later

\(^1\)For example, foundation or DFIRM data may not be available for a community.
corrected, with the results providing a damage estimate of commensurate quality as one obtained using a superior initial assumption.

Finally, while incorporating elevation correction into the surge damage model resulted in a more accurate representation of structure elevations in the Study Area, regardless of the elevation assumption initially applied, it should be emphasized that the damage model results are still subject to considerable uncertainty from other sources. Chapter 5 will provide greater insight into some of these remaining aspects of uncertainty.

Figure 4.13: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption D.
Figure 4.14: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption H.

Figure 4.15: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption max(H,D).
Figure 4.16: Spatial distribution of structural damage intensity for storm 3C under initial elevation assumption $\min(H,D)$. 
The previous two chapters of this thesis focused on addressing two shortcomings of current methodologies in modeling storm surge damage to single family residential structures: uncertainties due to initial assumptions about the elevations of residential structures and problems associated with using the standard method for flood damage assessment to model surge damage. However, these issues were with regards the mean values of the damage estimates. Essentially, the focus was on addressing major discrepancies between methodologies and not on understanding the variability in individual estimates produced by the damage model. The goal of this chapter is to perform a preliminary investigation of this variability.

To perform such an analysis, two additional aspects of uncertainty were incorporated into the BDM+SC+EC: uncertainty in depth-damage functions and uncertainty in CSVRs. An uncertainty analysis (UA) was then performed on the augmented model, with respect to different assumptions of independence/dependence between the variable parameters. Independence assumptions were assessed because it has been shown that they have the potential to substantially impact the variability of damage model results (Egorova et al., 2008). Lastly, while also considering different assumptions of independence, variance-based global sensitivity analysis (GSA)
was performed to assess the relative contributions of uncertain parameters to the variability of the modeled results.1

5.1 Uncertainty in Depth-Damage Curves

As mentioned in Section 2.5, there is a large body of literature surrounding uncertainty in flood damage estimates. These studies have assessed uncertainty due to a wide variety of parameters, including cost estimates (Saint-Geours et al., 2013), dike failure (de Moel et al., 2012, 2014), land use (de Moel and Aerts, 2011) and terrain models (Boettle et al., 2011). Still, depth-damage curves are almost universally accepted in the Literature as being one of the major, if not the primary, source(s) of uncertainty in flood damage estimates (Merz et al., 2004; Jongman et al., 2012; Saint-Geours et al., 2013). Figure 5.1 exemplifies this issue, as it is a plot of several depth-damage functions used in the United States to predict damage for single story, single family residences. The disparity between the different functions—all of which technically represent the same process—is a clear indicator of the uncertainty associated with their application.

To incorporate uncertainty in depth-damage functions into the BDM+SC+EC, a methodology developed by Egorova et al. (2008) was adapted to this study. This methodology has been incorporated into subsequent flood damage uncertainty studies by de Moel et al. (2012) and de Moel et al. (2014). The procedure involves fitting a beta distribution to a damage function so that the distribution’s mean value falls on

1While they may seem similar, the difference between uncertainty analysis and sensitivity analysis (SA), as described by de Moel et al. (2012), is that UA focuses on determining the range in model output that comes about from uncertain parameters. SA is an extension of UA and seeks to determine the relative contributions of uncertain parameters to the overall variability of the output.
Figure 5.1: Plot depicting various single story residential depth-damage functions. The PDF of the beta distribution is as follows:

$$f_X(x|\alpha, \beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}, \quad (5.1)$$

where $0 \leq x \leq 1$ for $\alpha > 0$ and $\beta > 0$, and where $\Gamma(x)$ is the gamma function:

$$\Gamma(a) = \int_0^\infty z^{a-1}e^{-z}dz. \quad (5.2)$$

The variance of the beta distribution is then adjusted per the damage function’s damage ratio, so that the variance is zero at the upper and lower limits of the curve and at its maximum at the function’s midpoint. To force this behavior, the alpha and beta parameters of the beta distribution are scaled using the following equations:

$$\alpha = \left(\frac{1}{k} - 1\right) r(d) \quad (5.3)$$
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Figure 5.2: Variance of the beta distribution as a function of damage ratio using the methodology of Egorova et al. (2008).

\[ \beta = \left( \frac{1}{k} - 1 \right) \left( 1 - r(d) \right), \]  \hspace{1cm} (5.4)

where \( r(d) \) is the damage function evaluated at a depth \( d \), and \( k \) is an uncertainty parameter determined by expert judgment. \( k \) dictates the magnitude of the beta distribution’s variance (a higher \( k \) results in a higher peak variance). To visualize these equations, Figure 5.2 plots the variance of the beta distribution as a function of the damage ratio using a \( k \) value of 0.1.

Egorova et al. (2008)’s assumption about how uncertainty in damage functions behaves at different damage ratios is appropriate for idealized versions of said functions. In such functions, variance in the estimated damage is minimized when the damage ratio is close to zero and one because neither negative damage nor greater than 100% damage can be done to a structure. When the idealized functions are
compared to actual functions utilized in the United States, the idealized functions tend to compare favorably in the lower and intermediate portions of the curves. As shown in Figure 5.1, there is less variability between functions at lower damage ratios and more variability at intermediate damage ratios.

In the upper regions of the functions, however, this assumption breaks down. The example functions never achieve 100% damage; instead, they behave asymptotically, leveling off at a maximum damage value, which can vary substantially, depending on the function. However, in the case of the most recent functions (NO 2006 and FEMA 2013 in Figure 5.1)—those used in this study—there is less variation in their peak damage ratios than in their intermediate regions.

To address this issue, Egorova et al. (2008)'s procedure was modified to allow the variance of the beta distribution at the functions’ asymptotes to be manually adjusted, resulting in the following updated equations for alpha and beta:

\[
\alpha = \frac{1}{k} \left( \frac{r(d)(1 - r(d))}{z - r(d)} \right) - r(d)
\]

\[
\beta = \alpha \left( \frac{1}{r(d)} - 1 \right),
\]

where 0 < z < 1, and can be adjusted to provide the desired amount of variance in the upper regions of the damage functions.

A k value of 0.1 was assumed for this study, as this value was used by Egorova et al. (2008), de Moel et al. (2012) and de Moel et al. (2014).\(^1\) Equations 5.5 and 5.6 were used to plot the 90% and 95% confidence intervals of the beta distribution.

\(^1\)While these studies were in Europe and were conducted using a different suite of damage functions, visual inspection of the confidence intervals in Figure 5.3 suggested that the choice of k value was appropriate for a preliminary analysis. Future work should assess the actual variability observed damage within coastal communities in the United States to provide insight as to the proper choice of this parameter.
relative to the damage function. The confidence intervals were used as a reference to select an appropriate value of $z$. Figure 5.3 shows two examples of such functions with their associated 90% and 95% confidence intervals.

5.2 Uncertainty in CSVRs

The second additional component of uncertainty added to the BDM+SC+EC was in the residential structures’ contents to structure value ratios, or CSVRs. CSVRs were chosen as the second aspect of uncertainty because they appeared to be one of the more subjective parameters used in residential damage modeling. The documentation for the CSVRs used in this study provided only a cursory overview of how the values were determined, and the range between the upper and lower CSVR estimates was large (USACE, 2006). Since it seemed unlikely that single family residences would share a single, constant CSVR throughout the Study Area (especially with the large variation in property value in Galveston County), CSVRs were a natural choice to add additional uncertainty to the model.
The damage model was updated to represent this uncertainty using the uniform
distribution, with the following function for its PDF:

\[
f_X(x) = \begin{cases} 
\frac{1}{b-a}, & \text{for } x \in [a, b] \\
0, & \text{otherwise},
\end{cases}
\tag{5.7}
\]

where \(a\) and \(b\) are the respective upper and lower bounds of the random variable. For
this study, \(a\) and \(b\) were chosen to be the upper and lower estimates of the CSVRs for
one and two story structures provided by USACE (2006). For one story structures,
the values for \(a\) and \(b\) were 0.59 and 0.71, respectively. And for two story structures,
the values were 0.43 and 0.67, respectively.

5.3 Computational Scheme of the Updated Model

With the addition of uncertainty in the damage functions and CSVRs, the computa-
tional procedure of the BDM+SC+EC was altered significantly. It was implemented
in MATLAB as follows:

1. An \(N_p\) by \(N_{\text{trials}}\) by \(N_{\text{homes}}\) array of pseudorandom values (PRVs) between 0
   and 1 was generated, where \(N_p\) is the number of uncertain parameters, \(N_{\text{trials}}\)
is the number of trials in the MCS and \(N_{\text{homes}}\) is the number of homes in the
   Study Area.

2. Structures outside of the surge zone were assigned zero damage and omitted
   from the MCS.

3. Structure elevations were estimated using a chosen elevation assumption.

4. The MCS was initialized, and the following procedure was repeated for each
   structure and for a specified number of trials:
(a) An elevation adjustment value was sampled using the appropriate PRV and the inverse CDF of the triangle distribution associated with the structure. The correction value was subtracted from the initial elevation estimate to adjust it.

(b) FFF inundation and LHSM freeboard values were computed using the adjusted elevation.

(c) Structural failure probabilities were estimated using Equation 3.14 from Tomiczek et al. (2014).

(d) A CSVR value was sampled using the inverse CDF of the uniform distribution and the appropriate PRV.

(e) The structure’s probability of failure was compared to the corresponding PRV. If it was greater than the PRV, the structure was considered to have collapsed; its structure and contents damage were set to 100%, the rest of the MCS loop was skipped and the damage estimates were stored in an array. Otherwise, the MCS proceeded to the next step.

(f) Alpha and beta values were computed for the structure and contents damage functions based on the depth of FFF inundation, using equations 5.5 and 5.6.

(g) PRVs for both the structure and contents damage functions were sampled and evaluated through the inverse beta distribution, using the previously-computed alpha and beta values. The resulting damage ratios were then used to compute structure and contents damage estimates, which were stored in an array.

5. For each trial, estimates of the total damage and the number of affected homes were computed for the Study Area.
5.4 Uncertainty Analysis of Independence Assumptions: Setup

Different assumptions of spatial independence in the behavior of uncertain parameters within a flood damage analysis can produce significantly different results in terms of the variability of damage estimates. Egorova et al. (2008) investigated the effect of different independence assumptions regarding the behavior of depth-damage functions, and concluded that the variability of flood damage estimates was either over-predicted or under-predicted, if variability in the damage functions was assumed to be fully dependent or fully independent between different assets.

Assuming full independence reduces variability because each asset being modeled is assigned its own damage function. Thus, different structures could have higher or lower damage at a given depth of inundation than others. However, less variability is reflected in the aggregate damage totals because opposite extremes in the estimated damage for a given depth of inundation tend to cancel each other out. Assuming full dependence—on the other hand—assigns one function to all structures within a study area. This means that if a function results in an extreme estimate of damage for a given depth of inundation, the same applies to all structures being analyzed. This substantially increases the variability of the total estimated damage because extreme estimates no longer cancel each other out.

Most recent studies of uncertainty in flood damage assessment have operated under the assumption of complete dependence (e.g., de Moel et al. (2012), Saint-Geours et al. (2013) and de Moel et al. (2014)). The likely reason behind the widespread use of this assumption is that simulating increasing independence requires more computer memory and computational time. These studies incorporated many more uncertain
parameters into their analyses than Egorova et al. (2008), precluding the evaluation of anything beyond full dependence.

Since this study is only focused on single family residential structures and incorporates only six random variables: structural damage function, contents damage function, CSVR, structural collapse and structure elevation, an uncertainty analysis of different independence assumptions was feasible. The following scenarios were considered:

- **Fully Independent (FI)** - All uncertain parameters are assumed to vary independently for each structure in the Study Area. For each trial of the MCS, separate PRVs are sampled for each structure and each uncertain parameter.

- **Fully Dependent (FD)** - All uncertain parameters are assumed to be fully dependent across all the structures in the Study Area. For each trial of the MCS, a single PRV is sampled for each parameter and then applied to the entire Study Area.

- **Partially Dependent (PD)** - All uncertain parameters were assumed to vary independently with exception to the two depth-damage functions. For each trial of the MCS, PRVs were sampled for each function and then applied to all homes in the dataset. For the other parameters, PRVs were sampled independently—on a structure-by-structure basis.

### 5.5 Uncertainty Analysis of Independence Assumptions: Simulations and Results

Because of the increased computational cost of running the updated model, it was decided to perform the independence assumption uncertainty analysis using a subset
of the storms assessed in chapters 3 and 4. Storms 3A, 3B, 3C and 3D were selected for analysis because they encompassed a variety of damage magnitudes and showed high sensitivity to the initial elevation assumptions.

Each storm was evaluated in the damage model for all three independence assumptions, while using max(H,D) as the initial elevation assumption. Convergence in the resulting distributions of total damage and the number of affected homes was determined by plotting estimates of the mean, median and 97.5 and 2.5 percentiles versus the number of simulations. Using this method, 2,000 MCS trials were determined to be adequate for the FI assumption, and 3,000 MCS trials were sufficient for the PD and FD assumptions. Figure 5.4 is an example plot of the convergence analysis. Like the BDM+SC and the BDM+SC+EC, the main loop in the MCS routine was parallelized. Regardless, damage model runs required about two hours to complete 3,000 simulations on a four-core desktop computer.
Figure 5.5 shows the results of the independence assumption uncertainty analysis for total estimated damage. For the four storms, it was evident that different independence assumptions resulted in substantial changes in the variability of the estimated damage, paralleling the results of Egorova et al. (2008). Figure 5.5 shows that for each storm, estimates of the mean damage remained essentially constant across the different independence assumptions, while the median values decreased slightly with increasing dependence. Under the fully dependent assumption, the span of 95% interval was substantial for all four storms. For storm 3C, for example, this range was $4.05 billion, with 2.5 and 97.5 percentile values of $777 million and $4.83 billion, respectively. Under the PD assumption, storm 3C’s 95% interval shrank to $1.12 billion, which is still quite large. However, under the FI assumption, variability decreased significantly; Storm 3C only had a $56 million range between its 2.5 and 97.5 percentile values.

The observed trend of decreasing variability with increasing independence was expected. As previously alluded to, increasing independence results in the introduction “averaging out” effects into the MCS. These occur when extreme values from some structures are canceled out by opposite extremes at other structures during the same trial of the MCS, reducing variability in the total damage estimates. When variable behavior is assumed to be fully dependent, low probability values are applied to all structures in the dataset simultaneously, resulting in similarly extreme aggregate damage estimates. Partial dependence results in variability somewhere in between the FI and FD extremes.

Intuitively, however, it is quite apparent that the FD assumption results in a significant overestimation of variability in the damage totals. Observations of the variation in structure elevations in Section 4.3 clearly indicated that—at least within this thesis’ Study Area—structure elevations tend to vary on a home-by-home basis.
Figure 5.5: Independence assumption uncertainty analysis results for the total dollar damage. Clockwise from the top-left: storm 3A, storm 3B, storm 3C and storm 3D. The mean value of the damage estimates is plotted across the independence assumptions in blue. The median value is plotted in black. Whiskers indicate the estimates of the 97.5 and the 2.5 percentiles of the distribution.
Such behavior is more in line with the FI assumption than the FD assumption. Similar inferences can be drawn regarding variability in structural failure and CSVRs; it is highly unlikely that their behavior would be at all coordinated across the Study Area.

In terms of the depth-damage functions, a tendency toward fully independent behavior is less evident. It’s possible that variability in the curves may be coordinated across building age groups or flood zones. Egorova et al. (2008) suggested that partial dependence may be observed in damage functions at different depths of inundation. Unfortunately, without data of observed damage within the Study Area, no conclusions could be made beyond such speculation. Because of this uncertainty, the PD assumption held damage curves under the fully dependent assumption while assuming independence for the other variables. Since the actual behavior of the depth-damage functions was assumed to likely fall somewhere in between partial dependence and independence, it was considered most likely that the actual variability in residential damage estimates fell somewhere in between the PD and the FI assumptions.

Regardless, the results of the uncertainty analysis clearly indicate that assumption of full dependence can potentially significantly overestimate the variability of damage estimates. Future studies of uncertainty in flood and coastal damage estimates should incorporate at least a cursory evaluation of the sensitivity of their results to assumed independence. Proving the range in variability between full independence and full dependence should provide adequate perspective until future work provides greater guidance as to what independence assumption is most appropriate.

Figure 5.6 plots the result of the independence assumption uncertainty analysis for the number of affected homes. Almost identical behavior was observed in the number of affected homes as the total dollar damage.
Figure 5.6: Independence assumption uncertainty analysis results for the number of affected homes. Clockwise from the top-left: storm 3A, storm 3B, storm 3C and storm 3D. The mean value of the damage estimates is plotted across the independence assumptions in blue. The median value is plotted in black. Whiskers indicate the estimates of the 97.5 and the 2.5 percentiles of the distribution.
5.6 Global Sensitivity Analysis: Introduction and Implementation

Having shown that different independence assumptions can produce significant changes in the variability of damage estimates, the natural next step was to perform a sensitivity analysis to determine what variables were driving the uncertainty. Sensitivity analyses of models can be performed using a variety of methods. Most commonly, model sensitivity is assessed using so-called “one-at-a-time” methods, where one uncertain parameter is varied and the other parameters are held constant (e.g., de Moel and Aerts (2011)). The problem with such “local” assessments of sensitivity is that only the sample space around the input parameters is explored—no attention is given to the interaction between uncertain parameters (Pappenberger et al., 2008; Saltelli and Annoni, 2010).

On the other hand, global sensitivity analysis (GSA) explores the entire sample space, quantifying uncertainty associated with a parameter on its own (first order effects) and uncertainty associated with the parameter’s interaction with other variable parameters (higher-order effects) (Pappenberger et al., 2008; Saltelli and Annoni, 2010). Consequently, for this study, it was decided that GSA would be performed instead of a local approach to account for these higher-order effects.

5.6.1 Sobol’ Global Sensitivity Analysis: Introduction

GSA was performed per the method of Sobol’ (Sobol’ (1990): original publication, in Russian; Sobol’ (2001)). This approach has been widely used in other flood damage sensitivity analyses (e.g., de Moel et al. (2012), Saint-Geours et al. (2013), de Moel et al. (2014) and Tate et al. (2014)), so the methodology was the natural choice for this study.
This section will only serve as a general introduction to the method of Sobol’. There are numerous other—more thorough—overviews in the Literature, and the reader is referred to these publications for more detail (see Saltelli (2002), for example). Sobol’ GSA is based on the assumption that uncertainty due to parameters with independent probability distributions can be based on the decomposition of the total unconditional variance of the model, $Y = f(X_1, X_2, ..., X_k)$, into its components:

$$V(Y) = \sum_i V_i + \sum_i \sum_{j>i} V_{ij} + ... + V_{12...k},$$  

(5.8)

where $V(Y)$ is the unconditional variance of $Y$, $V_i$ is the variance associated with variable $X_i$ and $V_{ij}$ is the variance associated with the interaction of variables $X_i$ and $X_j$.

Based on this decomposition, the following indices can be computed to evaluate the model sensitivity to each variable $X_i$:

$$S_i = \frac{V_{X_i}(E_{X_i}(Y|X_i))}{V(Y)}$$  

(5.9)

$$S_{Ti} = \frac{E_{X_i}(V_{X_i}(Y|X_{-i}))}{V(Y)}$$  

(5.10)

The numerator in Equation 5.9 is the expected reduction in variance obtained by using a fixed value for parameter $X_i$. Therefore, $S_i$ is the fraction of the total variance contributed independently by $X_i$ (Saltelli et al., 2010; Saltelli and Annoni, 2010). The numerator in Equation 5.10 is the expected remaining variance in $Y$ if all the other parameters but $X_i$ were fixed (Saltelli et al., 2010; Saltelli and Annoni, 2010). The $S_i$ index can be interpreted as the effect of that uncertain parameter $X_i$ has on the model.
variance, by itself. On the other hand, $S_{Ti}$ is the combined effects of the parameter $X_i$ by itself and its interaction with other parameters.

### 5.6.2 Sobol’ Global Sensitivity Analysis: Implementation

The Sobol’ GSA indices are typically estimated using Monte Carlo Simulation (Saltelli, 2002). To compute these indices, the procedure outlined by Saltelli (2002) was implemented in MATLAB, but using updated estimators for $E_{X\sim i}(V_{X_i}(Y|X\sim _i))$ and $E_{X\sim i}(V_{X_i}(Y|X\sim _i))$ provided by Saltelli et al. (2010). The updated estimators were chosen because they were shown by Saltelli et al. (2010) to result in faster convergence of the indices, compared to those used by Saltelli (2002). The estimators are computed as follows (using the same notation as Saltelli et al. (2010)):

$$E_{X\sim i}(V_{X_i}(Y|X\sim _i)) = \frac{1}{N} \sum_{j=1}^{N} f(B)_j(f(A_B^{(i)})_j - f(A)_j)$$  \hspace{1cm} (5.11)

$$E_{X\sim i}(V_{X_i}(Y|X\sim _i)) = \frac{1}{2N} \sum_{j=1}^{N} (f(A_j) - f(A_B^{(i)})_j)^2, \hspace{1cm} (5.12)$$

where $A$ and $B$ are two $N$-by-$k$ arrays of PRVs, where $N$ is the number of Monte Carlo trials and $k$ is the number of uncertain parameters. $A_B^{(i)}$ is a sample matrix, where column $i$ is replaced with column $i$ from sample matrix $B$. The estimator for $E_{X\sim i}(V_{X_i}(Y|X\sim _i))$ was proposed by Saltelli et al. (2010) and the estimator for $E_{X\sim i}(V_{X_i}(Y|X\sim _i))$ was proposed by Jansen (1999).\(^1\)

As implemented in MATLAB, the computational procedure began with first computing $f(A)$ and $f(B)$. Next, $V(Y)$ was computed using the results of $f(A)$. Then, $f(A_B^{(i)})$ was computed for each uncertain parameter $X_i$, and then Equations 5.11 and

---

\(^1\)For GSA of the FI assumption scenario, each entry of array $A$ corresponded to a vector of PRVs sampled for all the structures in the Study Area. $A_B^{(i)}$, therefore, was produced by replacing the $N$ sample vectors in column $i$ of $A$ with those from column $i$ of $B$. 
5.12 were used in conjunction with Equations 5.9 and 5.10 to compute the first-order and total-effects indices for each variable. To validate this implementation, the MATLAB code was used to evaluate the sensitivity of the test function provided by Saltelli (2002), with the results comparing favorably to the analytical values presented in the paper.

Unfortunately—even with the updated estimators—a large number of Monte Carlo trials was still required to obtain convergence of the Sobol’ indices, especially the $S_i$ values. Because of this, the GSA was performed only using 1,000 structures sampled randomly, without replacement, from the those affected by storm surge in the Study Area. 50,000 simulations were determined to be adequate for respectable convergence of the Sobol’ indices for total damage estimates. This was fortunate because this value was limited by available computer memory. Unfortunately, 50,000 simulations were inadequate for convergence of the $S_i$ indices for the number of affected homes with assumption of full independence. For this reason, GSA results for the number of affected homes will not be presented in this chapter.\(^1\)

Even in the case of the total dollar damage, the $S_i$ estimates could have benefited from additional simulations. However, the convergence plots indicated that the estimates were at least sufficiently stabilized to draw general conclusions about their relative magnitudes. In general, performance—in terms of the rate of convergence—was much better for the $S_{Ti}$ estimates than the $S_i$ estimates. Example convergence plots for the indices for both the total damage and the number of affected homes are shown in Figure 5.7.

Sobol’ GSA was performed for all four variations of storm 3 and under all three independence assumptions, for a total of twelve GSAs. Even after reducing the num-

\(^1\)Tabulated GSA results for the number of affected homes under the FD and PD assumptions are available in Appendix E.
Figure 5.7: Example convergence plots for the Sobol’ GSA for total dollar damage under the fully dependent assumption (left) and the fully independent assumption (right). $S_i$ values are represented as solid lines. $S_{Ti}$ values are represented as dashed lines. Note the relative rates of convergence between the two types of Sobol’ indices.

ber of structures and parallelizing the MCS routine, each GSA took approximately 12 hours, for a total of 144 hours of simulation.

5.7 Sobol’ Global Sensitivity Analysis: Results and Analysis

Table 5.1 shows the results of the Sobol’ global sensitivity analysis of estimated dollar damage for the four storms and three independence assumptions. When $\sum_{i=1}^{k} S_i = 1$, it indicates that uncertainty in the model is additive, and that there is little interaction between the uncertain components (Tate et al., 2014). The results presented in Table 5.1 suggest that such additivity was generally the case under the partially dependent and fully dependent assumptions. The only exception to this was storm 3A, where the FD GSA results suggested minor interactive effects.

Under the fully independent assumption, however, this did not appear to be the case, as the results suggested that the model may have had a portion of its variance
attributed to interactions between the different parameters. This observation was bolstered by the fact that the $\sum_{i=1}^{k} S_{Ti}$ values for all storms under the FI assumption were greater than all values observed under the PD and FD scenarios, indicating that parameter interaction played a larger part the FI variability. Since the numerical performance of the $S_{Ti}$ estimator was superior to that of the $S_{i}$ (see Figure 5.7, right), this conclusion was made with more confidence.

The results in Table 5.1 also demonstrate that—for the PD and FD scenarios—there was no significant variation in the $S_{i}$ and $S_{Ti}$ indices between different storms under the same independence assumption. While there were slight variations in the magnitudes of the different estimators, at no point did their relative contributions to overall uncertainty change.

Applying the FI assumption, the GSA results became more complicated to interpret. The $S_{i}$ estimates suggested relatively high variation between storms, but this was likely due to numerical error in the estimate because the more accurate $S_{Ti}$ estimates exhibited much less variability. However, the $S_{Ti}$ values did imply that variability under the FI assumption was higher than under the PD or FD assumptions, especially in the relative importance of the structural collapse and structure elevation. Additional work is required to investigate whether these discrepancies were actually due to the different storm characteristics or differences between the structure samples used to compute the estimators.\footnote{Numerical error could also be a factor, but is less likely here due to the robustness of the $S_{Ti}$ estimator.}

The relative importance of the uncertain parameters is best illustrated using Figure 5.8.\footnote{Because of the lack of significant variability between storms, storm 3C was the only storm analyzed in detail. However, the analysis' conclusions were considered valid for the other three storms.} Figure 5.8's results suggested that the independence assumptions had a significant impact on the relative contributions of each parameter to uncertainty in
Table 5.1: Results of the Sobol’ GSA of estimated total dollar damage. From top to bottom: storm 3A, storm 3B, storm 3C and storm 3D. Negative values and instances where $\sum_{i=1}^{k} S_i > 1$ are the results of errors in the numerical approximation of the estimators.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Storm 3A</th>
<th>Storm 3B</th>
<th>Storm 3C</th>
<th>Storm 3D</th>
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<td>0.00</td>
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<td>1.02</td>
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Figure 5.8: Pie charts showing the relative first order effects (left) and total effects (right) of the five uncertain parameters on total dollar damage estimates under the different independence assumptions for storm 3C.
the model. Under the FD assumption, most of the variance in the estimated total
damage was due to variability in structural elevations \( (S_i = 0.63) \), followed by uncer-
tainty in the occurrence of structural failure \( (S_i = 0.30) \). Fixing these two parameters
would have resulted in a 93% reduction in the variance of the estimated damage. On
the other hand, removing uncertainty associated with both damage functions would
have only yielded an 8% reduction. Essentially identical behavior was observed in the
total effect indices.

On the other hand, under the PD assumption, almost the exact opposite behavior
was observed. Variance in the total damage estimates was dictated by the structural
depth-damage curves \( (S_i = 0.71) \); and—to a lesser extent—the functions for home
contents \( (S_i = 0.26) \). Fixing both parameters under the PD assumption would have
resulted in a 97% reduction in the variance of the total damage estimates. Conse-
quently, the effects of structural elevation and the threat of structural collapse were
negligible under assumption PD. In terms of total effects, the relative contributions of
structure elevation and the possibility of structural collapse were no longer negligible,
but were still much less than the damage functions.

Results using the FI assumption were similar to those obtained assuming full de-
pendence. Because of a lack of complete convergence in the \( S_i \) estimates, conclusions
regarding the FI results were made with some reservations. Regardless of this com-
plication, applying the FI assumption appeared to transition control of uncertainty
in the model away from the damage functions, as was the case under the PD assump-
tion, to variability in structure elevation and the threat of structural collapse. These
parameters also dictated uncertainty under the FD assumption.

While the first-order indices did suggest that there were some changes in terms of
the relative importance of structure elevation and structural collapse between the FD
and FI assumptions, this was likely due to a lack of convergence in the \( S_i \) estimates.
This conclusion is supported because the $S_{Ti}$ values produced under FI were almost identical to those yielded under the FD assumption. Because of the stability of the $S_{Ti}$ estimator, these results should be given more weight. Finally, variability in CSVRs was shown to be negligible relative to the other parameters both in terms of its first-order and total effects, under all three independence assumptions.\(^1\)

The results of the preliminary global sensitivity analysis suggest that—in terms of the total monetary damage estimates—uncertainty was driven by structure elevation and the possibility of structural collapse under the FI and FD assumptions. The transition to damage functions dictating model uncertainty under the PD assumption was expected, especially considering the results of the uncertainty analysis, which were discussed in Section 5.5. The significant reduction in the variability of the damage estimates between the PD and the FI assumptions observed in the UA, essentially approximated the effect of removing all uncertainty associated with the damage functions while under the PD assumption. Since the $S_i$ estimator can be thought of as the parameter’s total independent contribution to the overall model variance, the large reduction in variance observed in the UA between the PD and FI assumptions indicated that the $S_i$ values for the damage functions should be similarly large in the GSA results obtained using the PD assumption.

Interestingly, because it is likely that actual behavior of variability in depth-damage functions has some degree of partial dependence, no immediate conclusions could be made from the GSA results as to whether variability was damage function driven, or dominated by some other parameter. Further complicating this observation was the fact that there remains significant room for improvement in terms of assessing

\(^1\)The slight increase in the first-order index for CSVRs under the FI assumption should be ignored as it was almost certainly due to error in the numeric approximation of the estimator.
the variability of the structure elevations\(^1\) as well in the fragility functions obtained from Tomiczek et al. (2014). Improving these components of the analysis could potentially result in different GSA conclusions. Finally, uncertainty in the depth-damage functions was dictated by the choice of \(k\) value, which—for this work—was chosen because it was used in prior studies. Observations of actual damage within the Study Area might suggest the use of a different value. Different \(k\) values would likely yield different GSA results.

5.8 Chapter Findings

From the results of the uncertainty analysis presented in the first half of this chapter, differing assumptions of the independence of uncertain parameters can have a large impact on the variability of surge damage estimates for SFRs. The UA results suggested that the assumption of full dependence likely overestimates variability in estimated damage from storm surge. The implication of this result is clear: future studies of uncertainty in flood and surge damage estimates should perform at least a cursory evaluation of the impacts of different independence assumptions on their results. Simply assuming full dependence—as is commonly done in current uncertainty studies—should no longer be standard practice.

In the second half of the chapter, Sobol’ global sensitivity analysis was applied in a preliminary attempt to provide insight into what parameters were the largest contributors to uncertainty in the dollar damage estimates. As with the uncertainty analysis, the effect of different independence assumptions was considered on the GSA results. The GSA results also showed that the independence assumptions also factored

\(^1\)Recall that, in Chapter 4, the triangle distribution was used to approximate the distribution of error due to the initial elevation assumptions. Because of the nature of the distribution it was possible variability in the building elevations may have been overestimated. Compounding this was the uncertainty associated with using the Google Street View elevation estimation tool to obtain building elevation data.
heavily in their conclusions. However, because of the role independence assumptions played, no clear conclusions could be drawn as to which parameters drove variability in the damage model estimates.
The primary objective of this thesis was to play a small role in a greater effort to advance current modeling practices in storm surge damage assessment from simple, low resolution models that are heavily dependent on assumptions, to more robust and data-rich analyses. This work specifically focused on improving storm surge damage estimates for single family residential structures, which are by far the most common residential asset class in the Houston-Galveston Region.

The first part of this thesis was focused on developing a damage model according the standard method for flood damage assessment (the BDM) and then extending the model functionality to incorporate a widely-documented, surge-specific damage mechanism: the potential for complete structural collapse (the BDM+SC). An uncertainty analysis was then conducted with respect to both models’ results under different initial assumptions of the elevations of structures within the Study Area. The following conclusions were drawn from the analysis:

• Applying the standard method for flood damage assessment (the BDM), differing assumptions of residential structure elevations resulted in highly variable damage estimates, both in terms of total dollar damage and the number of
homes affected by the storm. Variation in the total estimated damage across the elevation assumptions was highest for storm 3C at $1.37 billion.

- Updating the Standard Method model to include the possibility of structural collapse (the BDM+SC) led to large increases in estimated surge damage for all initial elevation assumptions. For storm 4C, the observed increase in total damage hovered around $2 billion. The magnitude of increase in damage observed for all storms suggested that applying the Standard Method results in an inaccurate representation of storm surge damage. Still, significant advancement in storm surge fragility modeling is required before the Standard Method can be completely superseded by more advanced methods. These advances could include fragility functions for a wider variety of residential asset types and development densities, consideration of the interplay between wind and surge damage and addressing the effect of waterborne debris.

- An increase in the variability in the estimated total dollar damage for the Study Area across the different elevation assumptions was observed between the estimates yielded by the BDM and the BDM+SC. For storm 3D, for example, the variability in damage estimates increased from $1.4 billion to $2.1 billion. Storm 4C was the exception to this trend, as variability actually decreased from the BDM to the BDM+SC (see Section 3.7 for discussion).

- Little change in the number of affected homes was observed between the BDM and the BDM+SC. This was because most structures with a non-negligible probabilities of failure were generally already classified as “affected homes”.

- Spatial analysis of the estimated structural damage resulting from the BDM+SC showed significant differences between the results produced using the different elevation assumptions. Such discrepancies present challenges in coastal risk
assessments because different regions could be labeled as having high or low risk depending on the elevation assumption used in the analysis. Likewise, the spatial inconsistency could present issues in prioritizing regions for protection measures. The results also reinforce the fact that while two modeling methodologies may result in similar damage estimates when compared in terms of their aggregate estimates, the spatial distribution of said damage may differ greatly nonetheless.

The next phase of the study attempted to rectify some of the issues associated with the initial elevation assumptions. To accomplish this, a methodology was developed using GIS software and Google Street View imagery to estimate the elevations of residential structures efficiently, on a large-scale. After validation, the tool was used to conduct a stratified survey of home elevations within Galveston County, the results of which were used to update the BDM+SC to correct the initial elevation assumptions; thus resulting in the BDM+SC+EC. The following conclusions were made from the analysis:

- The Google Street View elevation estimation tool was shown through validation to be sufficiently accurate for its application in this study. While adequate for this work, accuracy of the tool could likely be improved with improved aerial imagery, improved location data of Google Street View Vehicles and application of more advanced image processing techniques.

- The stratified sample results suggested that the max(H,D) assumption was the most accurate initial elevation assumption. The sample results also uncovered substantial variability in the performance of the elevation estimates in different regions of the Study Area as well as across different flood zones and construction dates.
After elevation correction, variability in the damage model results was significantly reduced between the initial elevation assumptions. For storm 3D, for example, the range between dollar damage estimates was reduced from $2.1 billion to $140 million from the BDM+SC to the BDM+SC+EC. Similarly, for storm 3A, a large reduction was observed in differences in the estimated number of affected homes: 7,245 to 735. Variability in the spatial distribution of damage was also noted to be minimized after elevation correction.

The BDM+SC+EC results confirmed the conclusions of the elevation survey—the max(H,D) assumption was the most accurate out of the four initial elevation assumptions. The results also suggested that the other elevation assumptions generally overestimated damage within the Study Area.

Since discrepancies between the different initial elevation assumptions appeared to be resolved after correction, it was suggested that in areas where data scarcity precludes making the most appropriate initial assumption, errors associated with using a lesser assumption could be minimized by utilizing the correction process. In studies where available data permit its use, the max(H,D) assumption is recommended for an initial analysis. Still, when possible, future studies should perform their own analyses of structure elevations within their study areas. This should especially be the case when elevation data are readily available, such as communities for which FEMA elevation certificates are published.

At the conclusion of Chapter 4, it was noted that while the BDM+SC+EC resulted in a more accurate depiction of the elevations of structures within the Study Area, the actual damage estimates provided by the elevation-corrected model were still subject to considerable uncertainty from other sources. With this observation in mind, the final objective of this thesis was to provide more insight into this uncertainty.
To accomplish this, two additional components of uncertainty were added to the BDM+SC+EC: uncertainty in depth-damage functions and uncertainty in contents to structure value ratios (CSVRs). An uncertainty analysis of the updated damage model was then performed to assess how different initial assumptions of independence between uncertain parameters affected variability in the damage estimates. The following independence scenarios were considered: full independence, full dependence and partial dependence. For the partially dependent assumption, variation in damage functions was assumed to be fully dependent and the other parameters were assumed to behave with full independence.

After completing the uncertainty analysis, global sensitivity analysis of the damage model was performed under the different independence assumptions. The GSA was a preliminary attempt to determine which of the uncertain parameters contributed the most to model variability, and how their relative contributions were affected by the independence assumptions. The following observations were made from the work:

- Differing assumptions of the independence of uncertain parameters resulted in significant changes in the variability in the damage estimates both in terms of the total dollar damage and the number of affected homes.

- The UA results suggested that the assumption of full dependence commonly employed in uncertainty studies likely substantially overestimates variability in damage estimates. Residential damage is more likely to behave somewhere in between the fully independent and partially dependent assumptions considered in this thesis. Future uncertainty studies should do more to consider the impact of their independence assumptions on their conclusions about variability in estimated damage.

- The global sensitivity results were inconclusive because it was observed that—depending on the independence assumption—different uncertain parameters
would dictate the model’s variability. Under the fully independent and fully
dependent assumptions, variability in the damage estimates was driven by un-
certainty in structural collapse and structure elevation. Under the partially
dependent assumption, damage functions became the principle contributors to
uncertainty.

In terms of future work, one of the priorities should be to obtain better data of
observed damage after tropical cyclones as well as the hydraulic conditions present
in such storms. Improved observations of TC surge and waves could improve the
calibration of hydrodynamic models. Data of the overland wave environment are
especially required to improve wave model performance in these areas. Prior to a
storm’s landfall, temporary gage networks should be installed to provide these obser-
vations. While the USGS already performs this service, denser networks than what
are currently deployed are required, as surge conditions can change substantially on
a small scale, especially in developed areas.

High resolution observations of tropical cyclone winds are also essential data. The
need for this data is not only because high winds can potentially interact with surge
damage (i.e., a structure in a high-wind environment may be more susceptible to
structural collapse from surge and waves), but because accurate observations of TC
winds are essential in developing the wind field data used in surge models.

Because tropical cyclone landfalls are relatively infrequent, consideration should
be given to gathering data using these temporary networks on a global scale. Overseas
deployment of surge, wave and wind sensors would produce a larger and more diverse
dataset of observed data much more quickly than if such data were collected in the
U.S. alone. With better data, and the subsequent improvements in wave and surge
modeling they will afford, the development of better—more nuanced—surge damage
models will become feasible, because uncertainty in the surge and wind parameters
used in such studies will be reduced, allowing researchers to focus on the fragility modeling.

Another essential data requirement are observations of post-storm damage. These data are essential to validating damage model performance and for the development of future modeling methodologies. These data could also be used for the development of improved surge damage models for other asset classes, such as commercial buildings, industrial facilities and infrastructure. With such data, insight could be gained in terms of the accuracy of depth-damage functions as well as the actual degree of independence between uncertain model parameters, addressing many of the questions raised in Chapter 5. Therefore, after a disaster, post storm damage surveys should be thorough and conducted on a structure-by-structure basis. High water marks and information about the elevation of the structure should be recorded as well as more qualitative information about the type of damage inflicted on the structure. This data could be self-reported by residents, or aggregated from flood insurance claims. Regardless of how it is obtained, however, the data should be made readily available to researchers.

Where data are already available but have not been made public, efforts should be made to do so. In terms of this study, a poignant example of this lack of availability is the elevation certificate data held by municipalities across Galveston County. While this data exists, in its current format, and with the restrictions placed upon its retrieval, it was effectively unobtainable for use in this study. If such data were readily available, much of the remaining uncertainty in this thesis associated with the use of the Google Street View elevation estimation tool would be eliminated, as elevation certificate data could be used in lieu of the tool’s estimates. This would likely result in a much more accurate depiction of the variability of the home elevations within the Study Area, improving confidence in the conclusions of this study.
However, since pre-NFIP structures are exempt from submitting elevation certificates under current FEMA regulations, future work should still be invested in improving the accuracy of the elevation estimation tool, because such gaps in the elevation certificate dataset will need to be addressed. The larger dataset of observed structure elevations resulting from the elevation certificate data will aid in validating the existing elevation estimation tool as well as any subsequent improvements to it. Repeating much of the work of this thesis with a more robust elevation dataset would be very insightful.

In some ways, this thesis raised more questions than it provided concrete conclusions. Substantial work remains to improve surge damage estimates, and without robust datasets of asset characteristics and detailed post-disaster damage surveys, it will be challenging to advance our understanding much further. This is the reason why such emphasis was put on data collection in the future work section—it really is the main thing holding the research community back. However, if there is one take-away to be gleaned from this work, it is that variability in the elevations of coastal structures are not inconsequential in large-scale coastal risk assessments. Therefore, structure elevations should be a key consideration in future coastal risk analyses and uncertainty studies. While future work will advance our modeling capabilities much, much further, this study will hopefully be considered another incremental step in the right direction.


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A.1 Parcel Data Preprocessing

The most important data to the damage model were the values, attributes and locations of the residential structures. These data were obtained from the Galveston Central Appraisal District (GCAD) as two datasets: a geographical information system (GIS) shapefile containing the 2015 parcel boundaries, addresses and improvement values\(^1\) as well as the 2015 Certified Roll, which consisted of several .csv files of the parcel attributes. Both datasets had to be preprocessed extensively using Esri’s ArcMap GIS software package to obtain the necessary data and format it properly for use in the BDM. The following steps were taken with the GCAD data before any additional information was added to the dataset:

1. All parcel types except single family residential parcels were removed from the shapefile.

2. Attributes of the main building corresponding to each parcel were joined to the shapefile in ArcMap from the appropriate .csv file in the Certified Roll, using

\(^1\)Improvement values: total value of any construction in the parcel.
the GCAD ID assigned to each parcel as a reference. These data included the
construction date,\(^1\) the foundation type\(^2\) and the number stories.\(^3\)

3. 2,730 parcels that did not have a corresponding main structure listed in the
Certified Roll were removed, leaving 100,292 residential parcels in the final
dataset.

4. Each structure’s location was assumed to lie at the centroid of each of the parcel
The polygon shapefile was converted to a pointfile according to this assumption.

### A.1.1 Adding Additional Spatial Attributes

Ground elevation data were extracted to the parcel pointfile from a 5 ft resolution
raster of the 2006 HCAD LiDAR digital elevation model (DEM),\(^4\) using the Raster to
Multipoint tool in ArcMap. Each residential structure’s municipality was assigned by
performing a spatial join of a polygon shapefile of the Galveston County municipal
boundaries obtained from the GCAD. Structures that did not fall in one of these
boundaries were designated as being in the unincorporated areas of Galveston County.
Figure A.1 is a map depicting the location of these municipal boundaries.

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1. The GCAD provided two dates per parcel: actual year and effective year. The actual year
was the actual date the structure was built, whereas the effective date was the date assigned to
the structure for tax depreciation purposes. Actual dates were preferred, however, they were not
available for all residences. Effective dates were used in such instances.

2. Foundation types were not available for 677 parcels. In this case, the building was assumed to
have the most common foundation type in its subdivision.

3. Residences with 1.5 and 3 stories were reclassified as two story structures for compatibility with
the damage functions.

4. This was the most up-to-date LiDAR dataset available for the Study Area.
A.2 Floodplains, Municipal Regulations and NFIP Adoption Dates

GIS shapefiles of the FEMA special flood hazard areas (SFHAs) and their corresponding BFEs were required so that the data could be easily associated with each of the structures in the dataset. Such data are contained in flood insurance rate maps (FIRMs). Historically, these have been paper maps, which are not easily incorporated into a GIS-based analysis; however, recently, FEMA has moved toward issuing digital flood insurance rate maps (DFIRMs), which are natively in a GIS format. Unfortunately, the only area where a currently-effective DFIRM is available in Galveston County is on Galveston Island, which was obtained online via FEMA’s Map Service Center. For the rest of the county, a preliminary DFIRM was obtained from the Galveston County Floodplain Administrator. The effective and preliminary flood-
plains were combined into one shapefile and their attributes, including the coastal BFEs, were spatially joined to the residential pointfile in ArcMap (Figure 3.3). For riverine SFHAs, BFE transect values were interpolated in ArcMap to estimate the effective BFE at each structure.

The year that each of the municipalities within Galveston County began regulating building construction under the NFIP were obtained from FEMA’s 2015 National Flood Insurance Program Community Status Book and joined to the parcel dataset. Each municipality’s specific freeboard requirements for new or substantially-improved construction in SFHAs were obtained and joined to the dataset as well. Table A.1 shows these data and their sources. In some areas, as much as two feet of additional freeboard was required in SFHAs under these regulations. To simplify the analysis, municipal construction regulations beyond those required under the NFIP (e.g., elevation requirements in the 500-year floodplain) were omitted, as it was unlikely that they would have a large impact on structure elevations relative to regulations in SFHAs.
Table A.1: NFIP regulation start dates and specific municipal elevation requirements for SFHA construction.

<table>
<thead>
<tr>
<th>Municipality Name</th>
<th>NFIP Reg. Year</th>
<th>Zone AE</th>
<th>Zone VE</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayou Vista</td>
<td>1971</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Clear Lake Shores</td>
<td>1970</td>
<td>FFF at BFE + 12&quot;</td>
<td>LHS at BFE + 12&quot;</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Dickinson</td>
<td>1971</td>
<td>FFF at BFE + 18&quot;</td>
<td>N/A</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Friendswood</td>
<td>1972</td>
<td>FFF at BFE + 24&quot;</td>
<td>N/A</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Galveston</td>
<td>1971</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Hitchcock</td>
<td>1970</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Jamaica Beach</td>
<td>1971</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Kemah</td>
<td>1970</td>
<td>FFF at BFE + 18&quot;</td>
<td>LHS at BFE + 18&quot;</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>La Marque</td>
<td>1970</td>
<td>FFF at BFE + 12&quot;</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>League City</td>
<td>1970</td>
<td>FFF at BFE + 18&quot;</td>
<td>LHS at BFE + 18&quot;</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Santa Fe</td>
<td>1971</td>
<td>FFF at BFE + 12&quot;</td>
<td>N/A</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Texas City</td>
<td>1970</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Tiki Island</td>
<td>1983</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Municipal Code</td>
</tr>
<tr>
<td>Unincorporated</td>
<td>1971</td>
<td>FFF at BFE</td>
<td>LHS at BFE</td>
<td>Flood Plain Management Regulations of Galveston County, Texas (2002)</td>
</tr>
</tbody>
</table>
B.1 ADCIRC+SWAN Computed Maximum Still Water Elevations

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 1A.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 1B.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 1C.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 1D.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 2A.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 2B.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 2C.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 2D.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 3A.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 3B.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 3C.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 3D.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 4A.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 4B.

ADCIRC+SWAN computed maximum $E_{STW}$ for storm 4C.
ADCIRC+SWAN computed maximum $E_{STW}$ for storm 4D.
B.2 ADCIRC+SWAN Computed Maximum Significant Wave Heights

ADCIRC+SWAN computed maximum $H_s$ for storm 1A.
ADCIRC+SWAN computed maximum $H_s$ for storm 1B.

ADCIRC+SWAN computed maximum $H_s$ for storm 1C.
ADCIRC+SWAN computed maximum $H_s$ for storm 1D.

ADCIRC+SWAN computed maximum $H_s$ for storm 2A.
ADCIRC+SWAN computed $H_s$ for storm 2B.

ADCIRC+SWAN computed maximum $H_s$ for storm 2C.
ADCIRC+SWAN computed maximum $H_s$ for storm 2D.

ADCIRC+SWAN computed maximum $H_s$ for storm 3A.
ADCIRC+SWAN computed maximum $H_s$ for storm 3B.

ADCIRC+SWAN computed maximum $H_s$ for storm 3C.
ADCIRC+SWAN computed maximum $H_s$ for storm 3D.

ADCIRC+SWAN computed maximum $H_s$ for storm 4A.
ADCIRC+SWAN computed maximum $H_s$ for storm 4B.

ADCIRC+SWAN computed maximum $H_s$ for storm 4C.
ADCIRC+SWAN computed maximum $H_s$ for storm 4D.
B.3 ADCIRC+SWAN Computed Maximum Water Velocities

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 1A.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 1B.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 1C.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 1D.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 2A.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 2B.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 2C.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 2D.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 3A.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 3B.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 3C.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 3D.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 4A.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 4B.

ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 4C.
ADCIRC+SWAN computed maximum $V_{H2O}$ for storm 4D.
Appendix C

C.1 Tabulated BDM Results

BDM estimated total monetary damage under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>$103 M</td>
<td>$54 M</td>
<td>$22 M</td>
<td>$135 M</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>$362 M</td>
<td>$429 M</td>
<td>$185 M</td>
<td>$607 M</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>$130 M</td>
<td>$141 M</td>
<td>$29 M</td>
<td>$243 M</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>$28 M</td>
<td>$8 M</td>
<td>$1 M</td>
<td>$35 M</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>$131 M</td>
<td>$79 M</td>
<td>$30 M</td>
<td>$180 M</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>$340 M</td>
<td>$232 M</td>
<td>$86 M</td>
<td>$487 M</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>$448 M</td>
<td>$678 M</td>
<td>$186 M</td>
<td>$940 M</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>$187 M</td>
<td>$123 M</td>
<td>$29 M</td>
<td>$282 M</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>$434 M</td>
<td>$210 M</td>
<td>$107 M</td>
<td>$537 M</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>$822 M</td>
<td>$730 M</td>
<td>$358 M</td>
<td>$1,193 M</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>$2,327 M</td>
<td>$2,847 M</td>
<td>$1,990 M</td>
<td>$3,184 M</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>$1,755 M</td>
<td>$2,295 M</td>
<td>$1,341 M</td>
<td>$2,710 M</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>$1,224 M</td>
<td>$1,073 M</td>
<td>$734 M</td>
<td>$1,562 M</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>$2,526 M</td>
<td>$2,888 M</td>
<td>$2,271 M</td>
<td>$3,143 M</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>$4,934 M</td>
<td>$5,070 M</td>
<td>$4,881 M</td>
<td>$5,123 M</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>$3,757 M</td>
<td>$3,942 M</td>
<td>$3,431 M</td>
<td>$4,269 M</td>
</tr>
</tbody>
</table>
BDM estimated total number of affected homes under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>H</th>
<th>D</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>2,203</td>
<td>1,118</td>
<td>600</td>
<td>2,721</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>5,052</td>
<td>5,145</td>
<td>3,289</td>
<td>6,908</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>1,953</td>
<td>1,856</td>
<td>660</td>
<td>3,149</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>555</td>
<td>115</td>
<td>40</td>
<td>630</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>2,663</td>
<td>1,531</td>
<td>758</td>
<td>3,436</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>6,498</td>
<td>3,758</td>
<td>1,936</td>
<td>8,320</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>7,765</td>
<td>9,487</td>
<td>4,008</td>
<td>13,244</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>2,894</td>
<td>1,650</td>
<td>638</td>
<td>3,906</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>8,217</td>
<td>3,589</td>
<td>2,276</td>
<td>9,530</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>11,887</td>
<td>9,365</td>
<td>6,640</td>
<td>14,612</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>20,290</td>
<td>21,644</td>
<td>19,475</td>
<td>22,459</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>18,508</td>
<td>17,906</td>
<td>14,440</td>
<td>21,974</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>15,128</td>
<td>12,969</td>
<td>11,474</td>
<td>16,623</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>19,644</td>
<td>22,472</td>
<td>19,221</td>
<td>22,895</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>25,896</td>
<td>25,888</td>
<td>25,888</td>
<td>25,896</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>25,778</td>
<td>25,086</td>
<td>25,018</td>
<td>25,846</td>
</tr>
</tbody>
</table>

Discrepancy in BDM estimates of the total monetary damage and the number of affected homes between the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>Total Damages</th>
<th>No. Affected Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>$112 M</td>
<td>2,121</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>$421 M</td>
<td>3,619</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>$214 M</td>
<td>2,489</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>$34 M</td>
<td>590</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>$150 M</td>
<td>2,678</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>$401 M</td>
<td>6,384</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>$754 M</td>
<td>9,236</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>$253 M</td>
<td>3,268</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>$430 M</td>
<td>7,254</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>$835 M</td>
<td>7,972</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>$1,194 M</td>
<td>2,984</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>$1,369 M</td>
<td>7,534</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>$828 M</td>
<td>5,149</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>$872 M</td>
<td>3,674</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>$242 M</td>
<td>8</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>$838 M</td>
<td>828</td>
</tr>
</tbody>
</table>
C.2 Affected Structure Threshold Sensitivity Analysis Results

BDM sensitivity to affected home threshold. Results are for the four storms at landfall location C under the max(H,D) assumption.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>1%</th>
<th>2%</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1C</td>
<td>946</td>
<td>849</td>
<td>736</td>
<td>660</td>
<td>580</td>
<td>491</td>
</tr>
<tr>
<td>2C</td>
<td>6,103</td>
<td>5,407</td>
<td>4,643</td>
<td>4,008</td>
<td>3,241</td>
<td>2,462</td>
</tr>
<tr>
<td>3C</td>
<td>20,749</td>
<td>20,238</td>
<td>19,817</td>
<td>19,475</td>
<td>18,844</td>
<td>17,896</td>
</tr>
<tr>
<td>4C</td>
<td>25,890</td>
<td>25,888</td>
<td>25,888</td>
<td>25,888</td>
<td>25,888</td>
<td>25,887</td>
</tr>
</tbody>
</table>

BDM sensitivity to affected home threshold. Results are for storm 2C under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm 2C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation Assumption</td>
</tr>
<tr>
<td>1%</td>
</tr>
<tr>
<td>2C, H</td>
</tr>
<tr>
<td>2C, D</td>
</tr>
<tr>
<td>min(H,D)</td>
</tr>
<tr>
<td>max(H,D)</td>
</tr>
</tbody>
</table>

BDM sensitivity to affected home threshold. Results are for storm 3C under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm 3C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation Assumption</td>
</tr>
<tr>
<td>1%</td>
</tr>
<tr>
<td>H</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>min(H,D)</td>
</tr>
<tr>
<td>max(H,D)</td>
</tr>
</tbody>
</table>
C.3 Tabulated BDM+SC Results: Total Monetary Damage

BDM+SC estimated mean total monetary damage under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>$111 M</td>
<td>$57 M</td>
<td>$24 M</td>
<td>$140 M</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>$396 M</td>
<td>$507 M</td>
<td>$201 M</td>
<td>$691 M</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>$153 M</td>
<td>$206 M</td>
<td>$42 M</td>
<td>$313 M</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>$30 M</td>
<td>$8 M</td>
<td>$1 M</td>
<td>$36 M</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>$142 M</td>
<td>$83 M</td>
<td>$32 M</td>
<td>$188 M</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>$371 M</td>
<td>$255 M</td>
<td>$94 M</td>
<td>$520 M</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>$501 M</td>
<td>$800 M</td>
<td>$215 M</td>
<td>$1,070 M</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>$206 M</td>
<td>$133 M</td>
<td>$33 M</td>
<td>$300 M</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>$470 M</td>
<td>$226 M</td>
<td>$116 M</td>
<td>$566 M</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>$902 M</td>
<td>$863 M</td>
<td>$391 M</td>
<td>$1,344 M</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>$3,219 M</td>
<td>$4,019 M</td>
<td>$2,467 M</td>
<td>$4,337 M</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>$2,330 M</td>
<td>$3,239 M</td>
<td>$1,598 M</td>
<td>$3,651 M</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>$1,358 M</td>
<td>$1,271 M</td>
<td>$799 M</td>
<td>$1,778 M</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>$3,292 M</td>
<td>$3,791 M</td>
<td>$2,990 M</td>
<td>$4,002 M</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>$6,921 M</td>
<td>$6,922 M</td>
<td>$6,920 M</td>
<td>$6,922 M</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>$5,577 M</td>
<td>$5,628 M</td>
<td>$5,005 M</td>
<td>$5,935 M</td>
</tr>
</tbody>
</table>
Change in the estimated total monetary damage between the BDM and BDM+SC under the different initial elevation assumptions (BDM+SC minus BDM).

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>$8 M</td>
<td>$3 M</td>
<td>$2 M</td>
<td>$6 M</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>$33 M</td>
<td>$77 M</td>
<td>$16 M</td>
<td>$84 M</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>$23 M</td>
<td>$65 M</td>
<td>$13 M</td>
<td>$70 M</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>$2 M</td>
<td>$0 M</td>
<td>$0 M</td>
<td>$1 M</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>$11 M</td>
<td>$4 M</td>
<td>$2 M</td>
<td>$8 M</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>$31 M</td>
<td>$22 M</td>
<td>$8 M</td>
<td>$33 M</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>$53 M</td>
<td>$121 M</td>
<td>$29 M</td>
<td>$130 M</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>$19 M</td>
<td>$10 M</td>
<td>$5 M</td>
<td>$18 M</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>$36 M</td>
<td>$17 M</td>
<td>$9 M</td>
<td>$29 M</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>$80 M</td>
<td>$133 M</td>
<td>$33 M</td>
<td>$150 M</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>$892 M</td>
<td>$1,172 M</td>
<td>$477 M</td>
<td>$1,153 M</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>$575 M</td>
<td>$944 M</td>
<td>$257 M</td>
<td>$941 M</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>$134 M</td>
<td>$198 M</td>
<td>$65 M</td>
<td>$215 M</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>$767 M</td>
<td>$903 M</td>
<td>$720 M</td>
<td>$859 M</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>$1,987 M</td>
<td>$1,852 M</td>
<td>$2,039 M</td>
<td>$1,799 M</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>$1,820 M</td>
<td>$1,686 M</td>
<td>$1,575 M</td>
<td>$1,666 M</td>
</tr>
</tbody>
</table>

Percentage change in the estimated total monetary damage between the BDM and BDM+SC under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>8%</td>
<td>6%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>9%</td>
<td>18%</td>
<td>8%</td>
<td>14%</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>18%</td>
<td>46%</td>
<td>46%</td>
<td>29%</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>7%</td>
<td>4%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>8%</td>
<td>5%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>9%</td>
<td>10%</td>
<td>9%</td>
<td>7%</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>12%</td>
<td>18%</td>
<td>16%</td>
<td>14%</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>10%</td>
<td>8%</td>
<td>16%</td>
<td>6%</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>8%</td>
<td>8%</td>
<td>9%</td>
<td>5%</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>10%</td>
<td>18%</td>
<td>9%</td>
<td>13%</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>38%</td>
<td>41%</td>
<td>24%</td>
<td>36%</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>33%</td>
<td>41%</td>
<td>19%</td>
<td>35%</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>11%</td>
<td>18%</td>
<td>9%</td>
<td>14%</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>30%</td>
<td>31%</td>
<td>32%</td>
<td>27%</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>40%</td>
<td>37%</td>
<td>42%</td>
<td>35%</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>48%</td>
<td>43%</td>
<td>46%</td>
<td>39%</td>
</tr>
</tbody>
</table>
Discrepancy in estimates of the total monetary damage between the different initial elevation assumptions for the BDM and the BDM+SC.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>BDM</th>
<th>BDM+SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>$112 M</td>
<td>$116 M</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>$421 M</td>
<td>$490 M</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>$214 M</td>
<td>$271 M</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>$34 M</td>
<td>$35 M</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>$150 M</td>
<td>$156 M</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>$401 M</td>
<td>$426 M</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>$754 M</td>
<td>$855 M</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>$253 M</td>
<td>$266 M</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>$430 M</td>
<td>$450 M</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>$835 M</td>
<td>$952 M</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>$1,194 M</td>
<td>$1,870 M</td>
</tr>
<tr>
<td>Storm 3D</td>
<td>$1,369 M</td>
<td>$2,053 M</td>
</tr>
<tr>
<td>Storm 4A</td>
<td>$828 M</td>
<td>$978 M</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>$872 M</td>
<td>$1,012 M</td>
</tr>
<tr>
<td>Storm 4C</td>
<td>$242 M</td>
<td>$2 M</td>
</tr>
<tr>
<td>Storm 4D</td>
<td>$838 M</td>
<td>$929 M</td>
</tr>
</tbody>
</table>
C.4 Tabulated BDM+SC Results: Number of Affected Homes

BDM estimated mean total number of affected homes under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>2,207</td>
<td>1,122</td>
<td>603</td>
<td>2,723</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>5,059</td>
<td>5,158</td>
<td>3,297</td>
<td>6,913</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>1,959</td>
<td>1,903</td>
<td>674</td>
<td>3,183</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>556</td>
<td>115</td>
<td>40</td>
<td>630</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>2,668</td>
<td>1,536</td>
<td>762</td>
<td>3,438</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>6,508</td>
<td>3,772</td>
<td>1,946</td>
<td>8,325</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>7,785</td>
<td>9,545</td>
<td>4,026</td>
<td>13,286</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>2,895</td>
<td>1,664</td>
<td>646</td>
<td>3,912</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>8,226</td>
<td>3,603</td>
<td>2,288</td>
<td>9,534</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>11,898</td>
<td>9,401</td>
<td>6,664</td>
<td>14,625</td>
</tr>
<tr>
<td>Storm 3C</td>
<td>20,381</td>
<td>21,655</td>
<td>19,491</td>
<td>22,460</td>
</tr>
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<td>16,628</td>
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<td>19,228</td>
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Change in the estimated total number of affected homes between the BDM and BDM+SC under the different initial elevation assumptions (BDM+SC minus BDM).

<table>
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<th>Storm ID</th>
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<th>min(H,D)</th>
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<tr>
<td>Storm 1A</td>
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<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>7</td>
<td>13</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>6</td>
<td>47</td>
<td>14</td>
<td>34</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Storm 2A</td>
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<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Storm 2B</td>
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<td>5</td>
</tr>
<tr>
<td>Storm 2C</td>
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<td>58</td>
<td>18</td>
<td>42</td>
</tr>
<tr>
<td>Storm 2D</td>
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<td>6</td>
</tr>
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<td>14</td>
<td>12</td>
<td>4</td>
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<td>Storm 3B</td>
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<td>13</td>
</tr>
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<td>Storm 3C</td>
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<td>16</td>
<td>1</td>
</tr>
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<td>Storm 3D</td>
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<td>25</td>
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<td>22</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>Storm 4B</td>
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<td>17</td>
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<td>11</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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Discrepancy in estimates of the total number of affected homes between the different initial elevation assumptions for the BDM and the BDM+SC.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>BDM</th>
<th>BDM+SC</th>
</tr>
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<tr>
<td>Storm 1A</td>
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<td>2,120</td>
</tr>
<tr>
<td>Storm 1B</td>
<td>3,619</td>
<td>3,616</td>
</tr>
<tr>
<td>Storm 1C</td>
<td>2,489</td>
<td>2,510</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>590</td>
<td>590</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>2,678</td>
<td>2,676</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>6,384</td>
<td>6,379</td>
</tr>
<tr>
<td>Storm 2C</td>
<td>9,236</td>
<td>9,260</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>3,268</td>
<td>3,266</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>7,254</td>
<td>7,245</td>
</tr>
<tr>
<td>Storm 3B</td>
<td>7,972</td>
<td>7,961</td>
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<tr>
<td>Storm 3C</td>
<td>2,984</td>
<td>2,969</td>
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<tr>
<td>Storm 3D</td>
<td>7,534</td>
<td>7,513</td>
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<td>Storm 4A</td>
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<td>5,136</td>
</tr>
<tr>
<td>Storm 4B</td>
<td>3,674</td>
<td>3,678</td>
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<td>Storm 4C</td>
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</tr>
<tr>
<td>Storm 4D</td>
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</table>
D.1 Tabulated BDM+SC+EC Results: Total Monetary Damage

BDM+SC+EC estimated mean total monetary damage under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>$16 M</td>
<td>$41 M</td>
<td>$28 M</td>
<td>$23 M</td>
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<tr>
<td>Storm 1B</td>
<td>$142 M</td>
<td>$231 M</td>
<td>$195 M</td>
<td>$174 M</td>
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<tr>
<td>Storm 1C</td>
<td>$39 M</td>
<td>$73 M</td>
<td>$43 M</td>
<td>$62 M</td>
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<tr>
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<td>$0 M</td>
<td>$3 M</td>
<td>$1 M</td>
<td>$2 M</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>$20 M</td>
<td>$57 M</td>
<td>$40 M</td>
<td>$29 M</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>$73 M</td>
<td>$152 M</td>
<td>$112 M</td>
<td>$101 M</td>
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<td>Storm 2C</td>
<td>$211 M</td>
<td>$387 M</td>
<td>$257 M</td>
<td>$309 M</td>
</tr>
<tr>
<td>Storm 2D</td>
<td>$26 M</td>
<td>$81 M</td>
<td>$28 M</td>
<td>$67 M</td>
</tr>
<tr>
<td>Storm 3A</td>
<td>$95 M</td>
<td>$165 M</td>
<td>$137 M</td>
<td>$111 M</td>
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<td>Storm 3B</td>
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<td>$385 M</td>
<td>$373 M</td>
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<td>Storm 3C</td>
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<td>$1,854 M</td>
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<tr>
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<td>$773 M</td>
<td>$719 M</td>
<td>$668 M</td>
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<tr>
<td>Storm 4B</td>
<td>$2,984 M</td>
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<td>$3,015 M</td>
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<tr>
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<td>$6,919 M</td>
<td>$6,921 M</td>
<td>$6,920 M</td>
</tr>
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<td>$4,935 M</td>
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Change in the estimated total monetary damage between the BDM+SC and BDM+SC+EC under the different initial elevation assumptions (BDM+SC+EC minus BDM+SC).

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
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<td>Storm 1A</td>
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<td>-$276 M</td>
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<td>-$517 M</td>
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<td>-$133 M</td>
<td>$1 M</td>
<td>-$251 M</td>
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<tr>
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<td>-$159 M</td>
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<tr>
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<td>-$103 M</td>
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<td>-$419 M</td>
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<tr>
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<td>-$413 M</td>
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<td>-$761 M</td>
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<td>-$970 M</td>
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<td>-$2 M</td>
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<tr>
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Percentage change in the estimated total monetary damage between the BDM+SC and BDM+SC+SC under the different initial elevation assumptions.

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<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
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<td>Storm 1A</td>
<td>-86%</td>
<td>-28%</td>
<td>18%</td>
<td>-84%</td>
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<tr>
<td>Storm 1B</td>
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<td>-54%</td>
<td>-3%</td>
<td>-75%</td>
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<tr>
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<td>-64%</td>
<td>2%</td>
<td>-80%</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>-99%</td>
<td>-67%</td>
<td>-47%</td>
<td>-96%</td>
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<tr>
<td>Storm 2A</td>
<td>-86%</td>
<td>-31%</td>
<td>25%</td>
<td>-84%</td>
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<tr>
<td>Storm 2B</td>
<td>-80%</td>
<td>-40%</td>
<td>20%</td>
<td>-81%</td>
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<tr>
<td>Storm 2C</td>
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<td>-52%</td>
<td>20%</td>
<td>-71%</td>
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<tr>
<td>Storm 2D</td>
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<td>-39%</td>
<td>-15%</td>
<td>-78%</td>
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<tr>
<td>Storm 3A</td>
<td>-80%</td>
<td>-27%</td>
<td>18%</td>
<td>-80%</td>
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<tr>
<td>Storm 3B</td>
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<td>-39%</td>
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<tr>
<td>Storm 4A</td>
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<td>-39%</td>
<td>-10%</td>
<td>-62%</td>
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<tr>
<td>Storm 4B</td>
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<td>-19%</td>
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<td>-25%</td>
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<td>0%</td>
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Discrepancy in estimates of the total monetary damage between the different initial elevation assumptions for the BDM, the BDM+SC and the BDM+SC+EC.

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<th>Storm ID</th>
<th>BDM</th>
<th>BDM+SC</th>
<th>BDM+SC+EC</th>
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</thead>
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<td>$112 M</td>
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<tr>
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<td>$31 M</td>
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<td>Storm 1D</td>
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<td>$35 M</td>
<td>$2 M</td>
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<td>Storm 2C</td>
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<td>$855 M</td>
<td>$130 M</td>
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<td>Storm 2D</td>
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<td>$266 M</td>
<td>$53 M</td>
</tr>
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<td>$450 M</td>
<td>$54 M</td>
</tr>
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<td>Storm 3B</td>
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<td>$82 M</td>
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<td>$71 M</td>
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<td>$140 M</td>
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<td>Storm 4A</td>
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<td>$105 M</td>
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<tr>
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<td>$1 M</td>
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<td>Storm 4D</td>
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<td>$42 M</td>
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D.2 Tabulated BDM+SC+EC Results: Number of Affected Homes

BDM+SC+EC estimated mean number of affected homes under the different initial elevation assumptions.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>413</td>
<td>857</td>
<td>672</td>
<td>535</td>
</tr>
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<td>Storm 1B</td>
<td>2,450</td>
<td>3,212</td>
<td>2,973</td>
<td>2,723</td>
</tr>
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<td>Storm 1C</td>
<td>587</td>
<td>993</td>
<td>668</td>
<td>816</td>
</tr>
<tr>
<td>Storm 1D</td>
<td>10</td>
<td>42</td>
<td>17</td>
<td>24</td>
</tr>
<tr>
<td>Storm 2A</td>
<td>488</td>
<td>1,147</td>
<td>906</td>
<td>650</td>
</tr>
<tr>
<td>Storm 2B</td>
<td>1,599</td>
<td>2,736</td>
<td>2,249</td>
<td>1,952</td>
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<td>4,899</td>
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<td>2,272</td>
</tr>
<tr>
<td>Storm 3B</td>
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<td>6,869</td>
<td>6,312</td>
<td>6,344</td>
</tr>
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<td>18,823</td>
<td>18,629</td>
<td>18,797</td>
<td>18,759</td>
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<td>Storm 3D</td>
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<td>Storm 4B</td>
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<td>25,893</td>
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<td>25,896</td>
</tr>
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<td>Storm 4D</td>
<td>23,903</td>
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<td>23,771</td>
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</table>
Change in the estimated number of affected homes between the BDM+SC and BDM+SC+EC under the different initial elevation assumptions (BDM+SC+EC minus BDM+SC).

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>D</th>
<th>H</th>
<th>max(H,D)</th>
<th>min(H,D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm 1A</td>
<td>-1,794</td>
<td>-265</td>
<td>69</td>
<td>-2,188</td>
</tr>
<tr>
<td>Storm 1B</td>
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</tr>
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<td>Storm 1C</td>
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<td>-2,367</td>
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<td>-4,910</td>
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<td>303</td>
<td>-6,374</td>
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<td>Storm 2C</td>
<td>-3,869</td>
<td>-3,565</td>
<td>580</td>
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<tr>
<td>Storm 2D</td>
<td>-2,257</td>
<td>-345</td>
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<td>-2,772</td>
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<tr>
<td>Storm 3A</td>
<td>-6,127</td>
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<tr>
<td>Storm 3B</td>
<td>-6,131</td>
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<td>Storm 3C</td>
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<tr>
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Discrepancy in estimates of the number of affected homes between the different initial elevation assumptions for the BDM, the BDM+SC and the BDM+SC+EC.

<table>
<thead>
<tr>
<th>Storm ID</th>
<th>BDM</th>
<th>BDM+SC</th>
<th>BDM+SC+EC</th>
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</thead>
<tbody>
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<td>Storm 1A</td>
<td>2,121</td>
<td>2,120</td>
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<td>Storm 1B</td>
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<td>Storm 1C</td>
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<td>Storm 1D</td>
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<tr>
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<tr>
<td>Storm 2B</td>
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<td>6,379</td>
<td>784</td>
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<tr>
<td>Storm 2C</td>
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<td>9,260</td>
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<td>Storm 3B</td>
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<td>Storm 3C</td>
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<td>2,969</td>
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<td>Storm 3D</td>
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<td>7,513</td>
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<tr>
<td>Storm 4A</td>
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<td>Storm 4B</td>
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<td>Storm 4D</td>
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## E.1 Additional GSA Results

Results of the GSA for the number of affected homes. N/A values for the $S_i$ indices under the fully independent scenarios are because of lack of convergence in the estimators.

### E.1.1 Storm 3A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$S_i$</th>
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<th>$S_{T_i}$</th>
</tr>
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<tbody>
<tr>
<td>Structural Depth-Damage Curves</td>
<td>N/A</td>
<td>0.35</td>
<td>0.94</td>
<td>0.97</td>
<td>0.15</td>
<td>0.19</td>
</tr>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CSVR</td>
<td>N/A</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Structural Collapse</td>
<td>N/A</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Structure Elevation</td>
<td>N/A</td>
<td>0.88</td>
<td>0.03</td>
<td>0.05</td>
<td>0.78</td>
<td>0.83</td>
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<tr>
<td>Sum</td>
<td>N/A</td>
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<td>0.98</td>
<td>1.02</td>
<td>0.94</td>
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### E.1.2 Storm 3B

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<tbody>
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<td>0.97</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CSVR</td>
<td>N/A</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Structural Collapse</td>
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<td>0.01</td>
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<td>0.03</td>
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### E.1.3 Storm 3C

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<th>$S_{T_i}$</th>
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</thead>
<tbody>
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<td>CSVR</td>
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### E.1.4 Storm 3D

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<td>0.00</td>
</tr>
<tr>
<td>CSVR</td>
<td>N/A</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Structural Collapse</td>
<td>N/A</td>
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