FILL AND FLOODS: ANALYSIS OF THE IMPACT OF PARCEL FILL ON RESIDENTIAL FLOOD DAMAGES

A Dissertation

by

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ABSTRACT

As property losses from flooding continue to rise in coastal communities, the need to examine the changing dynamics of these damages in relation to specialized mitigation methods at multiple scales becomes increasingly necessary. An example of such mitigation method at the parcel level is ‘Fill’, which allows development to occur in floodplains by raising parcels of land above base flood elevation using dirt/sand. This flood avoidance technique is often associated with low-density development in flood-prone suburban communities. However, with repetitive flood damages recorded in recent times, it is uncertain whether structures on fill still incur flood damages, or whether these fill parcels have potential adverse impacts on unprotected adjacent parcels. This research addresses the lack of comprehensive knowledge on the impact of fill by posing the following questions: 1) is filling a parcel effective in mitigating flood damages? 2) Does filling a parcel adversely impact flood damages of adjacent unprotected parcels? These questions are answered using a two-step analysis of propensity score matching and a spatial autoregressive model. First, propensity score estimation identified parcels that have the probability of receiving the ‘treatment’ of fill using machine learning methods with increased predictive accuracy compared to other traditional parametric measures. These ‘treatment’ parcels are then matched with fill parcels using appropriate treatment effects and matching calipers, creating a pooled sample of both fill and non-fill parcels in the study area.

A post-match analysis of 6,059 filled and non-fill parcels shows a 7% difference in flood damages between fill and non-fill parcels between years 2000 to 2014 in the Clear Creek watershed. A second order analysis of flood damage clusters using a bi-variate Ripley's K point pattern analysis indicates significant clusters of flood damages relative to fill parcel locations. These results highlight the importance of examining parcel-level flood mitigation methods that have cross-jurisdictional economic and planning implications, and the cumulative effect on flood damages at both the community and regional watershed scale. This research also provides insight into the need for synergistic flood risk reduction and incentives to compensate for the use of fill in floodplain development and planning.

DEDICATION

This dissertation is dedicated to my son, Tade Folarin ATOBA.

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I am grateful to my committee chair Sam Brody for his continual support of this dissertation and my graduate career over the past 4 years. You have been a great advisor and a wonderful person. I remember my first meeting with you right after admission into Texas A&M where you immediately put me to work. Your encouraging words and commendation are vital to the successful completion of my doctoral degree. I am also grateful to Wes Highfield for his help with my dissertation and my career as a researcher at the Center for Texas Beaches and Shores over the past 4 years. Thanks for all your help and the methodological expertise on this dissertation.

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I also owe my wife, Bisi a big gratitude for “tolerating” me throughout my time as a graduate student, and to my son Tade. I love you both.

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1. INTRODUCTION

1.1 Background

Flood damages continue to rise in urban areas around the United States (U.S.) despite flood infrastructure. A major factor responsible for this problem is increasing population and the pressure to develop in vulnerable areas like the floodplain (Brody et al. 2007b; Mileti 1999; Highfield & Brody 2006). This is felt partly because flood mitigation techniques enable development to occur in these vulnerable areas with excessive dependence on the protection they offer (Mileti 1999; Godschalk 2003; Birkland et al. 2003; Burby et al. 2000). This heavy reliance on structural mitigation measures and flood infrastructure is the typical response to flood reduction in the U.S. (Birkland et al. 2003). For example, recent research shows that even new urbanist development in floodplains often depend more on structural mitigation strategies than do conventional developments (Berke, Song & Stevens 2009). Allowing development to occur in vulnerable locations increases exposure to flood hazards and could likely increase flood damages.

Fill is one of such mitigation strategies that allow development in floodplains. Filling a parcel involves altering the naturally occurring landscape by increasing its elevation with dirt or sand, thereby reducing the likelihood of flood damage (FEMA 2001; FEMA 2013). This is common in low-lying areas that require additional dredge or fill material to make them suitable for development. As far back as the 1980s, about 50% of homeowners or developers either fill or elevate their structures when in the floodplain

(Bollens, Kaiser & Burby 1988). In recent times, fill elevation certificates continue to be granted in floodplains around the US. In the Houston metropolitan area alone, over 7,000 fill elevation certificates have been approved between 2000 and 2014 (Brody & Atoba 2018). That trend has since increased and is even more invasive in recent times in urban areas where the pressure to develop floodplains is common. It is important to examine how this built environment variable contributes to flood damages.

Apart from other serious ecological implications, allowing floodplain development through fill can lead to increased flooding both within floodplains and areas adjacent them (FEMA 2001), causing severe injury or death, loss to property and infrastructure, as well as direct and indirect economic impacts. For example, in Harris County, TX about half of insured flood claims occur outside the 100-year floodplain (Highfield, Brody & Blessing 2014), while other studies also show that the 100-year floodplain is an ineffective standard for flood risk exposure in the US (Highfield, Norman & Brody 2013; Blessing, Sebastian & Brody 2017). These statistics show it is important to identify the role that fill plays in contributing to flooding in urban areas.

Flood mitigation measures are expected to provide positive results by protecting either individual structures or an entire community. For example, between 1928 and 2000, the US Army Corps of Engineers (USACE) flood infrastructure prevented about $709 billion in flood losses (Birkland et al. 2003). Although structural mitigation measures like create opportunities for additional development in vulnerable locations, they may also cause adverse impacts on other areas.

While addressing flooding in urban areas, research has shown that stream channelization leads to increased flooding in adjacent wetlands, reducing downstream storage capacity, and increasing flow velocity (DeLaney 1995; Kreibich et al. 2009; Larson & Plasencia 2001), making downstream developments more vulnerable to flooding. Other researchers have also noted that levees can increase downstream water velocity, while stream hardening may increase downstream flooding (Birkland et al. 2003). Although several studies have been conducted on the impact of selected structural mitigation measures like those mentioned earlier, there is a paucity of scholarly research on the adverse impact of fill on surrounding developments despite the acknowledgment that such impact is possible.

Despite the extensive research on the impact of the built environment on flood damages, the effects of specific mitigation activities on flood damages remain vague. Previous research shows that non-structural mitigation measures like the Community Rating System (CRS) reduce flood damages (Highfield et al. 2014; Brody et al. 2008b), while wetland alteration permits increase flood damages in watersheds (Brody et al. 2007a). Also, the use of a suite of non-structural approaches embedded in the CRS has been shown to reduce flood damages (Highfield & Brody 2012; Highfield et al. 2014). Although previous studies assess the effectiveness of the CRS in reducing flood damages, the actual effect of specific landscape alteration methods such as fill has not been addressed in flood mitigation literature. In summary, there has been no empirical study on the effects of fill in mitigating flood damages.

1.2 Research Purpose and Objectives

The overall goal of this research is to assess the effectiveness of parcel fill in mitigating flood damages, and the subsequent effect of fill on adjacent non-fill parcels. This dissertation will answer the questions: 1) *Will filled parcels significantly have reduced flood damage? 2) Are there adverse impacts to neighboring parcels that have not been filled*?

The specific research objectives are to:

1. Identify filled properties through FEMA elevation certificates and quantify the spatial-temporal patterns of fill through exploratory space-time analysis;
2. Examine flood damage clusters relative to fill locations.
3. Quantify the difference between flood damages to fill and unfilled parcels through a spatial autoregressive model.
4. Identify the policy implications of parcel fill at a watershed scale and recommendations for long-term regional planning across multiple watersheds

1.3 Justification of the Study

First, there is a rapid population increase in areas prone to coastal flooding, leading to a rise in the pressure to build in flood zones. For example, between 1996 and 2007, insured residential losses in the US alone was about $2.77 billion per year, most of which occurred around counties along the Gulf of Mexico (Brody et al. 2011). There is no sign that economic losses from flooding will decrease considering the increase in development and the general disregard for incorporating adequate planning tools to prevent development in these vulnerable areas.

Second, parcel-level mitigation strategies and its effect on adjoining properties have economic implications that are not borne by homeowners alone, but the community as a whole. In fact, by the year 2013, from covering flood insurance payments, the NFIP is already in a debt of about $24 billion from the federal treasury (Kousky & Kunreuther 2014). Flood loss is spiraling throughout the US because of activities that are carried out at the parcel level and become cumulative over time in increasing flood damages. A previous parcel-level mitigation study found that decisions made at the parcel level can have a significant cumulative economic effect on coastal communities (Highfield et al. 2014). An improved understanding of how fill reduce or increase flooding will provide important recommendations for economic flood resiliency.

Third, this research is being conducted at a time when there are repetitive flood loss and places that never experienced flooding now does. There is a growing interest in understanding the role that changing socio-ecological conditions play in cases of flooding. This dissertation provides quantitative measures for assessing the use of fill either independently, or in addition to a suite of other mitigation methods. It addresses the ethical issue of whether filling a parcel can increase flood risks to other parcels. Techniques used by engineers to examine whether there are adverse effects from fill are ineffective because it is carried out on individual building project basis (Larson & Plasencia 2001). This dissertation examines the combined effect of parcel fill on flood damages for an entire watershed.

Fourth, research on fill is almost non-existent in the hazards literature. Hundreds of fill permits are granted each year in many jurisdictions, and no study has attempted to address how a serious landscape alteration process can impact the environment or examine how effective they are in mitigating flood damages. This lack of research occurs at a time when literature has shown that built environment variables significantly affect flooding in vulnerable areas (Brody et al. 2008b). It is important to address how a relatively unexplored built environment variable like fill will contribute to flooding in urban areas.

1.4 Structure of Dissertation

This dissertation consists of seven sections. Section one provides a general background of the topic, presents the research problem, identifies the research objectives, and provides justification for the study. The second section reviews existing literature on fill and other flood mitigation activities in the U.S. It also traces the history of elevating structures, the pros and cons of different elevation methods, and the effectiveness of other flood mitigation strategies. This section compares fill and land reclamation activities and discusses the existing literature on adjacent flood damages.

Section three discusses the framework for this research. It presents a conceptual model to help understand the relationship between parcel fill and residential flood damage. It identifies the primary dependent variable, which is flood damage from historic flood claims as well as the primary independent variable, which is parcel fill. In this section, specific hypotheses are formulated as well as measurable variables for the exploratory data analysis of fill parcels and their characteristics. This section also discusses the various control variables that are used in the regression model.

The fourth section discusses the research methodology for this dissertation. It explains the reason for choosing the study area, how the sample was selected and provides justification for the methodology in achieving the study objectives. The section also discusses the variable constructs, their selection, source, and how they are operationalized. The section discusses the reliability and validity threats facing this research and how they are addressed.

Section five discusses the results of the exploratory data analysis of fill and insured flood claims and identifies the possible adverse impacts of fill on adjacent properties. The section identifies the clusters of fill and discusses their closeness in distance and time, as well as a univariate analysis of fill and flood damage locations.

Section six discusses the results of the spatial autoregressive model and summarizes the result of the hypotheses presented in this dissertation. The primary objective of this research is also addressed in this section where the difference between flood damages for fill and non-fill parcels is quantified. The relationship between flood losses and other independent variables is also addressed in section six. Section seven discusses the results and implications of the exploratory data analysis and the regression model. It further discusses the policy implications of the finding s in this dissertation. The final section summarizes the findings in this research and discusses other important contents such as assumptions, limitations, and areas of improvement for future research.

2. LITERATURE REVIEW

This section is a review of existing literature on areas necessary to help formulate a conceptual framework for the relationship between flood damages and parcel fill. The section identifies the relevant variables used in the final model and the gaps in the literature that are discussed in the final analysis. This section gives a general overview of fill and how it is perceived in relation to other flood mitigation methods. It also discusses how flood mitigation is categorized in the U.S. and where fill fits in this classification. Adjacent flooding and how fill can be combined with other flood mitigation methods are also discussed.

2.1 Background on Fill

Urban sprawl has increased the pressure to develop floodplains and wetlands in many US metropolitan areas (Brody 2013, Brody & Zahran 2008), leading to the need to accommodate floodplain development by ‘vertically’ altering ground elevation in many communities. This act is known as ‘filling’ or the use of dirt/sand to increase ground elevation before building construction (FEMA 2001; Brody & Atoba 2018). When fill is used in wetlands, they are categorized as wetland alteration activities that fall under the Clean Water Act. In this case, a Section 404 permit is usually required when fill or dredge materials are collected from wetlands and used to change its elevation or for turning wetlands into dry lands (Dennison & Berry 1993).

Increasing ground elevation or placing fill in water surfaces for development is not a new phenomenon. Early developers in the U.S. started the conversion of marshes and wetlands to habitable spaces in Boston, while the Chesapeake Bay shoreline was also altered to allow for both commercial and residential development as far back as the 15th century (Vileisis 1999). The conversion of wetlands and marshes in 1641 in Boston and New York grew out of the need to accommodate rising populations in these areas by collecting fill from local hills to elevate wetlands, a trend that also affected Baltimore, Philadelphia and Charleston, and different parts of the US Industrial development (Vileisis 1999). Floodplain and wetland development continue till date and are major causes for urban flooding and its associated adverse impacts.

In many coastal communities, new towns are even built on reclaimed land using fill. New Towns in coastal communities springing from large-scale land reclamation activities and are even becoming much more prominent. Coastal communities with large metropolitan populations face the increasing pressure of housing the urban population and maximizing the amount of land available in these areas, thus taking advantage of dredging technologies to either create reclaimed land by elevating them above sea levels or creating polders to drain areas that exist below sea levels. Clear examples of new towns across the world are those in the Flevoland region of the Netherlands, Palm Islands in Dubai, Kavala in Greece, Eko Atlantic in Nigeria and so on. These areas all have different levels of flood risk and are thus expected to have different levels of adaptive capacity to their respective flood risks, especially with consideration of climate change.

Wetlands were also filled during the post-colonial period which resulted from the construction of transportation facilities like the shoreline railroad and trolley in the 1800s, and the construction of an east-west I-95 road in the 1900s (Rozsa 1995). This was followed by filling sections along the highway for use as parking lots, railroad yards and airports which were further extended for development. Industrial development and the need for environmental health awareness led to the dredging of swamps to provide navigation for boats, while areas not used for boat transportation were filled for development during this period, filling wetlands for mosquito control after the civil war and creation of hand ditches during the great depression (Vileisis 1999; Rozsa 1995). Between the 1600s and the 1990s, almost half of the US wetlands have been converted to other uses, and a loss of 13,800 acres of estuarine and freshwater wetlands per year between 2004 and 2009, with high percentages attributed to urban development (Dahl 2011).

While wetland alteration can occur by filling navigable waters and marshes, filling in floodplains involves using fill or dirt material to elevate parcels of land in the floodplain above slated flood levels. This requires an elevation certificate through FEMA’s Letter of Map Reduction based on Fill (LOMR-F). LOMR-F is granted for properties, a section of properties, or a described area that have been elevated to or above the base flood elevation (BFE) using fill materials to remove the property from the Significant Flood Hazard Area (SFHA) (FEMA 2001; Larsen 2012). This letter is approved based on the application submitted with letters showing new ground elevations by a licensed surveyor. This data also includes parcel information, flood zone, BFE, new elevation, and lowest adjacent elevation. Although LOMR-F is granted at the individual parcel level, many developers often fill entire subdivisions that fall within the floodplain.

2.1.1 Elevation Methods for Flood Mitigation

2.1.1.1 Structure Elevation

Although compacted fill may elevate individual buildings above BFE, this is not common. This elevation technique requires raising just the building above flood levels. In the LOMR-F description of this technique, it categorized ‘what is removed from SFHA’ as ‘Structure’. This implies that only the structure is elevated while the other part of the parcel is below BFE. Additional foundation methods to raise individual structures can be used in addition to fill such as stem wall and crawlspace foundations as shown in figure 2.1 (FEMA 2001). FEMA recommends that even if fill is used, buildings should be placed on crawlspace foundation to allow for additional protection and allow water passage beneath the property when floodwater exceeds the BFE.

In V-Zones where fill is prohibited, individual structures are elevated by using specific foundation types. FEMA policies restrict the use of fill in V-zones and in floodways in floodplains (FEMA 2001). It is not feasible to fill large areas with dirt along V-zones and floodways; therefore, elevating structures with piles and piers is a feasible alternative that can allow development while also providing protection from extreme flood events.

FEMA (2013) describes the characteristics of some of these foundation types. For example, pile foundation uses an open foundation method, with single element piles driven deep into grounds to support buildings and can withstand high-velocity wave events. Pier foundation is another example of open foundation types that are built from masonry units and are smaller than pile foundations. These foundation types are common in coastal areas and areas with frequent inundation from flooding. Other examples of elevating individual structures include using stem wall foundations or crawlspace foundation.

A major advantage of these elevation types is that they are easier to adopt freeboard regulations. Freeboard is the use of additional height requirement to elevate structures above the required elevation (FEMA 2001; FEMA 2013). It is more cost-effective to raise buildings on these foundation types than it is for slabs. An evaluation of building standards by the NFIP showed that there is a large amount of cost saving when applying freeboard to pier and pile foundations than there is to slab foundations, and even more to slab on fill foundations (Jones et al. 2006). In terms of the ecological advantage, elevating individual structures with piles will allow the natural flow of wave action from floodwaters.

Depending on the flood event, it is expected that elevated buildings on pile and pier foundations have some level of protection from frequent flood events. However, during extreme flood events, elevating structures might not be effective in preventing damages from inundation (Pistrika & Jonkman 2010). When flooding also exceeds the expected design level, these foundation types might still be vulnerable to flood loss.

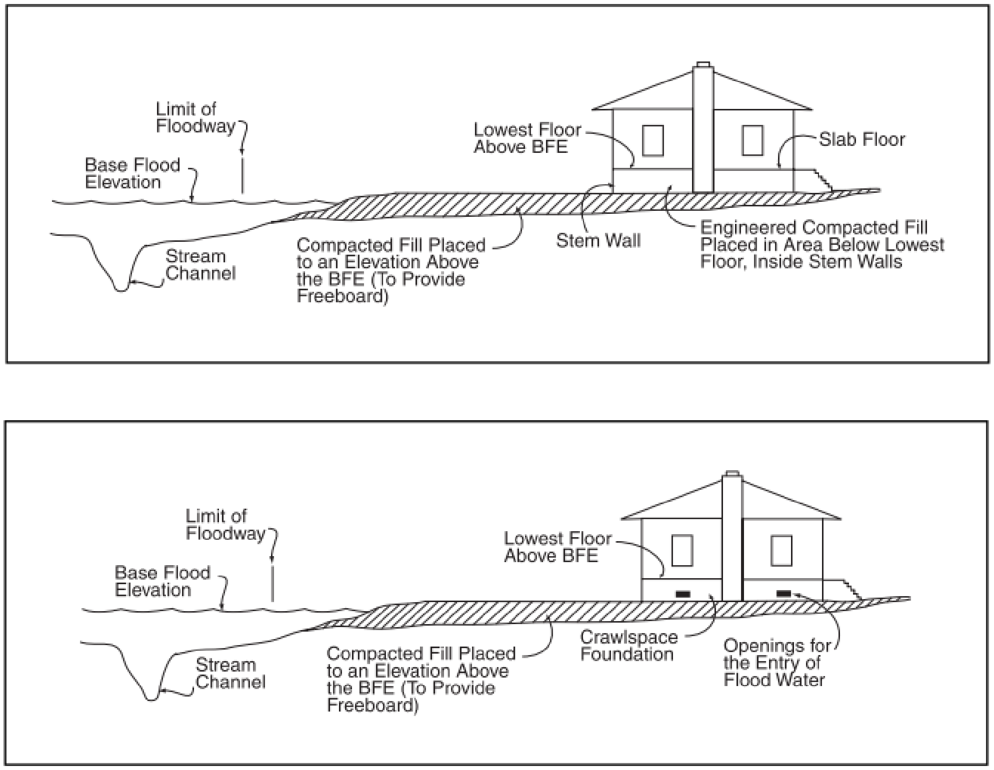


Figure 2.1 Stem Wall and Crawlspace Foundation in Addition to Fill.
Reprinted from FEMA (2001).

2.1.1.2 Property/Parcel Elevation based on Fill

This type of parcel elevation involves elevating portions of, or entire parcel of land to, or, above BFE (FEMA 2001). LOMR-F certificates granted for this designate ‘property’ or ‘portions of property’ as what is removed from the SFHA. This means that when a parcel of land falls within the floodplain before development occurs, the developer fills the entire parcel, or a section of the parcel to enable the first floor of the building is above BFE. As shown in figure 2.2, filled parcels generally use slab on grade rather than other foundation protection techniques.

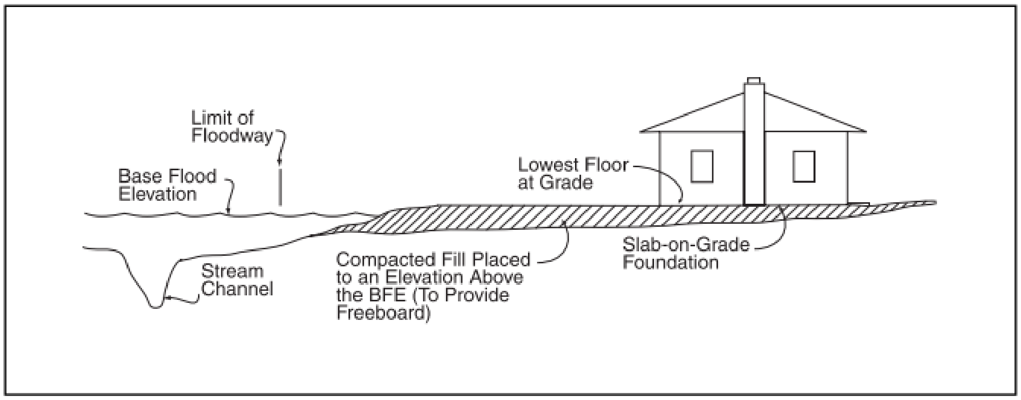


Figure 2.2 Slab on Grade Foundation Based on Fill.
Reprinted from FEMA (2001).

2.1.1.3 Multiple Parcel elevation based on fill

Multiple parcel elevation uses fill techniques on a larger area of land. In the LOMR-F requirements from FEMA, this fill permit grants elevation certificates to multiple contiguous lots within a subdivision. Properties in floodplains are likely to be less attractive to potential homebuyers because of the need to purchase flood insurance under the NFIP program for federally backed mortgages. Since flood insurance is optional for property owners outside the floodplain, it is not surprising that developers fill parcels to raise them above BFE rather than construct buildings on existing ground elevations in large subdivisions. Previous studies have identified the positive effect of Letters of Map Amendment (LOMA) on discounts and property values (Larsen 2012), while other studies show the impact of protected lands on property value (Kousky & Walls 2014).

As highlighted in table 2.1, one benefit of filling entire subdivisions is that it allows for development to occur in jurisdictions with limited land availability while also protecting these developments. However, adverse impacts on adjacent areas should be considered when large subdivisions are filled. Filling entire subdivisions should be done alongside other structural and non-structural mitigation methods; compensatory storage should be provided to accommodate flood waters that will have settled in the areas that have just been filled (FEMA 2013; Larson & Plasencia 2001). Most subdivisions do this by building detention ponds and provision for open space. Table 2.1 shows additional pros and cons of the different fill techniques highlighted above.

Table 2.1 Summary of Elevation Techniques

Elevation Technique	**Pros**	**Cons**
Structure Elevation (fill or elevated foundation)	• Protects individual structures instead of entire areas • Can be used in areas where fill is not permitted such as Coastal V-Zones. • May allow for passage of flood waters beneath foundation without causing significant damages. • May protect structures from wave action. • May use additional building elevation methods such as placing structure on piles	• Susceptible to failure from debris action. • Subject to height requirements within the jurisdiction. • Increased risk of structural failure by placing pile foundation on compacted fill.
Parcel Elevation (fill and/or elevated foundation)	• Allows some development within floodplains rather than a large amount of development. • Allows for sections of parcels or entire parcels to be above BFE • Allow for additional freeboard	• Protection is not distributed around entire areas • Possibility of adjacent damages

Table 2.1 Continued

Elevation Technique	**Pros**	**Cons**
Multiple Parcel Elevation (fill and/or elevated foundation)	• Protects entire subdivisions rather than individual structures. • Large areas of open spaces and detention ponds can be provided for large subdivisions to compensate for fill.	• Increased level of subsidence of entire subdivision. • Likely to increase losses in adjacent areas especially since more floodplains have been altered. • Increased exposure to flood events since entire areas is on fill. • Likely to increase the height of the floodplain if freeboard is not enforced.

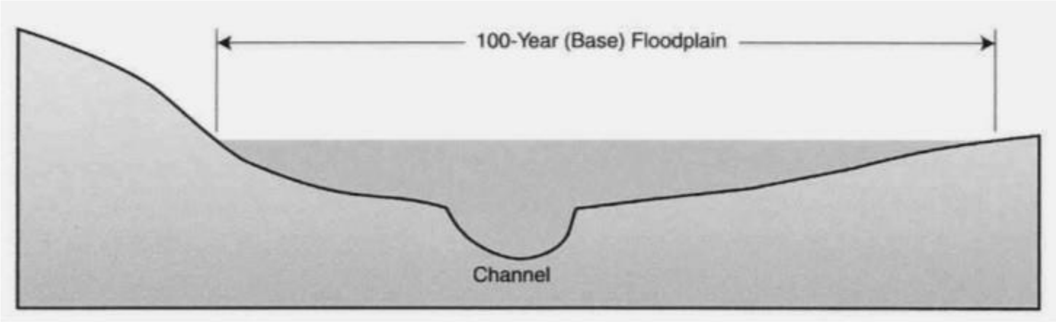
2.1.2 Adverse Impacts of Parcel Fill in Floodplains

Existing flood risk maps are inefficient in capturing actual exposure to flood events and some suggest that a more conservative confidence interval be used in determining floodplain boundaries (Burby 2001; Birkland et al. 2003). Floodplain maps are reviewed every five years; however, several backlogs of floodplain revisions exist (Burby 2001). By the time floodplain maps are implemented, they are already out of date since several developments already occurred inside the floodplain during the revision process. This delay results in a floodplain whose depth and boundary extends far beyond what is presented in the revised maps. Due to the uncertainties of determining floodplain maps, current standards for filling parcels may not be an effective method of mitigating floods, as fill parcels may still be vulnerable to flood risk due to increased floodplain development.

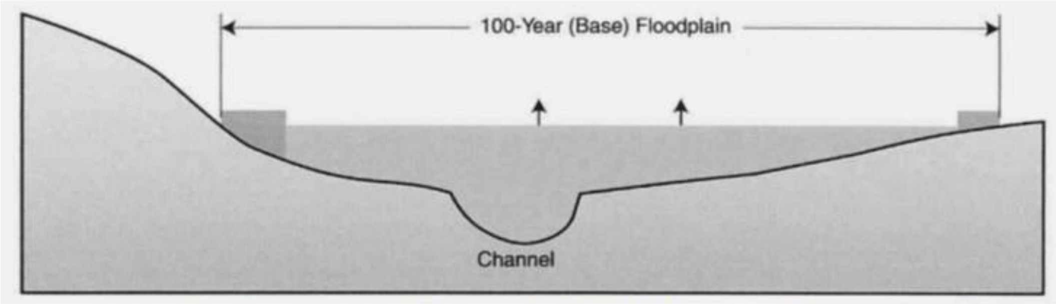
Due to the possibility of adverse impacts from floodplain development, FEMA permits fill in floodplains but requires that it must not increase the 100-yr base flood elevation by over 1 foot (Birkland et al. 2003; FEMA 2001; Larson & Plasencia 2001). Some communities, however, have a ‘zero-rise policy where there is no fill allowed unless there is an additional purchase of adjacent easements to make way for residual flooding and compensatory flood storage, while other communities even have additional freeboard requirements of 1 or 2 foot in addition to fill (Birkland et al. 2003; Burby 2001). Although NFIP requirements specify that fill should cause no more than 1 foot in the increase of flood heights (see figure 2.3), in Charlotte, North Carolina for example, fill has resulted in increasing floodplain heights by at least 3 feet (Burby 2001). Further analysis also shows that if fill continues to be approved in floodplains, the rise in flood levels will be greater than expected (Larson & Plasencia 2001). Surprisingly, some communities even allow fill in the floodway even though it is restricted by FEMA, and they then require developers to produce a no-rise certificate which indicates that the use of fill in the floodway will not lead to any adverse impacts and will not raise flood levels in the floodplain. Such provisions expose floodplains and surrounding developments to greater susceptibility to flooding.

Besides restricting fill, providing adequate storage to compensate for filled parcels is essential. For example, the CRS discussed earlier, grants additional points to communities for providing compensatory storage to accommodate the rise in elevation because of floodplain development (FEMA 2013). An example of such compensatory storage is detention basins. Detention basins can serve significant storage purposes for floodwaters and are appealing to homeowners when also used for recreational purposes

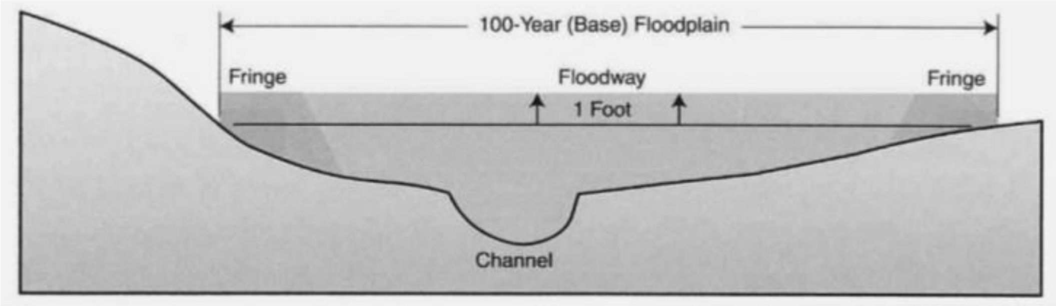
(Lee & Li 2009). Low impact development strategies as practiced in Prince George's County are also examples of activities that can provide compensatory storage for floodwaters (Li, Dvorak & Sung 2010). Thus, it is expected that communities that have additional compensatory storage measures, as reflected in the CRS scores, will significantly perform better in reducing flood loss.



Current conditions



Computer simulation shows fill is used in the edge of the floodplain thereby increasing base flood elevations because there is less room for floodwaters



The obstructions in the fringe is moved closer to the channel thereby increasing elevation by 1 foot.

Figure 2.3 How Floodplains Change Due to Fill.
Reprinted from FEMA (2013).

Allowing compensatory storage is like building new wetlands in other areas to avoid a net wetland loss as provided by wetland protection policies. The most effective flood attenuation function is to allow natural wetlands and floodplains to compensate for excess floodwaters, limiting the impact on development (FEMA 2013). While FEMA acknowledge that compensatory storage in the form of detention ponds retain excess flood waters, research is yet to identify how these compensatory storage facilities translate into flood damage avoidance.

In fact, one of the specific warnings provided by FEMA on the use of fill in floodplains is that it can increase the chance of flooding in places that would not flood otherwise (FEMA 2001, FEMA 2013). It is not surprising then that fifty percent of flood claims occur outside the floodplain even when these areas are expected to be less vulnerable to inundation (Highfield et al. 2013). This is because the effect of altering naturally occurring landscapes extend far beyond the areas that have been altered. Increasing development in vulnerable areas exposes surrounding areas to increased flood risk. For example, channelization increases flooding in adjacent wetlands, especially reducing downstream storage capacity, and increases flow velocity, making downstream developments more vulnerable to flooding (DeLaney 1995; Kreibich et al. 2009). As shown in figure 2.4, floodplain managers continue to educate the public and developers on the residual impacts of using fill in the floodplain and promote a no adverse impact approach to floodplain management (Sauvageot 2015).

While addressing the issuance of wetland alteration permits in Texas and Florida, Brody et al. (2008a) noted that although new wetlands are built to replace altered ones, there is a spatial mismatch as the new wetlands protect other areas rather than the development that just occurred. The authors also found that there was an increase in permits that affect palustrine wetlands showing a sprawling pattern of development. This pattern of alteration within floodplains, can contribute to flooding homes that were not inundated by less frequent flood events.

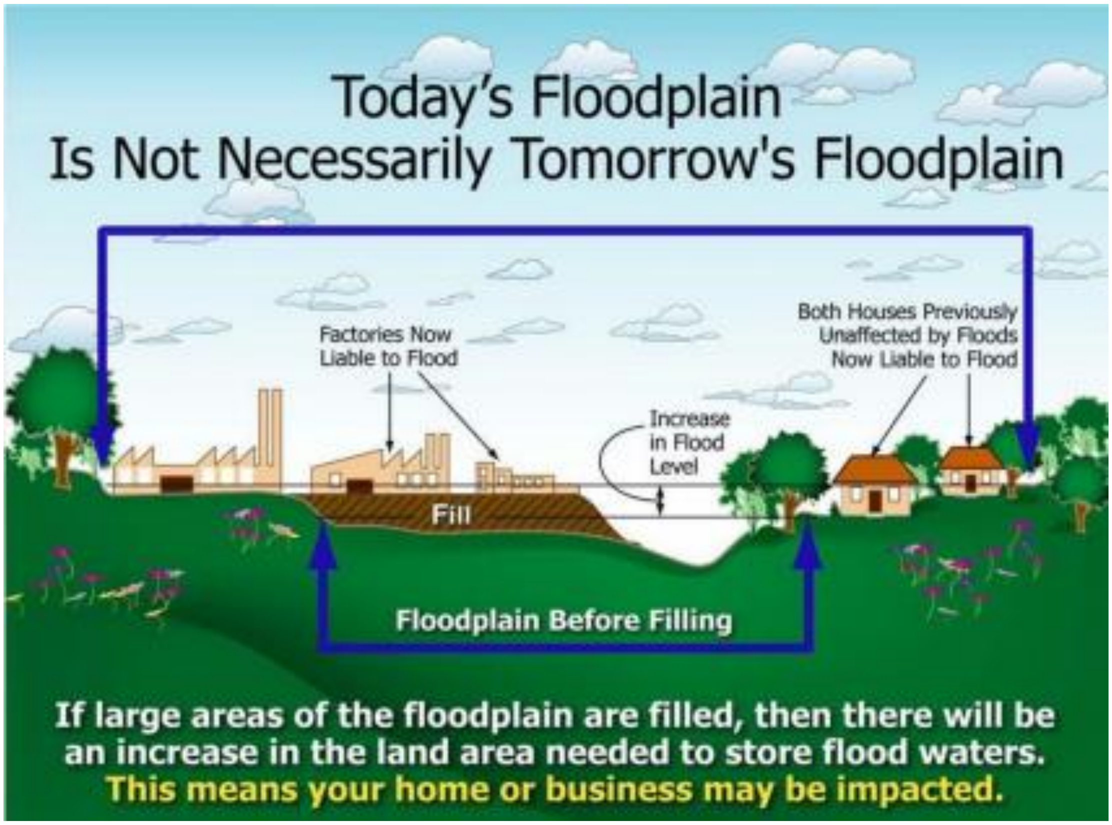


Figure 2.4 Adverse Impact of Fill.
Reprinted from City of Roseburg (2017).

Just like levees can raise water levels and increase downstream velocity and potentially increase flooding (Birkland et al. 2003), raising land elevations within the floodplain without provision for compensatory storage can significantly increase losses in adjacent areas with limited infrastructure to deal with those losses. These natural compensatory storage provisions are limited when fill is used in floodplains (Larson & Plasencia 2001). Even floodplain levels are expected to rise when fill is used on the floodplain fringe (see Figure 2.3) (FEMA 2013).

Building elevation, besides other CRS measures significantly impacts flood damages (Highfield et al. 2014). It is expected that the filled property will have lower flood damages. It is also expected that fill will increase flood risk for adjacent properties. Other studies have also found improvement year relative to the Flood Insurance Rating Mapping to significantly impact flood damages (Highfield & Brody 2012; Highfield et al. 2014). This is expected if local building codes have adequate standards for flood risk reduction.

2.2 Fill in the Context of Flood Mitigation in the United States

Parcel fill is just one of many flood mitigation strategies used in the U.S. Flood mitigation is categorized into structural and non-structural (Thampapillai & Musgrave 1985). A structural method is the use of flood infrastructure for flood mitigation and resembles a command-and-control system of altering the natural landscape. It involves the use of engineering methods such as the construction of levees, seawalls, dikes etc., Structural mitigation measures are capital and time intensive. Filling parcels is an example of structural mitigation.

Following the 1927 flooding of the Mississippi River, there has been a dependence on engineering methods to altering the landscape and the natural environment to reduce flooding (Birkland et al. 2003). Flood control methods like building seawalls in coastal areas, revetments, stream hardening, dams, and bulkheads and so on are still common today. These structures are vital to reducing flood damages especially in densely populated areas and provide a great deal of protection on a larger scale. Although structural mitigation benefits large areas, they can also occur at a more localized site/parcel scale. This dissertation focuses on one of such site-level mitigation strategy, where buildings and parcels are raised above Base Flood Elevation (BFE) to prevent inundation from flood events. These methods have been in use for several years: even as far back as the 80s, studies have shown that a combined 50% of homeowners or developers either fill or elevate their structures when in the floodplain (Bollens et al. 1988).

Non-structural mitigation involves development policies and incentive programs which reduce flood impacts (Alexander 1993). This is usually achieved through land use management strategies, public awareness and protecting sensitive areas and floodplains. The CRS is a major vehicle for implementing non-structural flood mitigation. This program was established in 1990 by NFIP and provide insurance policy premium discounts for participating jurisdictions through a point-system where the discount is based on the number of points accumulated from a suite of flood mitigation and preparation practices (FEMA 2013). Land use planning also provides tools that can be included in a city’s comprehensive plan to reduce flood impacts (Burby et al. 2000, Burby et al. 1999).

CRS communities with high CRS scores have a significant reduction in flood damages (Brody & Zahran 2008; Brody et al. 2009; Highfield & Brody 2012). A longitudinal assessment of CRS scores in Florida shows that local jurisdictions adopt non-structural approach in areas like public information and map regulations, however, these communities shy away from activities that address structural issues and stringent land use policies perhaps due to its high economic or political cost of implementation, relative to the benefits of reducing loss of life, and property loss (Brody et al. 2009). Areas with a high percentage of land in floodplain find it difficult to adopt CRS policies due to land constraints along with the political and social challenges of mitigation efforts, where reduced insurance premiums may not be worth the cost of implementing these mitigation methods (Brody et al. 2009).

Although flood mitigation has been historically categorized as structural and non-structural, flood mitigation goes beyond these. A new framework now categorizes flood risk reduction into *Resistance, Avoidance, Acceptance*, and *Awareness* strategies (Brody & Atoba 2018). This framework also categorized fill as an avoidance strategy. Resistance and avoidance strategies fall within structural methods while acceptance and awareness measures fall between non-structural methods (Brody & Atoba 2018).

Fill is categorized as a ‘vertical avoidance’ technique where structures are raised to avoid flood waters and subsequent damage from flood events (Brody & Atoba 2018). Because fill involves engineering interventions, it is also a structural approach, but depends on local policies for its effective implementation. For example, the NFIP allows for properties within floodplains to be elevated above flood levels but prevent the use of fill in floodplains in some jurisdictions to avoid foundation failure or residual impacts to neighboring areas (FEMA 2013; FEMA 2001).

2.2.1 Combining Fill with other Mitigation Techniques

Although it is challenging to prevent floodplain development for planners, this remains the best way to avoid flooding in SFHA areas (Mileti 1999; Burby et al. 2000; Godschalk 2003). The only justifiable use of fill after considering its pros and cons is to employ additional hazard mitigation strategies such as enforcing mitigation policies and urban planning tools. As highlighted by Brody and Atoba (2018), flood risk reduction can be achieved by a synergistic approach where avoidance techniques such as fill is combined with other structural and nonstructural mitigation methods highlighted in this dissertation. The following discusses additional methods that can be used besides using fill for mitigating flood hazards. These circumstances are important in low-lying areas. Note that these efforts are not expected to be effective when used independently but may be effective when combined with other planning tools and non-structural flood mitigation attempts.

Additional flood protection through freeboard is often recommended to reduce flood risk (FEMA 2001; FEMA 2013). Communities that have additional freeboard requirements as reflected in their CRS score record less amount of flood damages (Highfield & Brody 2012, Highfield et al. 2014). A longitudinal research by Highfield and Brody (2012) shows the freeboard requirement as a specific activity under the CRS significantly reduce loss from flood events, saving almost $8,300 per year for each community. When structures are elevated above BFE, as additional requirements, it can reduce flood impacts.

Other non-structural approaches will also be beneficial in addition to fill. A longitudinal assessment of CRS scores in Florida shows that local jurisdictions that have high scores in specific sections that encourage public information record reduced loss from flood events (Brody et al. 2009). Community-scale level activities like open space protection, freeboard requirements, and retrofitting significantly reduce flood loss (Highfield & Brody 2012). Site-level activities like series 530 on flood protection in the CRS that deal with structural methods like retrofitting and flood-proofing were significant for reducing flood loss (Highfield & Brody 2012).

When floodplain filling is inevitable, adequate provision should also be made for compensatory storage to account for current and future fill. The CRS point structure assigns points to communities that not only avoid the use of fill in the floodplain but also provides compensatory storage to accommodate for the rise in elevation; this storage can be through retention ponds and open spaces that can collect flood water. Detention basins can serve significant storage purposes for floodwaters. Detention basins used for recreational activities are welcomed by the public and can improve property value. However, people perceive single-use detention basins as needing maintenance, worsens health conditions and as unsafe (Lee & Li 2009).

Using these detention basins is an effective way of compensating for areas that have been filled, allowing for the collection of floodwaters. However, research has not been conducted on how the presence and location of these detention basins will compensate for fill in low-lying areas. These methods must be combined with sophisticated engineering approach to ensure that the open spaces and detention basins are compensating for areas that have been filled and not for other areas. Compensatory storage in floodplains cannot provide the natural floodplain function for storing flood waters (FEMA 2013). This is like constructing new wetlands in place of altered one, whereas, they do not provide the flood attenuation functions that the natural wetlands produce.

Additional storm water management methods can also be used, for example, using Bio retention ponds and a combination of other low impact development strategies in areas where fill is used might be plausible. Bio retention reduces peak discharge from storm events by holding storm water temporarily (Hunt et al, 2007; Davis, 2008; Sharkey & Hunt, 2005). Low impact development strategies as practiced in Prince George's County are also examples of activities that can provide compensatory storage for floodwaters (Li et al. 2010).

Initial designs in the Woodlands used a combination of ecological consideration in development design. The major design principles that guided the development of the Woodlands, TX was to preserve permeable soils for open space development and based development density on soil permeability characteristics, preservation of forest cover, and allow open surface drainage (Yang, Li & Huang 2015). This implies that soil permeability factors have to be considered when making provisions for open spaces and compensatory storage. Open drainage not only provided higher capacity for infiltration but was also cheaper than using conventional storm drains (Yang et al. 2015). Such design considerations besides stricter requirements for using fill in floodplains can significantly reduce the impact of urban flooding.

2.2.2. Fill in the Context of Regional Environmental Planning

Many municipalities within the same watershed have different approaches to the use of fill; while some have stricter rules, some encourage the use of fill to enable development in the community. However, Conservationists, Ecologists, and Planners have long advocated for managing ecological units rather than restrict policies based on jurisdictional boundaries. Generally, there is limited state mandate where local comprehensive plans consider trans-boundary interactions of the ecological system (Berke et al. 2013). Other ethical foundations of regional ecological thinking by early ecologists and planners have been summarized and give us more insight on the need to incorporate ecological systems into regional planning (Beatley 1994). Studies have also recommended tracking of ecological disturbances like wetland and floodplain alteration on a broader regional and spatial-temporal scale rather than on a site-by-site basis as flooding cross jurisdictional boundaries (Brody et al. 2008a; Brody et al. 2007b).

This discussion for focusing on regional considerations and planning at the watershed scale has often been described in the literature as regionalism. Regions fall right in-between small and bigger geographies that have already been defined geographically, i.e. larger than metropolitan cities or towns, but smaller than the states where they are present (Thibert 2015). In this context, a region can be defined by biological boundaries like a watershed.

Restricting the use of fill in the context of a region is difficult to achieve based on some challenges raised by Foster (2001). Mainly, the philosophical aspect creates a classic challenge of protecting ‘common good’ without compromising individual freedom rights. There is also a political challenge in which deciding to do something regionally usually implies not focusing on it locally.

Since the 1960s, regulations such as the National Environmental Policy, Clean Water Act, National Endangered Species Act, and so on has increased awareness of ecological design and planning and has promoted increased research in concepts and methodology (Ndubisi 2014; Michaels 2001). However, urban planning efforts are still struggling to have a regional focus and plan from an ecological systems point of view. Suggestions on integrating land use planning decisions with ecological principles were suggested by Dale et al. (2000). They emphasized that decisions made locally must consider wider regional implications, planning must be long-term, as well as protecting rare species and critical habitats, maintain landscape contiguity, compensate for areas where ecological losses will occur and consider the natural environment in all planning activities for new land use. Such considerations are necessary when approving floodplain development permits within a wetland.

2.3 Empirical Research on Wetland Alteration in Relation to Fill

Past research has recommended examining the impact of specific mitigation strategies on flood loss (Brody et al. 2007b, Brody, Kang & Bernhardt 2010), but no empirical study has addressed fill as a mitigation method for reducing flood impacts. Studies on fill and flood loss are limited, but earthquake damage to residential fills in Japan have been seen to cause groundwater depletion and rain action before the earthquakes occur, causing significant damages to the structures placed on fill (Yoshida, Nishi & Nanbu 2001).

Although empirical research on fill is limited, some component of wetland alteration research can apply to floodplain filling. It should be noted however that wetland permits (Section 404 permits) are granted for filling “waters” (wetlands) for development, construction of dams, levees, and for infrastructural projects like roads and airports (EPA, 2015), while fill is primarily used for increasing “land” elevation. These two activities are closely related but differ in scope and implementation.

Individual wetland alteration permits (IP) are granted for projects greater than 0.5 acres. These IPs were found to significantly impact watershed flooding in Texas and Florida (Brody et al. 2007a; Highfield & Brody 2006). These permit types are typical of large development projects which, not surprisingly, impacts watershed flooding because of the increase in the imperviousness that accompanies such projects. Similarly, the number of fill permits for entire subdivisions is expected to increase imperviousness and subsequently reduce the capacity of floodplains to store floodwater. The effect of this is increased flooding either for the filled areas or even for surrounding areas.

General permits (GP) which signify small-scale wetland alteration permits typical for residential development have been seen to cumulatively impact flooding

(Brody et al. 2007a). In their study, Brody et al (2007) found that this alteration permit represented about 22% of the permits issued in Texas and Florida. The result showed a cumulative effect of filling wetlands by these small scaled projects and it provides insight into the individual parcel fill technique discussed in this dissertation, especially in considering the role of clustering of individual fill permit types on flooding in residential communities.

While no empirical research has compared fill with wetland alteration, the comparison in this dissertation is only an attempt to identify similarities and differences between fill and wetland alteration that could inform decisions on whether these two approaches have similar impacts on flood damages.

3. CONCEPTUAL FRAMEWORK

This section discusses the dissertation's conceptual framework. The conceptual model describes the relationship between parcel fill and residential flood damages. This section also describes the primary dependent and independent variable. Specific hypotheses are formulated and measurable variables for the exploratory data analysis of fill parcels and their characteristics are also described in this section. Following each variable also are specific measurable hypotheses on their relationship with the flood damages.

3.1 Conceptual Framework

Below in figure 3.1 is a conceptual model on the relationship between each independent variable and the dependent variable. The dependent variable in this research is flood damage. The research focus is to identify how individual mitigation, locational, and environmental factors impact flood damage.

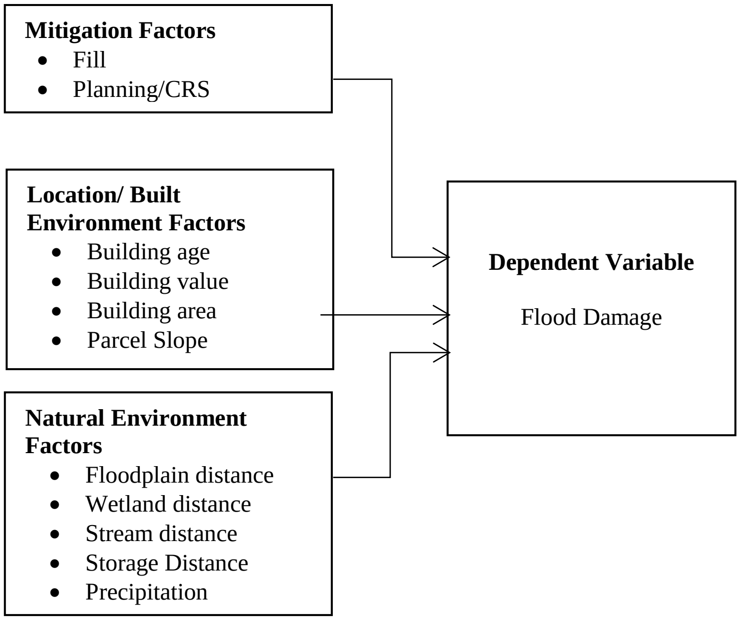


Figure 3.1 Conceptual Framework.

As shown in the conceptual model above, flood damage is the dependent variable in this dissertation. Damages that occur from flood inundation can be seen from several perspectives. However, for a manageable scope, this dissertation will focus on direct economic losses to structure and contents from flood events. Even though fatalities from flood events has significantly reduced in this century, property losses continue to rise. Effective flood mitigation efforts, and adequate urban planning interventions and techniques, can reduce these losses.

As shown in the conceptual model, flood mitigation factors represent the first category of independent variables expected to impact flood damages. Section 2 of this dissertation discussed several flood mitigation strategies and identified the role of fill, compensatory storage and the CRS in mitigating flood damage both at the parcel and jurisdictional level. Studies have also been conducted on the impact of both structural and non-structural mitigation approaches to flood damage. Fill and compensatory storage are primary structural mitigation methods in this research while the CRS is used to account for other non-structural mitigation methods that will reduce flood damage at the parcel level. As seen in the literature review section, these variables are expected to significantly reduce flood damages at the parcel level.

The second dimension in the conceptual framework is the locational factors which are important control variables for modeling flood damages. This represents the physical and economic characteristics of the individual parcels in the study area. Age and improvement value have also been used as a proxy for building quality while an additional locational variable discussed in the literature is the extent of a parcel that has been filled.

Environmental factors represent the third dimension of factors that influence flood damage. Parcels close to, or in floodplains, are expected to have higher flood damages; proximity to large wetland alteration permits can also increase property damage. The fourth environmental factor implies that the location of a parcel relative to streamflow can impact the extent of flood damages. Precipitation is expected to be directly proportional to flood damage while parcels located within or near flood zones are likely to experience higher flood damages

The following sections discuss each variable in the conceptual framework and describe ways they are measured in this dissertation. The specific hypotheses based on the expected relationship between these variables is also proposed.

3.2 Dependent Variable: Flood Damage

The dependent variable in this research is flood damage in dollars at the parcel level in the clear creek watershed between 2000 and 2014. This parcel-level damage is represented by insured flood claims from data provided by FEMA under the National Flood Insurance Program (NFIP). The NFIP was established in 1968 as the sole provider of flood insurance to residents in the 100-year floodplain. The dataset includes a nationwide inventory of all flood claims and payment to each parcel for damage to structure and contents. This dataset is limited to only insured flood damages and does not reflect losses to uninsured properties both within and outside the floodplain. Previous research use flood claims dataset as a proxy for flood damage in relation to other physical, socio-economic and environmental factors (Highfield, Brody & Blessing 2014; Highfield & Brody 2012).

3.3 Independent Variables

3.3.1 Flood Mitigation Factors

This dissertation focusses on specific structural mitigation methods and how they impact flood damages. To control for planning and non-structural interventions, the CRS score related to fill and compensatory storage requirements are also included as control variables. These variables are discussed below.

3.3.1.1 Fill

Fill is the use of dirt to raise parcel above BFE and is the primary independent variable in this research. Filled parcels are identified by digitizing the LOMR-F elevation certificates from FEMA. Using fill, parcels are officially removed from the 100-yr floodplain and are expected to record reduced flood damages.

Hypothesis 1: Filled parcels will experience significantly lower amounts of flood damages.

3.3.1.2 CRS Score

The CRS score for activity 430 which is the activity related to fill regulations is as a control variable. This variable accounts for the urban planning component in the conceptual framework. Specifically, activities covering open space preservation, higher regulatory standards, stormwater management, flood protection and drainage system maintenance are used to account for fill regulations affecting parcels in the study area.

Hypothesis 2: Parcels in communities with higher CRS points will experience significantly lower amounts of flood damages.

3.3.2 Location/ Built Environment Factors

As discussed in the conceptual framework, locational factors are control variables that determine the extent of flood damages expected for each parcel. They are primarily built environment variables that also contribute to adverse impacts of flooding.

3.3.2.1 Building Age

Building age is a proxy for building quality. In many cases, building age has been used to determine whether or not building standards are applied. Older buildings adopt outdated building codes and are more susceptible to flood damages. For example, buildings constructed pre-firm are not required to build up to BFE in flood zone compared to buildings that adopt higher flood mitigation requirements.

Hypothesis 3: Parcels with newer structures will experience significantly lower amounts of flood damages.

3.3.2.2 Building Value

Improvement value for each parcel is used to determine the impact of property value on flood loss. This is an important control variable because wealthier neighborhoods perform better in mitigating flood damages than poorer neighborhoods. Improvement value is also used in many flood loss estimation models and a good proxy for building quality.

Hypothesis 4: Parcels with higher structural values will experience significantly lower amounts of flood damages.

3.3.2.3 Building Area

Improvement area measured in square foot will be used as a proxy for the size of the building and an additional building characteristic in the model. This is an important control variable because building area also reflects the location of buildings whether in suburban communities or in built-up areas and are also important variables to consider in flood damages.

Hypothesis 5: Parcels with larger building areas will experience significantly lower amounts of flood damages.

3.3.2.4 Fill Type/Extent

Fill can be used for either individual parcels or a contiguous number of parcels in a subdivision. At the site level, the use of fill can result in either only the property, portions of the property, or entire subdivisions been removed from the floodplain. The higher the portion of parcel filled, the lower the expected flood damage to that parcel.

Hypothesis 6: Parcels with higher fill extent will experience significantly lower amounts of flood damages

3.3.2.5 Slope

The slope represents the level of the steepness of parcels. The study area is generally flat, making it susceptible to flooding, however, steeper parcels respond differently to flood damages.

Hypothesis 7: Parcels with higher slope percentages will experience significantly lower flood damages.

3.3.3 Natural Environment Factors

In past research, environmental variables are usually categorized as biophysical factors and built environment variables. However, in this research, most of the built environment variables have been categorized as mitigation factors. These factors are necessary to control for the actual effect of fill on flood damages. Natural environment variables deal with factors that determine the extent or intensity of flood.

3.3.3.1 Floodplain distance

The 100-yr floodplain has been used historically as a flood risk indicator. In this research, individual parcels distance from the floodplain serve as a flood damage risk indicator. Properties farther from the floodplain should record smaller flood damages. Even though there are parcels outside the floodplain, those in proximity to the floodplain are still expected to experience flood damages.

Hypothesis 8: Parcels farther away from the FEMA-defined 100-year floodplain will experience significantly lower amounts of flood damages.

3.3.3.2 Wetland distance

Altering naturally occurring wetlands impact both ecosystem hydrology and flood damages. This research uses the USACE wetland alteration permits as one of its control variables.

Hypothesis 9: Parcels located farther away from wetland alteration sites will experience significantly lower amounts of flood damages.

3.3.3.3 Stream distance

Stormwater best management practices aim to reduce runoff and downstream flooding. Distance of a parcel to the stream is an important indicator of flood risk. This research will examine how fill parcels perform vis-à-vis their location to the nearest stream.

Hypothesis 10: Parcels farther away from streams will experience significantly lower amount of flood damages.

3.3.3.4 Storage distance

Compensatory storage provisions usually accompany fill in subdivisions where floodplains have been developed. It is expected that parcels closer to compensatory storage provisions experience lesser amounts of flooding. This research will examine how fill parcels perform in relation to their distance to compensatory storage areas.

Hypothesis 11: Parcels farther away from compensatory storage ponds will experience significantly lower amounts of flood damages.

3.3.3.5 Precipitation

Precipitation is a proxy for identifying the intensity of flooding within the study area. When precipitation is high, the natural capacity of soils to hold floodwater is overwhelmed, resulting in flooding. Precipitation is usually collected at specific point locations and interpolated to represent larger areas. This variable has been shown by several studies to be a major predictor of flood damages.

Hypothesis12: Parcels with higher amounts of precipitation during the study period will experience significantly higher amount of flood damages.

3.4 Measurement and Variable Operationalization

Table 3.1 is a summary of the variables used in this research and how they are operationalized. The dependent variable, *flood damage*, is measured by the total insured flood damages from 2000 to 2014. This data from FEMA comprise both structural and contents claims amount granted to individual parcels. They are measured in U.S. dollars. This ratio scale variable identifies the actual flood damages that occurred for each parcel rather than using a flood damage estimation model. This approach ensures that actual losses from past flood events are used in the research.

The primary independent variable is *Fill*. It is represented as a dummy variable of whether a parcel is filled or not filled. Since this research is the first to examine the impact of fill on flood damage, it begins by digitizing the LOMR-F dataset from FEMA using locational tools in GIS. The ideal way of identifying parcel fill is a spatial-temporal analysis of land elevation to identify areas where elevation has been increased. However, due to the unavailability of temporally appropriate spatial data and the cost associated with them, it would be impractical to quantify parcel fill based on Geospatial data analysis. LOMR-F certificates remain the most viable way of identifying fill parcels. Previous research has also been conducted on the impact of Letters of Map Amendment (LOMA), which is a similar elevation certificate granted by FEMA, on floodplain property values (see Larson, 2012).

Compensatory storage is measured by identifying the distance of a parcel to the nearest retention or detention pond in the floodplain where the parcel is located. Retention and detention are identified through the pond classification in the National Hydrography Dataset (NHD) in the study area.

The *CRS score* is measured by computing the average CRS score for activity 430 score for the community where the parcel is located. The CRS score data is provided by NFIP and has been used for several flood mitigation studies. This activity specifically focusses on rewarding communities with higher fill restrictions in the floodplain and higher freeboard requirements.

Building Age is one of the locational or built environment factors that impact flood damage and is measured in this research as the age of the building on a parcel in years. Building age is derived from the property characteristics from the county appraisal district where the parcel is located.

Building value is also an important locational factor measured in U.S. dollars and is based on the tax assessor's appraised value of the building on the parcel.

Building area is the square footage of the improvement on the parcel of study.

The *Fill Type* used for each parcel is determined by evaluating the components of the LOMR-F certificate issued for that parcel. This is a dummy variable that specifies whether sections of or entire parcel has been filled or whether even entire parcels, portions, described or structures have been filled. The base layer is non-fill.

Slope is represented by the percentage of steepness of each parcel.

One major variable among the natural environmental factors is precipitation. *Precipitation* has historically been the major predictor of flood damages. This is measured based on the average monthly rainfall amount in inches for the grid where a parcel is located. This dissertation uses the Parameter-elevation Regressions on Independent Slopes Model (PRISM) and uses the mean annual precipitation for the parcel of study during the study period of 2000 to 2014.

Floodplain distance is measured in foot as the distance from the centroid of the parcel to the centroid of the nearest floodplain.

Wetland distance is measured as the average distance of the parcel to the nearest section 404 permit.

Stream distance is the distance from the center of the parcel to the closest edge of the nearest stream segment in the watershed.

Table 3.1 Variables and their Operational Definition

Variable	Description	Scale	Sign	Source	Temporal
Dependent Variable					
Flood Damage	Total insured flood damage for each parcel (2000-2015)	Ratio	NA	FEMA	Invariant
Mitigation Factors					
Fill	Parcels with approved LOMR-F certificates for fill	Dummy	-	FEMA	Invariant
Fill Extent	Extent of parcel that has been filled	Dummy	-	FEMA	Invariant
CRS	CRS score for the community where the parcel is located	Ratio	-	FEMA	Annual
Location/Built Environment Factors					
Building Age	Age of building located within a parcel	Ratio	+	CAD	Invariant
Building Value	Dollar value of structure on parcel	Ratio	-	CAD	Invariant
Building Area	Square footage of building on the parcel	Ratio	-	CAD	Invariant
Slope	Slope percentage of parcel	Ratio	-	LULC	Invariant
Natural Environment/ Distance Factors					
Floodplain Distance	Distance of parcel centroid to edge of nearest floodplain	Ratio	-	FEMA	Invariant
Wetland Distance	Distance of parcel centroid to nearest section 404 permit	Ratio	-	USACE	Invariant
Storage Distance	Distance of parcel centroid to edge of storage pond	Ratio	-	NHD	Invariant
Stream Distance	Distance of parcel centroid to edge of nearest stream	Ratio	-	NHD	Invariant
Precipitation	Average monthly precipitation level for grid where parcel is located	Ratio	+	PRISM	Annual

4. RESEARCH METHODS

This section discusses the data and methods used to achieve the objectives in this dissertation. It begins by describing the study area and justifying the spatial sampling frame selection and the unit of analysis. The section describes the research methods specific to each objective highlighted in the first section.

4.1 Study Area and Spatial Sample Frame

The spatial sample frame for this research consists is the Clear Creek watershed (see map in figure 4.1). According to the Harris County Flood Control District (HCFCD), the 197-square mile watershed is located within four counties in the Houston-Galveston area of Texas; Harris, Galveston, Brazoria and Fort Bend. There are 16 major cities in the watershed, with the city of Houston being the largest. There are 5 flood control districts within the boundaries of the watershed and several other cities that are part of the Houston metropolitan area. About 70% (137 square miles) of the watershed is within Harris County with a population of 164,172 living within the watershed in 2010, a population rise of 39% from 2000 (HCFCD 2016). This is noticed from the development occurring especially in the lower part of the watershed and the increasing level of suburban development in the Houston area.

The watershed has tidally influenced water bodies that flows west-east towards the Galveston Bay with approximately 154 miles of stream. Major streams in the watershed include Clear Creek and Turkey Creek. The study area is a typical gulf coast environment with characteristics such as low topographic relief, large floodplain boundaries, and low soil permeability, all of which contribute to high amounts of damages from flooding. The Harris County Flood Control District has completed several projects in the Harris County section of the watershed. For example, since 1975, over $1.2 billion has been spent on capital projects and new projects continue to be authorized (HCFCD 2016). New projects such as the mud gully stormwater detention basin, improvements of the upper Clear Creek conveyance and a watershed master plan are currently in place in the Harris county section (HCFCD 2016).

Despite expensive capital improvements to reduce flood impacts in the area, both small and large-scale flooding continues to be a problem. Between 1999 and 2009, over 9,000 insured flood claims alone were recorded for the Clear Creek watershed (Highfield et al. 2014). The environmental characteristics of the area combined with the nature of built environment approach make it suitable for examining the impact of fill on watershed flooding. This is important because fill is an urban phenomenon and is closely associated with areas where there is pressure to develop in vulnerable areas due to rising population.

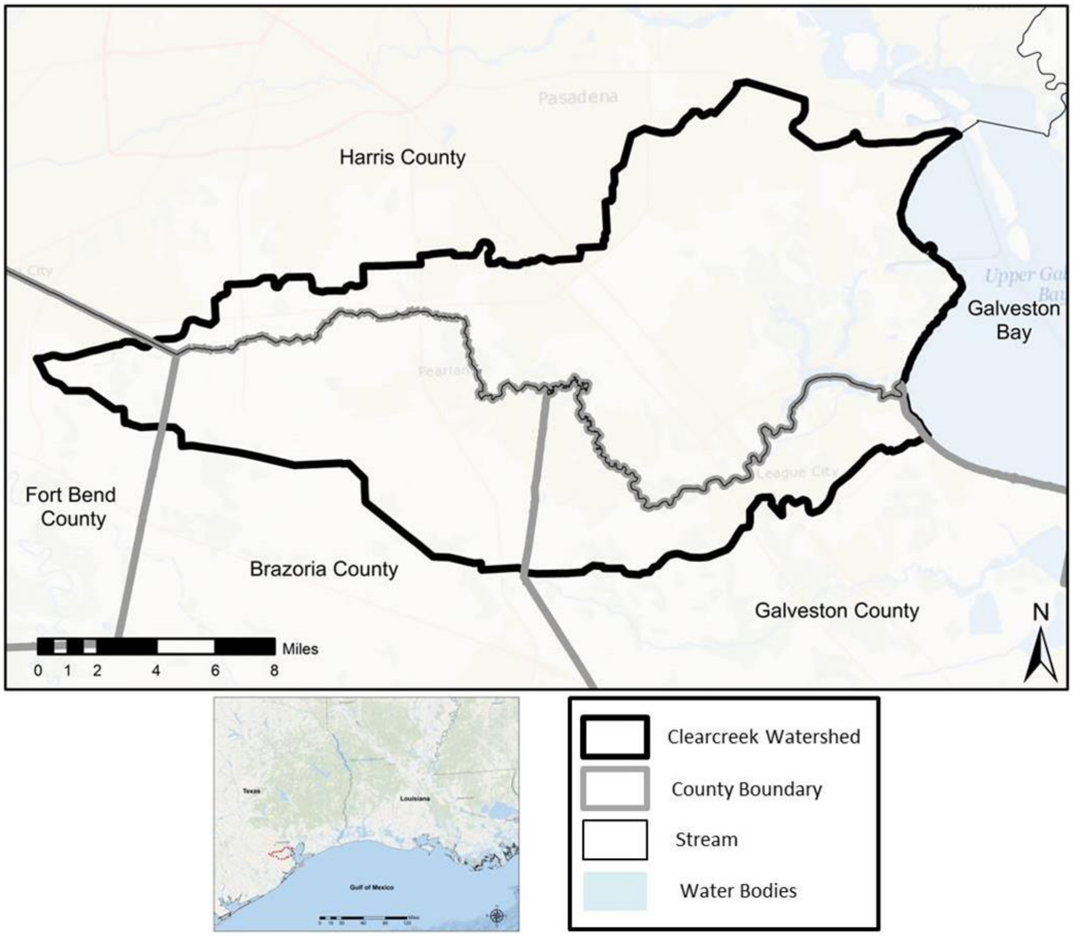


Figure 4.1 Clear Creek Watershed Study Area and Surrounding Counties.

4.2 Sample and Matching Procedure

The unit of analysis in this research is the residential parcel. This unit was selected because fill usually occurs at the parcel level, although some developers in new subdivisions fill a contiguous number of parcels. Figure 4.2 shows the total number of over 157,000 parcels in the study area. From these parcels, a study sample was selected from all filled parcels in the watershed and matched pairs of unfilled parcels over a 15-

year period between 2000 and 2014. The filled and unfilled parcel sample were balanced using a Propensity Score Matching (PSM) technique, which also accounts for time-invariant independent variables to select the appropriate regression model. The match of the filled and unfilled parcels that compose the final sample was used for the regression and spatial analysis component of the dissertation.

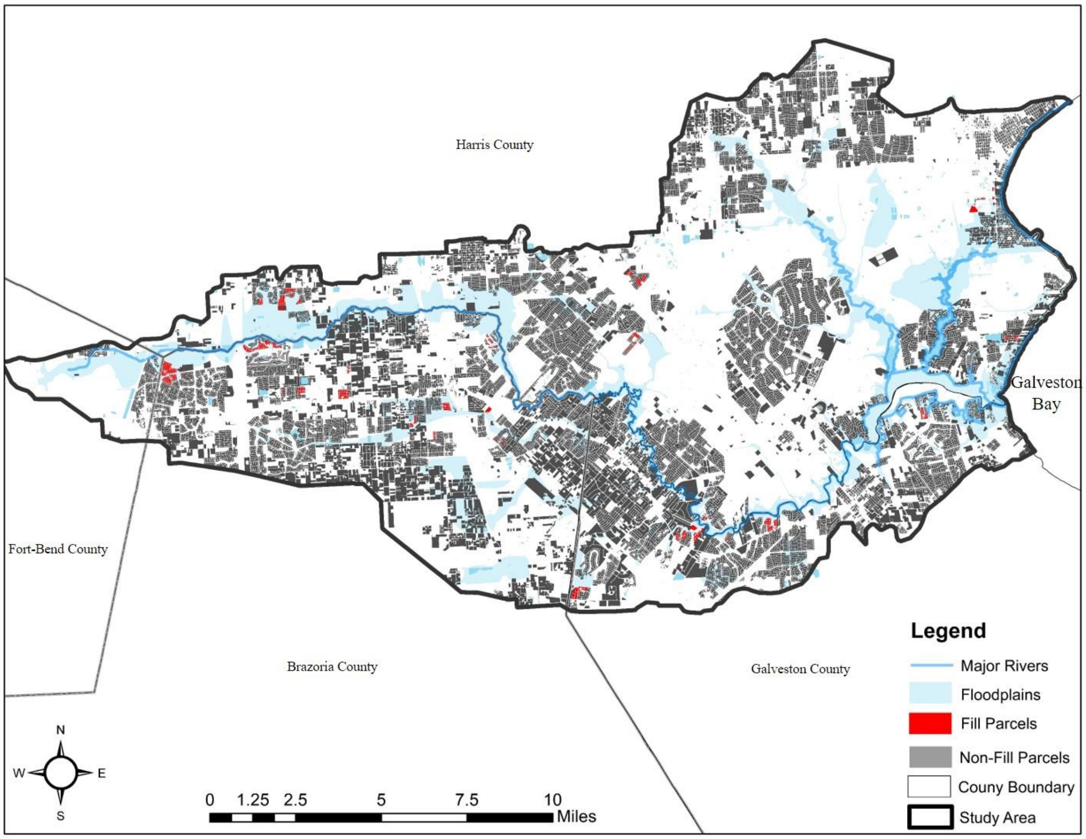


Figure 4.2 Fill and Non-Fill Parcels before PSM.

The PSM procedure ensured that parcels with similar characteristics were compared to avoid sample selection bias (Rosenbaum & Rubin 1983). The PSM method was developed by a Roy-Rubin model that provides information about the impact of a treatment effect on an outcome, i.e. how an individual will perform if they had not received that treatment (Caliendo & Kopeinig 2008). This procedure estimates the probability of receiving a treatment, which in this dissertation is filling a parcel of land to prevent flood inundation. The treatment is based on a set of control criteria that ensures appropriate matching of the samples and a reduction of bias by ensuring that only similar parcels are matched together. Previous research has used the PSM procedure to evaluate the effect of flood mitigation activities and for evaluating the impact of the CRS on flood damages at the community level (see Hudson et al. 2014; Highfield & Brody 2017).

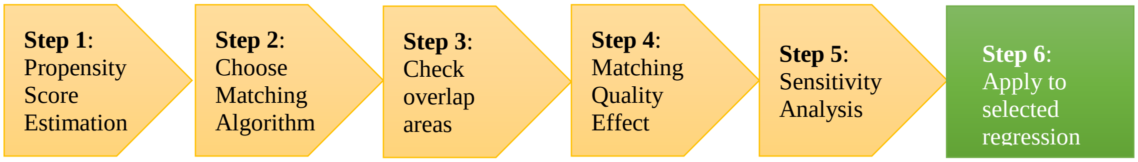


Figure 4.3 PSM Implementation Procedure proposed by Caliendo and Kopeinig (2008) and Ho et al, (2007).

As shown in figure 4.3, the PSM procedure begins by selecting either a logit or probit model for the propensity score estimation. The probit or logit model requires the use of all the independent and control variables for which the matching will be based, and the exclusion of the dependent variable (Caliendo & Kopeinig 2008; Ho et al. 2007). In choosing the matching variables, only variables that influence participation/treatment and eventually the outcome variable should be included in the matching procedure (Caliendo & Kopeinig 2008). The matching process also avoids using an over-parametrized model to prevent the effect of extraneous variables on the treatment (Bryson et al. 2002). When there is no consensus as to whether any of the variables are relevant to the treatment, to avoid 'trimming' of the model, it is often advised to include the variable as much as theory supports them (Rubin & Thomas 1996). Other methods, such as the hit or miss method, cross-validation and over-weighing some variables are alternatives to including different variables for the logit estimation (Caliendo & Kopeinig 2008). The model set up supports using the all the variables in a conceptual framework, except the dependent variable, to conduct the matching procedure.

This dissertation adopted a boosted logistic regression method to estimate the propensity scores. This is because of the large number of independent variables and the possibility of large interactions between the covariates. The boosted logistic regression method uses a machine learning approach which increases the accuracy of the predicted values as compared to the traditional regression method (Schonlau, 2005), an approach that has been shown to increase the explanatory power in studies that use the PSM method (Highfield & Brody, 2017; Schonlau, 2005; Lee et al, 2010).

The second and third step in the matching procedure ensures that the appropriate matching algorithm is adopted. In this step, several options are available; however, the nearest neighbor matching was adopted in this research. To avoid dropping too many matches, the matching was iterated with replacement, while oversampling was permitted so that more than one nearest neighbor will be allowed in the matching. (Smith & Todd 2005; Caliendo & Kopeinig 2008). However, because the nearest neighbor matching faces the risk of poor matches when neighbors are far away from the treatment observation, the nearest neighbor with caliper and radius matching method was used, introducing a tolerance caliper into the model (Smith & Todd 2005; Rosenbaum & Rubin 1983).

The third step was to examine the quality of the match and assess the balance between the control and treatment groups (Caliendo & Kopeinig 2008). A sensitivity analysis was performed after which the combined matched and treated parcels was used in the final regression model in this dissertation. Software commands used in STATA for carrying out the match include *pscore, attnd, attnw, atts, attk* for the propensity score estimation (Becker & Ichino 2002), *psmatch2* for the propensity score matching (Leuven & Sianesi 2015), and *nnmatch* for selecting the distance metrics (Abadie et al. 2004).

4.2.1 Sampling and Matching Results

The Propensity score matching process began by randomly sorting the treated and non-treated cases of all parcels within the watershed. Before the matching process begins, the propensity score is first determined. The boosted logistic regression approach was used to predict the treatment (the use of fill). Several iterations were conducted, and a final maximum iteration was set to be 5,000 and a shrinkage value of 0.001, a bagging value of 0.05, training value of 0.8. The boosting process improved on the regular logistic regression with an increase in r-square from 0.2464 to 0.369. To continue the matching process, the first treated case *i* is followed by the search for the non-treated case *j* within a caliper *E.* As this search proceeds, I find the smallest pairs of the difference (absolute) between the individual cases of treated *i's* and non-treated *j's*, repeating the process until all the matches are found.

The parameters used for the PSM procedure is as follows. The caliper is set as 0.2 of the standard deviation of the initial propensity score (0.2* 0.0435) giving a caliper size of 0.0087. However, because the variance of the propensity score for fill parcels was greater than non-fill parcels, and due to the loss of matched observations, the caliper size was increased to 0.03. This caliper size was selected because it produced the most optimal matching result for this dataset after evaluating several caliper sizes from 0.01 to 0.025. To avoid the loss of observations, the matching procedure was performed with replacement which had no significant impact on the final pooled sample.

After performing the PSM, the balance between the variables was further assessed by comparing the mean of the treated with that of the control groups, and the covariates that appear significantly larger or have a large difference in means. The overall mean bias was 4.3% while the overall median bias was 3.1%. These values are both smaller than the general cut-off values of 10% used in previous research (Highfield & Brody 2017; Normand et al. 2001; Rosenbaum & Rubin 1983). As shown in table 4.1, the standardized bias for most variables is less than 10%, while the bias reduction values are high.

The optimized matching procedure reduced the difference between the means and matched the treatment and control variables as closely as possible. Although the p-value of some variables are significant (e.g. building value, building area, building age and wetland distance), the actual mean differences are small considering the that these variables in general are expected to have low standard deviations. Some of the variables are also expected to have significant differences in their means, for example properties with fill are expected to have a lower stream, wetland and floodplain distances compared to non-fill parcels. Overall, the differences in means for the treated and control variables show the expected relationships from the PSM procedure.

Table 4.1 Bias Reduction from Matching (%)

Variable	Treated Mean N=3165	Control Mean N= 2894	% Bias	% Bias Reduction	P-value for diff (t-test)
Building Value ($)	199483.2	177082.7	12.7	145.9	.000
Building Area (sq. ft.)	2513.387	2421.69	8.7	70.5	.000
Building age (years)	10.813	10.291	4.6	97	.0000
Wetland Distance (ft)	2230.187	2112.243	6.2	82.4	0.003
Stream Distance (ft)	788.0701	781.3431	1.1	96.3	0.209
Pond Distance (ft)	1752.258	1778.166	2.9	89.5	0.421
Floodplain Distance (ft)	1440.905	1271.558	3.2	92.9	0.003
Precipitation Avg (in)	54.62845	54.49271	2.6	96.8	0.208
Slope Average (%)	1.878134	1.846998	0.2	99.7	0.638
CRS Activity 430	179.3925	177.7008	1.0	93.7	0.1

4.2.2 Pooled Sample Statistics

Matching fill and non-fill parcels using the PSM procedure resulted in reducing the sampling frame of 157,000 parcels to a sample size of 6,059 covering the 15-year period of the study in the watershed. The final sample is a balance of fill and non-fill parcels, which is seen by similar mean values of the independent variables of both fill and non-fill parcels. As shown in table 4.1, in some occasions, the differences are significantly different as shown by the p-value of the t-statistic, especially for variables that are fill-specific, for example, the p-values for the difference in the parcel/building characteristics are all significantly different. These differences are expected due to the large sample size of the pooled dataset in this research.

Building value has a 12% bias level between treated and control observations, while building area has an 8.4% bias value with a p-value that is also significant. Building age also has a 4.6% bias level. Although the bias level for these variables is significant, the PSM procedure also reduced the bias level as shown by percent bias reduction of between 70-145% percent for the building variables. On the average, a maximum value of 10 is usually considered appropriate for percent bias in PSM. The selected study samples comprising 6,059 parcels with strict matching procedure that lead to bias reduction and acceptable values for matching treatment and control variables.

Except for wetland distance, the other distance variables show no significant differences between the treated and control observations. The treated mean and control mean values for floodplain distance, stream distance and pond distance show no significant differences. This is also reflected in the percent bias of all the variables with none above 4%. Precipitation, slope average, and CRS score also show no significant differences between the treated mean and the control mean.

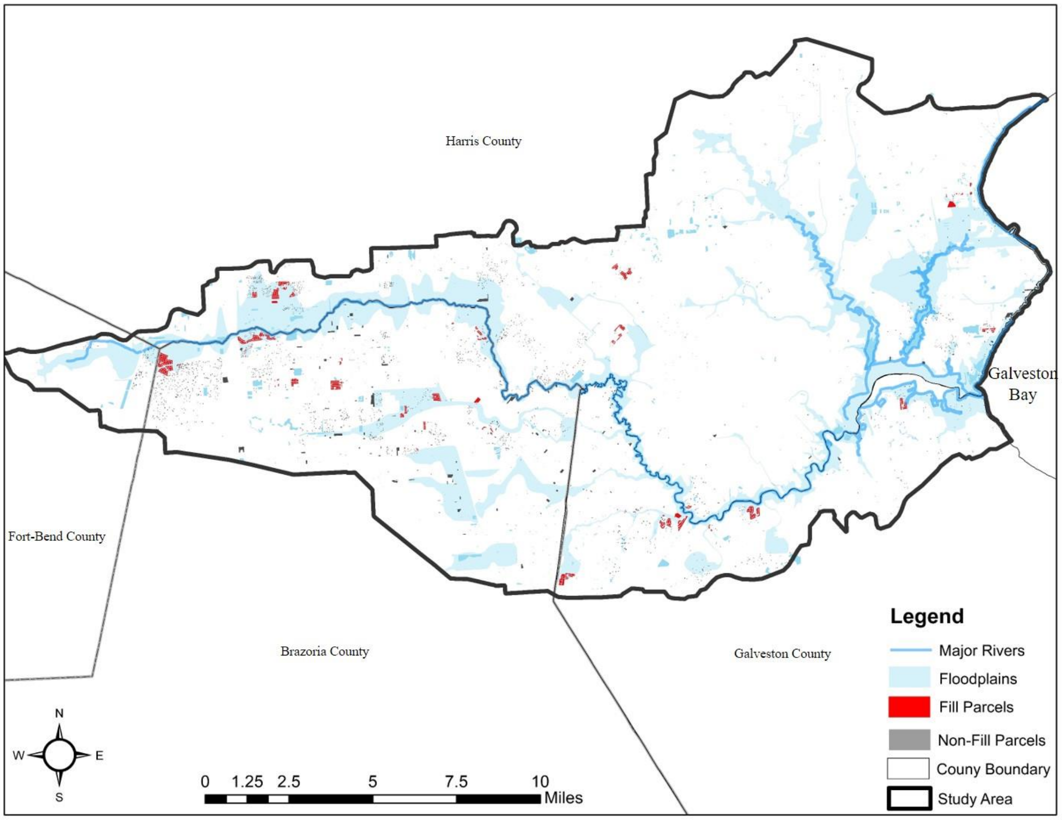


Figure 4.4 Fill and Non-Fill Parcels after PSM

The spatial distribution of the pooled sample is shown in figure 4.4 while the descriptive statistics is shown in table 4.2. This pooled dataset represents a balanced sample that was used for further quantitative analysis. The pooled sample from the PSM shows that over the 15-year study period, a total amount of about $5.6 million was claimed as insured flood damages in the study area with a mean of about $924 per property and a maximum of $332,573. The highest amount of floodclaim occurred in 2008 during hurricane Ike with over $4.3 million in flood claims, accounting for about

77% of floodclaims during the study period. The average annual amount of floodclaim during the 15-year study period is about $373,256.

Table 4.2 Pooled Sample Descriptive Statistics (N= 6,059)

Variable	Mean	SD	Min	Max
Total Damage	924.05	10850.91	0	332,573
Fill	0.5223634	0.4995409	0	1
Building Value ($)	187,782	282041.8	0	2,070,000
Building Area (sq. foot)	2465.488	951.4255	0	9847
Building age (years)	10.5923	5.00147	1	45
Wetland Distance (foot)	2168.577	1602.249	8.923885	10935.14
Stream Distance (foot)	784.5561	545.3934	2.26378	3508.858
Pond Distance (foot)	1765.791	1189.117	0	11055.25
Floodplain Distance (foot)	1352.444	1999.161	0	12457.12
Precipitation Avg (inches)	54.55755	2.462997	51.58861	60.12956
Slope Average (%)	1.86187	1.187124	0	16
CRS Activity 430	125.3821	141.2041	0	522

4.3 Methods for Specific Objectives

4.3.1 Spatial-Temporal Pattern of Parcel Fill

The LOMR-F elevation certificates serve as a proxy for fill. To digitize this dataset for GIS analysis, I used the legal description, physical location, and lowest elevation of the filled parcel components, which led to identifying individual parcel fill locations. Additional parcel information for filled parcels was derived by joining LOMR-F elevation information with the respective county appraisal district parcel's legal description. This resulted in a complete parcel database with fill and appraised parcel information used for the regression model.

After filled parcels were identified, their characteristics, whether they are stand-alone parcel fill or part of combined subdivision fill were examined. This component is important because it is expected that fill characteristics will impact how flood damage is distributed within the floodplain. For example, individually-isolated parcel fills are likely to have a lower impact on adjacent developments than multiple parcel fill. The expectation is that fill will cluster around low lying areas and will resemble individual wetland permits of <0.5 acres and general permits which are both indicators of sprawling development (Brody et al. 2007a).

I began the process with a descriptive analysis of fill permits in the watershed through maps and figures of fill statistics. Exploratory Spatial Data Analysis (ESDA) tools in GIS were used to identify how fill is distributed across different jurisdictions in the study area. ESDA is useful in visualizing distributions spatially and helps identify outliers, clusters, association and spatial autocorrelation (Anselin 1998). This spatial analysis method is receiving increasing use in literature, especially combining a temporal component through space-time analysis to identify spatial and temporal dependencies (Rey & Janikas 2006), and further in this study using a spatial autoregressive model (Anselin 2003).

The space-time interactions of fill parcels were tested using the Mantel index. The Mantel index tests the correlation between distance and time intervals for pairs of incidents (Mantel 1967). The main idea is a correlation test for two dissimilarity matrices between space and time (Mantel & Bailar III 1970). A practical application example is the CrimeStat software which uses the Mantel test and Knox test for space-time crime analysis (Levine 2006). The Knox Index compares the relationship between fill permits in terms of distance (space) and time when fill was used in the parcel (Knox, 1963; 1964). The results generated an output of distances that are close in time, and those not temporally clustered. The results also show parcels that are clustered spatially and those that are dispersed.

The Mantel test is achieved by crossing distance and time interval variables. The crossing is described below:

$$\mathrm{T} = \sum_{j=1}^{N} \sum_{j=1}^{N} (X_{ij} - Mean\,X)(\,Y_{ij} - Mean\,Y)$$

Where X_{ij} is an index of similarity between two observations, i and j, for one variable (e.g., distance) while Y is an index of similarity between the same two observations, i and j, for another variable (e.g., time interval). Furthermore, the cross-product is normalized by dividing each deviation by its standard deviation and generating a mantel index as shown below:

$$r = \frac{1}{(N-1)} \sum_{j=1}^{N} \sum_{j=1}^{N} \frac{X_{ij} - Mean\,X}{S_X} * \frac{Y_{ij} - Mean\,Y}{S_y}$$

Where S_x and S_y are the standard deviations of the space and time distances, respectively, and n is the number of events. The mantel test is basically a Pearson product moment correlation of distance and time and is highly interdependent; so instead of using this traditional correlation coefficient, the mantel test uses a Monte Carlo simulation to derive confidence interval around its index. The hypothesis tested was to determine if time and space distances of fill parcels are interdependent.

4.3.2 Flood Damage Clusters Adjacent Fill Parcels

To identify whether flood claims are clustered relative to fill locations, a bi-variate Ripley's K function for point pattern statistics was analyzed. This is a second-order analysis of spatial autocorrelation that identifies what scale points are aggregated, hyper-dispersed or random (Ripley 1979). This function works by creating Monte Carlo simulations where points are rearranged and randomized to generate a reference distribution and compared to the original point pattern to determine randomness. The bi-variate Ripley's K is modeled by the following equation:

$$K_{12}(t) = \left(\frac{|A|}{n_1 * n_2}\right)\left(\Sigma_i^{n1}\Sigma_j^{n2} w_{ij}^{-1} I_t\left(u_{ij}\right)\right)$$

Where n_1 is the number of points of type 1 and n_2 is the number of points for type 2, A is the area of the plot, I is the counter variable, u_{ij} is the distance between points *i* and *j*, while w_{ij} is the weighing factor to correct for edge effects. This has been used to identify variation across scales for vegetation sizes and to determine competition or facilitation between vegetation (Haase et al. 1996; Dixon 2002). The bivariate analysis cluster examined whether clustering of claims is facilitated by fill. The Ripley's k function creates a confidence interval based on the Monte Carlo simulations to determine what scales are significant.

4.3.3 Flood Damage Difference Between Fill and Non-fill Parcels

To determine the difference between fill and non-fill parcels, a linear multivariate regression model of the pooled dataset provides a second set of analysis while controlling for other important variables. A correlation matrix of all variables in the model was performed and no significantly high correlations were recorded, limiting the possibility of multicollinearity among the variables. As shown in table 4.3, additional regression diagnostics also indicate that there is heteroscedasticity in the model based on the result of the Brueusch-pagan test ($p<0.0001$) and the white test also show significant results for random coefficients ($p<0.0001$).

Table 4.3 Diagnostics for Heteroscedasticity: Random Coefficients

Test	DF	Value	Prob
Breusch-Pagan test	29	162482.3887	0.00000
Koenker-Bassett	29	4964.8505	0.00000
Jarque-Bera	2	1013116.9771	0.00000

When considering whether to use a traditional OLS model, some regression diagnostics are necessary. First, it is important to ensure that there is no violation of the assumption of independent observations, thus a spatial autocorrelation test is necessary to identify the impact of spatial effects in the model (Anselin 1998). The Moran’s I and the Lagrange multiplier (LM) test was used to determine spatial autocorrelation and the test for spatial dependence in the model.

4.3.3.1 Spatial autocorrelation

The initial diagnostics of the residuals of the OLS model indicate that there was significant spatial autocorrelation ($p<0.0001$) from an LM test. The robust LM test for both the spatial lag and spatial error model were also significant indicating spatial effects on the dependent variable of flood loss. The Moran's I test also indicates that there was significant spatial autocorrelation in the model, requiring that the data be analyzed using a spatial autoregressive model (see table 4.4). The LM test statistics also led to the decision to estimate a spatial lag model. (Anselin, Syabri & Kho 2006; Anselin 2004). A spatial lag model accounts for the value of the dependent variable in neighboring locations as an extra explanatory variable (Baller et al. 2001; Anselin, 1998). The spatial lag model is often used where a neighbor's influence is suspected on the outcome of the dependent variable in nearby places (Baller et al. 2001). The spatial lag model is presented in the form of:

$$y = p\mathrm{W}_y + \mathrm{X}\beta + \in$$

Where *y* is a vector of observations on the dependent variable, *Wy* is a spatially lagged dependent variable for weights matrix W, X is a matrix of observations on the explanatory variables, ε is a vector of error terms, and ρ and β are parameters.

Table 4.4 Diagnostics for Spatial Dependence

Test	MI/DF	Value	Prob
Moran's I (error)	0.2377	22.9347	0.00000
Lagrange Multiplier (lag)	1	619.6186	0.00000
Robust LM (lag)	1	133.9779	0.00000
Lagrange Multiplier (error)	1	517.0482	0.00000
Robust LM (error)	1	31.4074	0.00000
Lagrange Multiplier (SARMA)	2	651.0260	0.00000

Spatial effects were accounted for by calculating a spatial weight matrix. The distance matrix of 250 meters was used and found to be the most optimal for the spatial lag model after multiple sensitivity analysis.

The nature of the data restricts the use of other modeling types. For example, flood damages per parcel could occur for a parcel only once within the study period, or not occur at all in the case of some fill parcels. As a result, using a linear panel regression model is inappropriate for this research. A cross-sectional time series model is also not a good alternative to answer the research questions. This is because the time-series will be based on the year of fill, and since there are several non-fill parcels in the sample, a temporal variation based on fill will not produce viable results. Using a time series based on year of damage will also not be optimal since a high percentage of the sample do not have flood damages. The temporal variation in the data is adjusted by adding a dichotomous variable that represent the year of the flood claims to the spatial model. Based on the model in this study, tests for contemporaneous and serial autocorrelation are unnecessary.

4.4 Validity Threats

Like many other well-designed studies, this dissertation is not free of validity or reliability threats. Several efforts were made to avoid these threats; recognizing areas that such threats still exist are essential in a dissertation of this scope. Validity specifically addresses threats that will affect inferences made by the statistical analysis. This dissertation only addresses threats dealing with statistical conclusion validity, internal validity, external validity, and construct validity (Cook, Campbell & Day 1979).

4.4.1 Statistical Conclusion Validity

Statistical conclusion validity deals with how the researcher uses statistics to make correct conclusions regarding the null hypothesis. This validity type addresses an issue like the statistical power to detect effect size, the possibility of saying there is an effect when an effect does not exist, and the confident estimation of the slated effect of the variables. Although low sample size and power was not a problem in this research, there are other statistical conclusion validity issues that this research faces. Maxwell and Delaney (2004) noted additional statistical conclusion validity issues such as high variability in the variables, and liberal biases where one is overly optimistic that a relationship occurs or even exaggerating its strength. For the impact of fill on adverse flood damage, one might be ‘overly optimistic’ that fill contributes to adverse flood impacts, because it is widely believed but not empirically determined. Other threats such as high variability between fill and non-fill parcels were controlled by using the propensity score matching procedure to ensure optimal matching of treated and control variables

4.4.2 Internal Validity

Internal validity describes the situation where the researcher infers that there is a relationship between two variables regardless of what they represent theoretically. An internal validity threat of concern in this research is Maturation. Maturation occurs when the observed changes occurring for an event is because of naturally occurring processes or another account rather than the slated effect from the dependent variable (Maxwell &

Delaney 2004). In this dissertation, flood damages may be on the rise due to other factors other than fill. Flooding is a natural phenomenon whose effect can be controlled by a variety of factors that might not be accounted for in the regression model. There is also the possibility that the independent variables are influenced by other local and regional ecological factors that cannot be realistically captured in the regression model. However, this internal validity issue was addressed by ensuring that variables that theoretically impact flood damage are controlled for in order to measure the effect of fill on flood damages in the regression model.

4.4.3 External Validity

This validity threat deals with the generalization of the outcome of a research to other study areas. External validity affects this study because the Clear Creek watershed has unique characteristics which may limit the application of the findings in this research to other watersheds in the US. For example, some watersheds in the U.S. have steeper slopes and different physical conditions which may limit or accelerate the impact of fill on flood damages. The results of this research are best applied and generalized to areas with flat topography and closer to urban areas where the pressure to develop and fill floodplains is high. Other watersheds may have a different approach to the use of fill and other flood mitigation methods relating to fill than those employed in the Clear Creek watershed which may affect the generalization of the results of this research to such watersheds.

4.4.4 Construct Validity

Construct validity describes the situation where there is an agreement between the theoretical framework and the measurements used to describe that relationship. This can be eliminated by ensuring that literature is properly reviewed to identify how the variable can be measured, the possibility that the method of measuring the variable in the research may not be the correct representation of the variable. In this research, insured flood claims are used as an indicator of flood damages, whereas, there is no perfect data available to capture actual flood damages from flood events, especially since damages from other parcels that are not part of the NFIP will not be accounted for in the model. The alternative to that is to perform flood damage estimation using eco-hydrologic models, but those also have serious flaws (Tate et al. 2014). Till date, insured flood claims are the best available data to capture actual losses from flood events. Additionally, the primary independent variable, fill, is determined by LOMR-F elevation certificates, which is an indicator of fill but not a substitute for actual elevation change that can be derived from other methods. There is also the possibility that newly approved parcel elevations may not be properly implemented during the building construction process. However, linking fill data with parcel data corrected some of the data gaps or misrepresentations in the LOMR-F elevation certificates.

4.5 Reliability Threats

Reliability is threatened when there are inconsistencies in the data collection process due to human error, instrument error and so on. A reliability problem in this research was the digitizing of LOMR-F certificates. Although word processing software was used to pull texts into spreadsheets, some manual cleaning and arrangement could have led to misrepresenting the numbers. The process of linking LOMR-F and appraised parcel data may also have caused some data inconsistencies that are critical to the information represented for each unit of analysis. However, this was addressed by conducting appropriate statistical diagnostics that will address the influence of outliers and missing values to make the research more reliable.

5. EXPLORING THE SPATIAL AND TEMPORAL PATTERN OF FILL IN THE CLEAR CREEK WATERSHED

This section explores the distribution of fill across several communities in the Clear Creek watershed, including the characteristics of the type of fill used. There are two major subsections in this chapter. The first examines the descriptive statistics and graphics on fill in the Clear Creek watershed; the second section explores the spatial distribution of fill and the temporal patterns observed using ESPDA tools like the Knox Index, Mantel Index, and Ripley's-k analysis to analyze fill and flood claim clusters.

5.1 Descriptive Statistics of Fill in the Clear Creek Watershed

The LOMR-F permit categorize fill into four major types. *Property* is used when the entire parcel has been raised above BFE, *Describe*d is used when parts of subdivisions on the parcel is filled and the area filled is described in the certificate. This usually occurs for large properties. *Portion* is the term used when only part of a parcel is filled, while *Structure* is used when only the area where a building is constructed only is filled on a parcel.

Fill data was computed over the 15 years of the study period (see table 5.1) in the watershed with a total of 3,165 permits issued. Almost 76 percent (2,406 permits) of the parcels that were filled had the entire property removed from the floodplain, while about 10 percent (318 permits) have a described part of the parcel filled throughout the study period. Almost 8 percent (247 permits) of the parcels in the watershed have just portions of the property filled in the clear creek watershed during the study period. About 6 percent (193 permits) have only the land where the structure is constructed filled within the watershed.

Table 5.1 Distribution of Fill by Year and Type of Fill in the Clear Creek Watershed from 2000 to 2014

Type	Property		Described		Portion		Structure		**Total**	
Year	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent
2000	101	36.07	179	63.93	0	0	0	0	**280**	**8.85**
2001	193	64.55	0	0	0	0	103	34.45	**299**	**9.45**
2002	36	29.75	0	0	0	0	83	68.60	**121**	**3.82**
2003	0	0	0	0	0	0	0	0	**0**	**0**
2004	170	70.54	69	28.63	2	0.83	0	0	**241**	**7.61**
2005	743	92.07	48	5.95	16	1.98	0	0	**807**	**25.50**
2006	146	98.65	0	0	0	0	2	1.35	**148**	**4.68**
2007	867	82.49	0	0	183	17.41	1	0.10	**1,051**	**33.21**
2008	54	67.50	0	0	22	27.50	4	5.00	**80**	**2.53**
2009	0	0	0	0	0	0	0	0	**0**	**0**
2010	88	100	0	0	0	0	0	0	**88**	**2.78**
2011	0	0	0	0	0	0	0	0	**0**	**0**
2012	0	0	0	0	1	100	0	0	**1**	**0.03**
2013	0	0	0	0	0	0	0	0	**0**	**0**
2014	4	8.163	22	44.90	23	46.94	0	0	**49**	**1.55**
Total	**2406**	**75.89**	**318**	**10.05**	**247**	**7.80**	**193**	**6.10**	**3165**	**100**

Figure 5.1 also shows the spatial distribution of fill and the type of fill used in the watershed throughout the study period. Filling entire properties and raising them above BFE dominate most of the communities in the study area, especially in the Pearland area on the western end of the watershed. Many parcels in the Friendswood area also experience entre parcels being filled. The contiguous nature of the parcels being filled indicates that these are possibly subdivisions where new residential development is expected to occur at the time of filling. Structure only filling are also concentrated in the

Pearland area and not as common in other communities in the study area. Portions of parcel fill and described portions are also distributed across the study region without visible clusters of those fill types. As expected, most of the fill irrespective of the type falls within the SFHA in the watershed.

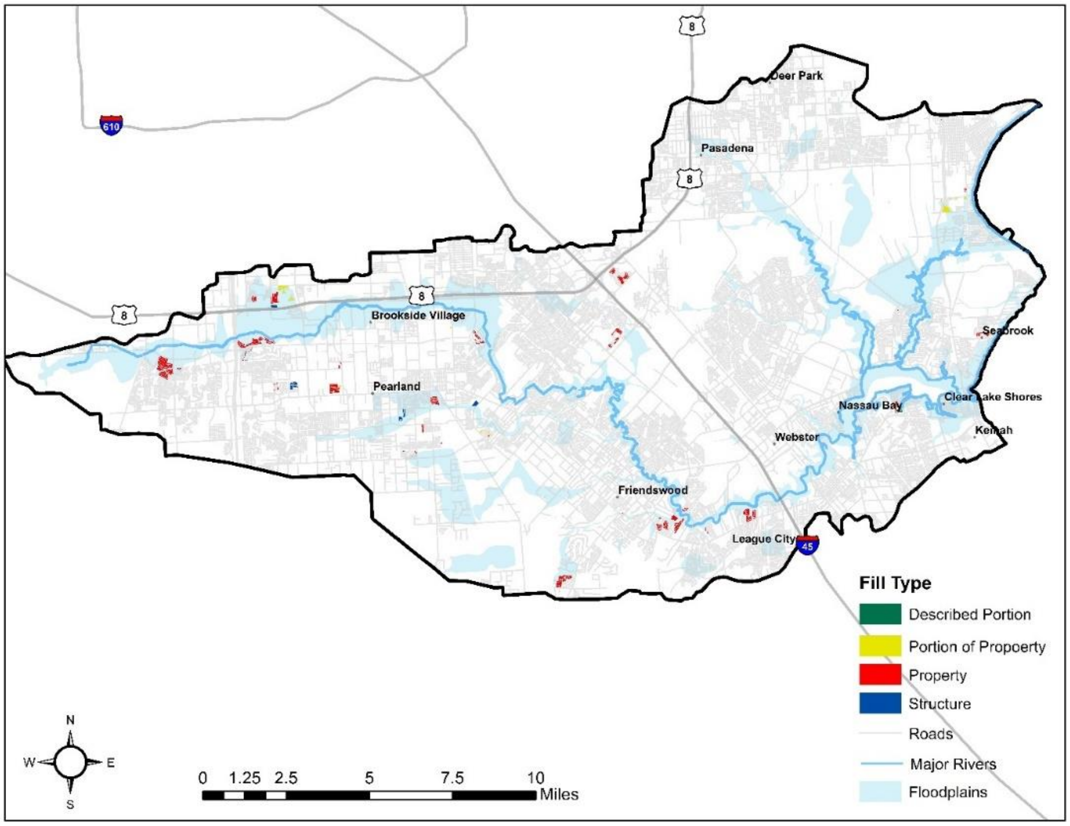


Figure 5.1 Distribution of Fill Parcels in Study Area by Fill Category.

Figure 5.2 shows the temporal trend of fill permits from 2000 to 2014. A total of 280 parcels were filled in 2000, while the number increased to 299 permits in 2001, the year of tropical storm Allison. Fill use dropped to about 121 permits in 2002, and no permits granted in 2003. The number of fill permits rose afterward as an additional 241 permits were granted in 2004 and further increased to 807 permits in 2005. There was a slight drop in the number of permits in 2005, however, the peak of filling in the clear creek watershed occurred in 2007 with over 33% (1,051 permits) of the fill in the 15-year period occurring in that year alone, the year before hurricane Ike. On the year of hurricane Ike in 2008, only 80 permits were granted in the watershed and no permits were granted in 2009. A total of 88 permits were granted in 2010. The final year in the study shows about 49 fill permits have been issued in the watershed.

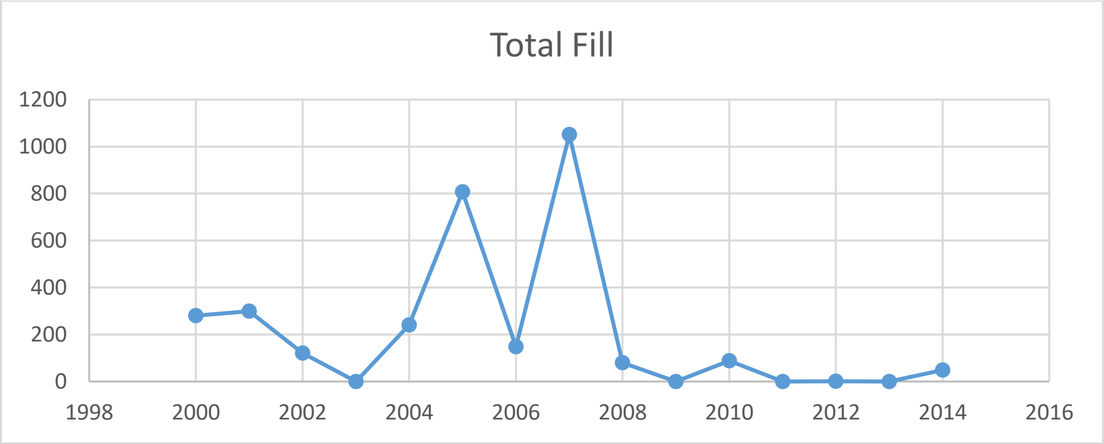


Figure 5.2 Temporal Trend of Fill Permits in the Clear Creek Watershed from 2000 to 2014.

Fill permits vary by community. As shown in table 5.2 and figure 5.3, the city of Pearland has the largest number of fill permits of about 1,350 with the mean year of 2003. Pearland continues to grant fill permits until the last year of the study period of 2014. The unincorporated areas of Harris county scattered around different areas of the watershed is second in the number of fill permits granted with a total of 684 permits granted through the 15-year study period but with the last fill permit granted in the watershed in 2007. League city ranks third with a total of 293 permits. Unincorporated areas of Brazoria county continue to use fill until the end of the study period in 2014 with a total of 250 permits. The city of Friendswood also has 238 fill permits in the clear creek watershed. The individual fill parcels are also highlighted for the Friendswood and Pearland areas in figure 5.5 and 5.6.

Table 5.2 Fill Permits by Community

Community	Fill Number	Avg BFE (ft)	Fill Elevation	Mean Year	Last Year of fill	Avg Property Value ($)	Avg Building Area sqft	Floodplain percent
Pearland	1350	50.69	51.56	2003	2014	204,793	2,543	18%
Harris	684	46.59	46.74	2007	2007	97,635	1,781	28%
League City	293	11.57	10.81	2004	2007	208,815	3,181	17%
Brazoria	250	45.53	49.73	2006	2014	168,541	2,210	19%
Houston	244	44.21	32.07	2007	2007	119,635	1,944	10%
Friendswood	238	7.72	8.11	2000	2008	299,866	3,604	18%
Seabrook	64	11.59	11.93	2007	2008	164,077	2,326	29%
La Porte	42	12.29	11.92	2008	2012	64,703	1,062	10%
Total	3165							

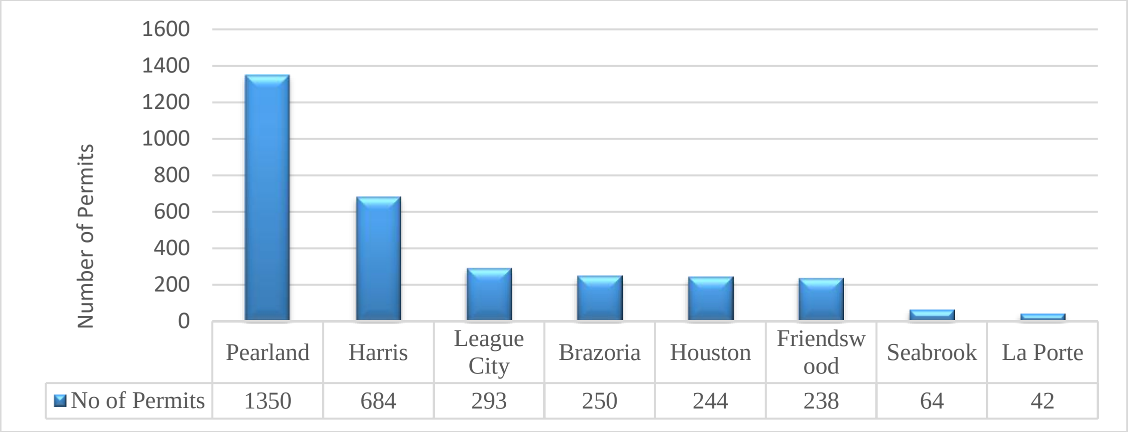


Figure 5.3 Fill permits by community

As shown in table 5.2, communities with a high percentage of floodplain seem to allow lots of fill, for example, Pearland has almost 20% of its land area within the floodplain while Harris County has about 28% of floodplain area in the clear creek watershed. In contrast, Seabrook has the highest percentage of floodplain area in the watershed, however, a low number of fill permits, possibly because of the area of the city that falls within V-zones and the floodway. Property values average between $64,703 to $299,866 while the area of the buildings constructed on filled parcel average between 1,062 and 3,604 per square foot. Base flood elevation also varies. Comparing averages between BFE and lowest lot elevation for filled parcel shows little variation between the elevations. On average, a difference of just about 1 foot is observed where parcels or sections of parcels are barely above the BFE.

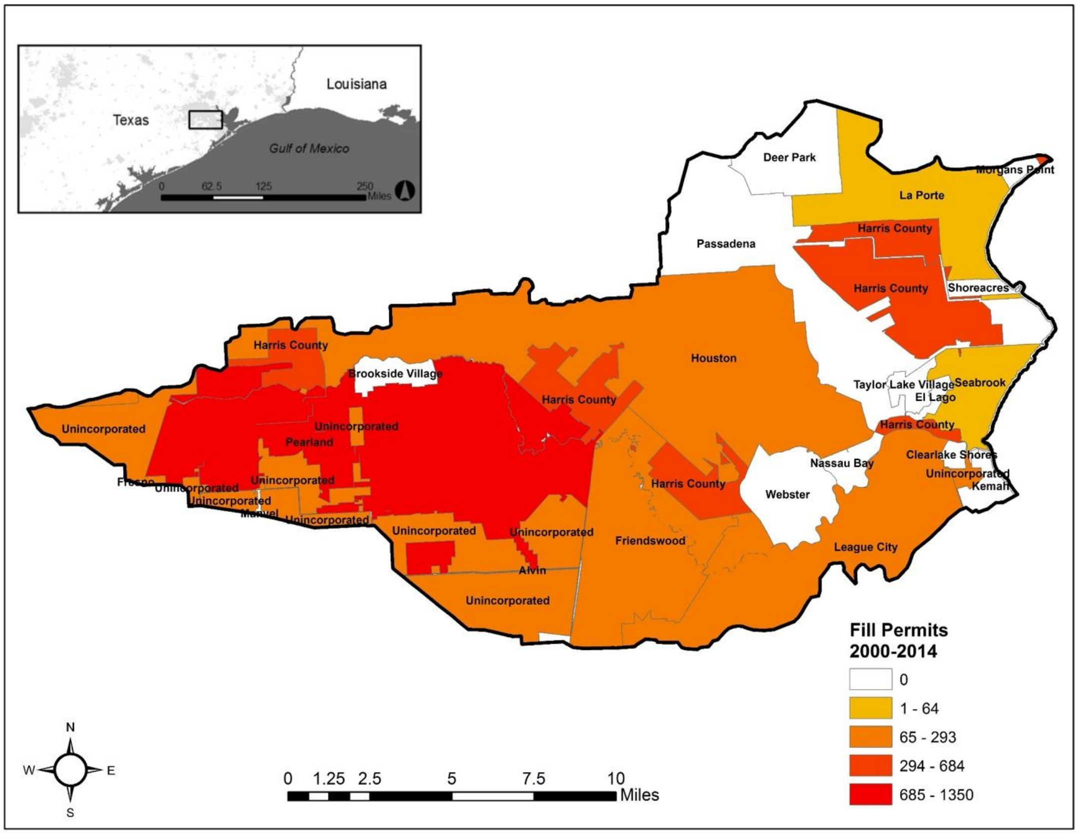


Figure 5.4 Number of Fill Permits per Community in the Study Area.

One of the major characteristics of fill in the study area is that a contiguous number of fill parcels are clustered in different subdivisions in the study area. For example, as shown in figure 5.4, rather than pockets of fill distributed across different parcels in the study area, clusters of fill exist in subdivisions and are pronounced within the floodplain. Although individual pockets of fill can be observed, most fill use is in subdivisions and neighborhoods within the floodplain in the study area.

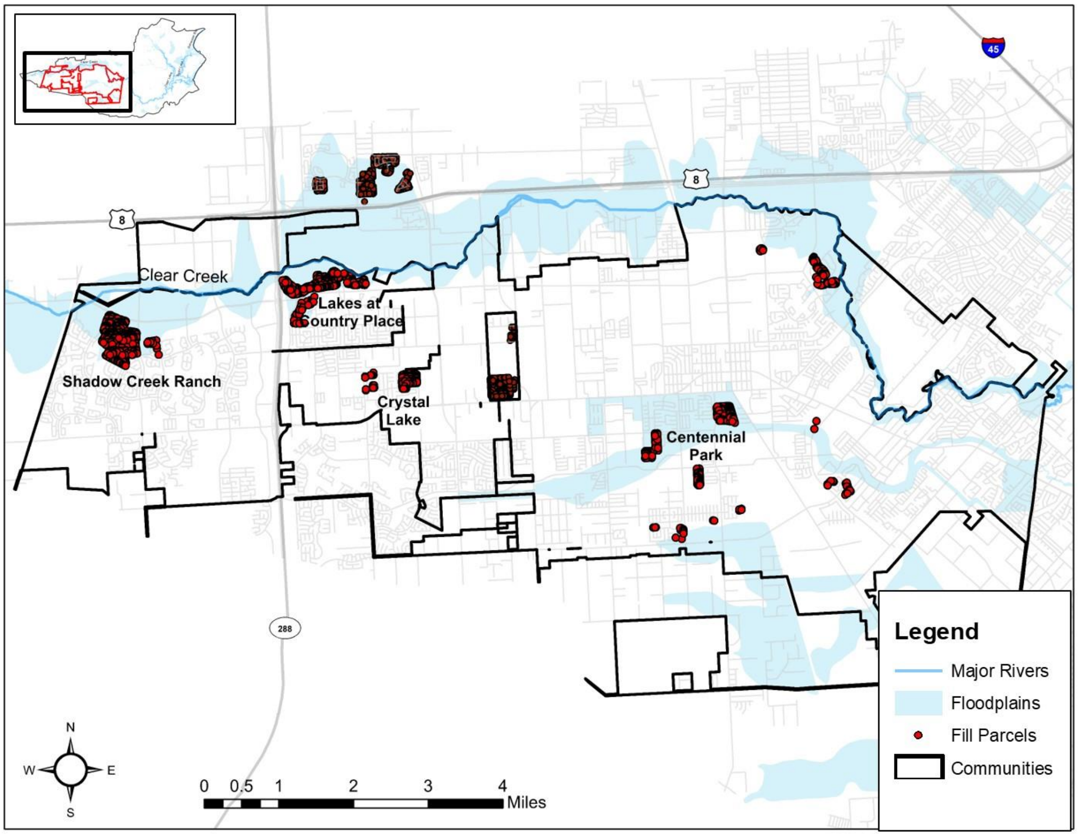


Figure 5.5 League City Fill Clusters.

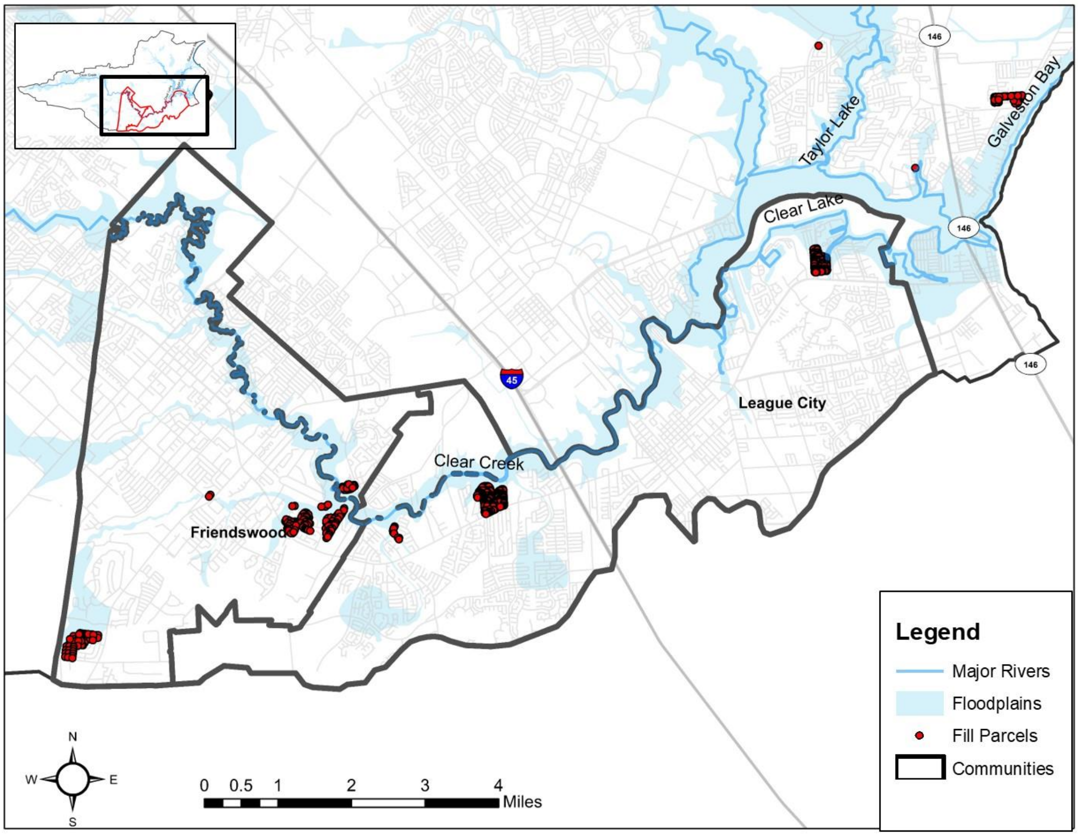


Figure 5.6 Friendswood Fill Clusters.

5.2 Spatial-temporal Analysis of Fill in the Clear Creek Watershed

This section describes the spatial and temporal pattern of fill in the study area using the spatial statistics method of the nearest neighbor index, the Knox index, and Ripley’s k analysis. These methods, as discussed in chapter 4, are used to examine the spatial clusters of fill using spatial autocorrelation techniques to identify whether the use of fill in the watershed is clustered in space and time.

5.2.1 Spatial and Temporal Relationship between Fill Permits

The first process was calculating the nearest neighbor analysis which helped to identify distances between granted permits and test for randomness between them. This test was conducted to determine if distances between fill parcels are random, i.e. by chance, or clustered, and gives a sense of a continuous use of fill in a subdivision to provide extensive protection from flooding.

A significance test was carried out to examine whether the average nearest neighbor distance is significantly different than it would be expected based on chance. This nearest neighbor index was computed for the different types of fill in the study area as well as for all filled parcels combined. As shown in table 5.3, the dispersal distance calculated shows that for all parcels filled in the study area, there is a mean nearest neighbor distance is 22.12 meters while the mean nearest neighbor distance under randomness is about 234 meters. The nearest neighbor index, i.e. the ratio of the actual to the random nearest neighbor distance, was 0.0943, with a significant Z-value. This implies that the distribution of the nearest neighbors of all fill parcels in the clear creek watershed is significantly smaller than what would be expected by randomness. All type of parcel fill irrespective of the method has significant clusters as indicated by the nearest neighbor index less than 1 for each case.

Parcels with the entire property filled have the lowest mean nearest neighbor distance of 19.35 meters compared to other fill types, while structure fill has the highest mean nearest neighbor distance of 75.75 meters. Examining the nearest neighbor index seem to imply that parcels with entire property fill are more clustered in space than to other parcel fill types. On the other hand, examining the relative nearest neighbor indices (i.e. comparing the nearest neighbor indexes) show that portion parcel fill and described parcel fill tend to also be clustered around themselves.

Table 5.3 Nearest Neighbor Analysis of Fill Parcels in the Study Area

Fill Type	Sample Size	Mean NN distance	NN Index	Mean Random Distance	Mean Dispersed Distance	Standard Error	Test Statistic
All	3165	22.1188	0.0943	234.54	504.04	2.18	-97.4756***
Described	318	25.07	0.03388	739.92	1590.14	21.69	-32.9591***
Portion	245	22.6681	0.02689	842.98	1811.61	28.15	-29.1391***
Property	2407	19.3532	0.07196	268.94	577.98	2.87	-87.1032***
Structure	193	75.7541	0.0798	949.78	2041.13	35.74	-24.4574***

Note: P-Value 1 and 2 tailed: *p <0.05; **p <0.01; ***p <0.001.

One thousand simulations were computed for the Knox index to produce a better test of significance of the results. Distance and time were divided by the mean distance and mean time interval. Table 5.4 shows the result of the Knox index, which compares the relationship between fill permits in terms of distance (space) and time when fill was used in the parcel. Since this is a one-tailed test, the upper threshold of the 95th percentile was compared to the observed chi-square value to test for the significance of the Knox index. The cases where the observed chi-square is higher than the 95th percentile show a significant relationship between space and time clusters of fill parcels. If the observed chi-square is larger than the 95 percentiles, we reject the null hypothesis. The Knox index for all the permit types was statistically significant with the actual /observed chi-square larger than the 95-percentile value, thereby indicating that the fill permits are both close in distance and time. This is also the case for the other fill types with the property fill type having the highest chi-square value.

Like the nearest neighbor analysis, the Knox index also shows that the fill parcels are close in distance with a mean distance closeness of about 14 meters for fill parcels in the watershed. They are also close in time as fill parcels that are clustered spatially also tend to be clustered temporally at an average of about 3 years for all parcels and even less clustered temporally considering individual fill types.

Table 5.4 Pseudo Significance Levels for Knox Index

Fill Type	Sample Size	Actual Chi-Square	Observed chi-squares	Closeness in distance (m)	Closeness in time (years)
All	3165	47092.31	84.70085***	13,434.20	3.08896
Described	318	423.74173	9.30403***	15,659.57	3.97
Portion	245	4481.17	8.90397***	7,833.90	1.65861
Property	2407	6767.76	59.09815***	13,403.27	2.39
Structure	193	17535.89	8.16555***	4,029.55	0.87

Note: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

5.2.2 Relationship between Fill Clusters and Flood Claims Clusters

The Ripley’s k statistic was used to test the non-randomness across different scales, in this case between fill parcel and floodplain clusters. It is a super-order analysis of nearest neighbor spatial autocorrelation across varying distances and a good indicator of local clustering. This method performed a univariate and a bivariate analysis to explore the spatial relationship between fill parcels and the spatial relationship between fill and flood claims.

Using a 1% maximum scale, step distance of 10 meters, and a randomization test of 99 iterations, a univariate analysis showed that fill parcels also cluster up to a distance of 410 meters (figure 5.7). Increasing the dataset percentage to 5% and the step distance to 50 meters indicate that fill continues to cluster up to 2,000 meters, but the clusters reach its peak at about 800 meters (figure 5.8).

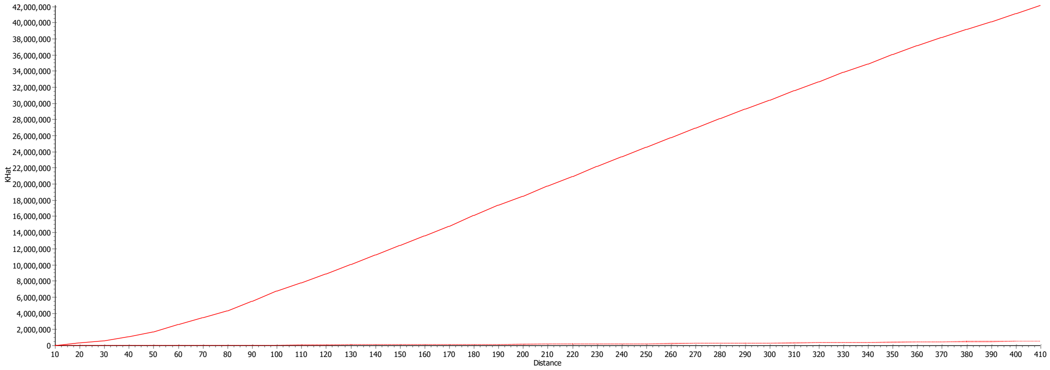


Figure 5.7 Ripley's K Analysis with Step Distance of 10 meters and 1% Dataset Level

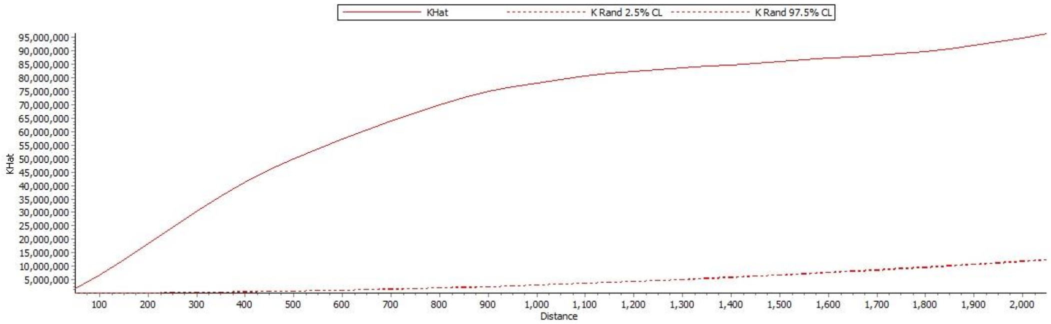


Figure 5.8 Ripley's K Analysis with Step Distance of 50 meters and 5% Dataset Level

Bivariate analysis of fill clusters relative to flood claim clusters also show significant relationships. We can be 95% confident that clusters of fill to flood claims does not occur by chance (see figure 5.9). This analysis is a bivariate analysis of a maximum scale of 5%, step distance of 50 meters based on 99 iterations of all fill parcels and 14,756 flood claims in the study area. As shown in figure 5.10, the significant relationships indicated by the Ripley's-K analysis are seen from the clusters of fill parcel locations to a kernel density cluster analysis of flood claims in the study area.

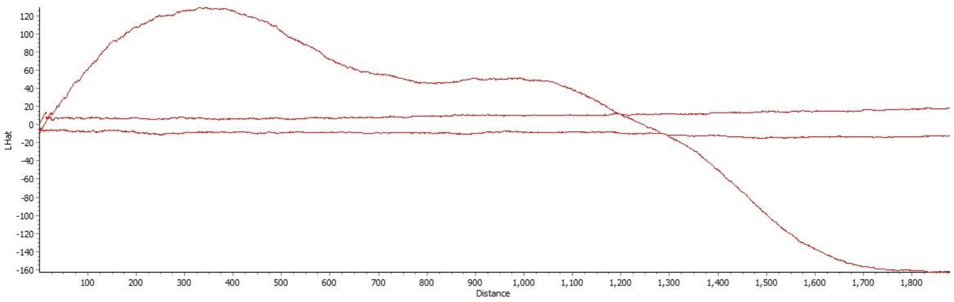


Figure 5.9 Bi-variate Ripley's Analysis of Fill Parcel Clusters and Flood Claims Parcel Clusters.

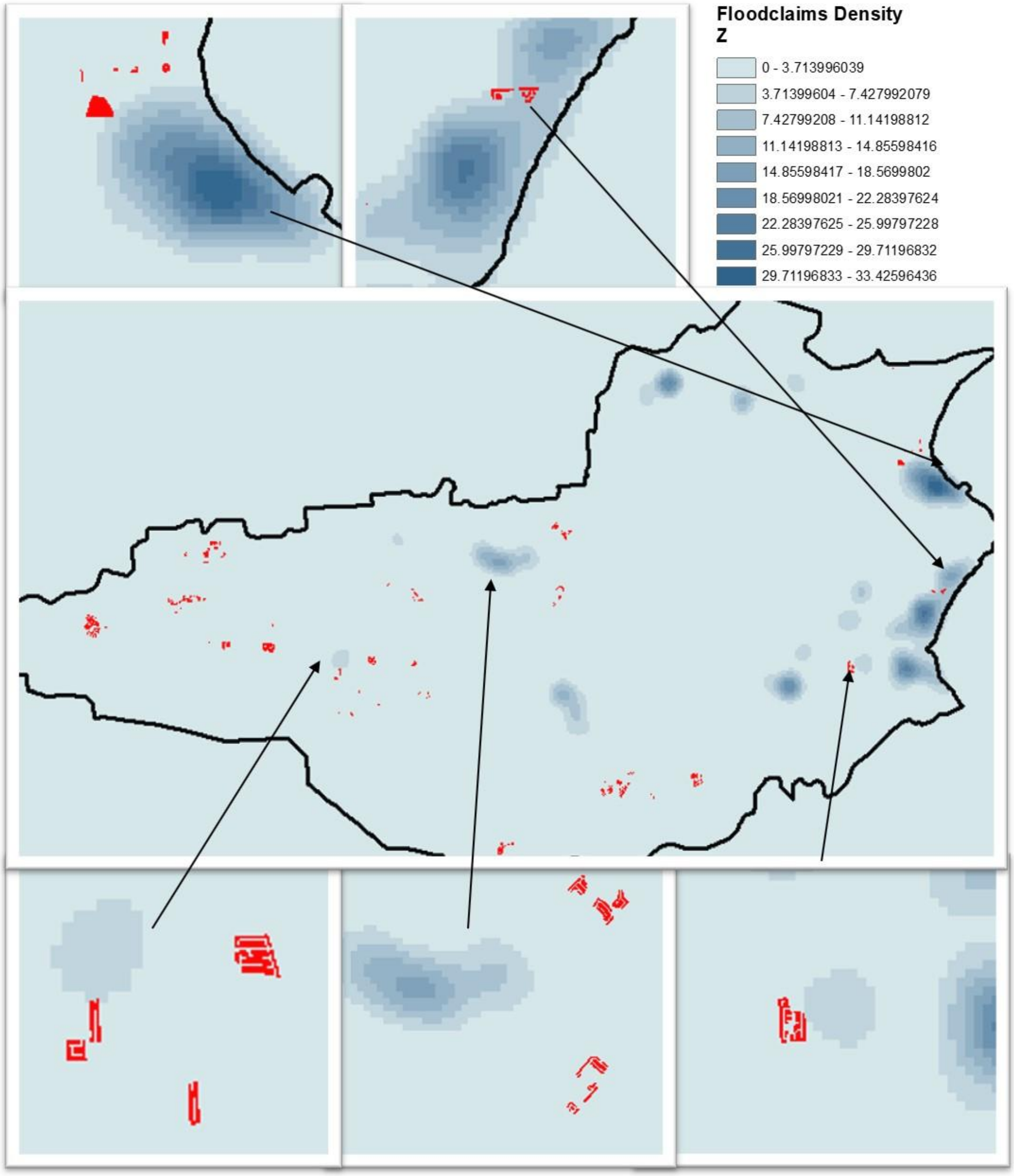


Figure 5.10 Kernel Density Clusters and Fill Clusters in the Study Area.

5.3 Summary of Spatial-temporal Analysis of Fill Permits

Examining the descriptive statistics of fill in the Clear Creek watershed highlight some important details about the flood mitigation technique. First, the percentage of fill type used indicate that a large number of entire parcels are being filled in the floodplain rather than portions of parcels. Described, portions, and structure type fills are only a smaller percentage, a combined 24% of fill, compared to entire property fill of over 75% in the watershed. This result implies that fill is not just being used in individual cases of flood mitigation, but as an approach to removing large portions of land from the floodplain. Additionally, communities with large numbers of fill permits also tend to have a higher mean building square footage, meaning that large areas of land within the floodplain are been developed.

Second, the number of fill permits granted also vary by the community. Some communities have stricter laws that make it difficult for fill to be used or for permits to be granted. As shown in figure 5.4, the communities further inland of the watershed, especially major suburbs of the metro Houston area, have the highest amount of fill permits approved. Pearland leads the way while most communities within Brazoria County in record significantly high number of fill parcels during the study period. La Porte experiences the least amount of fill in the entire watershed. Out of the twenty communities in the watershed, only 8 have approved fill permits between 2000 and 2014. This trend shows that some communities maintain the same requirements for fill while others are becoming stricter in their regulations, thereby the reducing trend in the number of fill used.

Another observed trend is that after a major storm event like Hurricane Ike and Tropical Storm Allison, the number of fill permits granted in the following year is low, but the permits granted tend to increase subsequently. There is no statistical analysis to observe this trend, but the spatial-temporal analysis of fill permits shows a closeness in time of about 3 years which implies that there is generally not so much a break in time in terms of granting fill permits. Notably, though, the number of fill permits granted towards the end of the study period drops compared to the peak occurring around 2006 and 2007, but an additional examination of the fill requirement and other socio-economic conditions in the area is essential to identify the reason for this reduction. A closer examination of current fill permits is important to identify whether the drop in the number of fill in the study area continues.

Third, the floodplain area of the communities in the clear creek watershed is rather high with some communities having almost 30% of their land within the SFHA. Considering the amount of land in the floodplain and the pressure to build and profit from property taxes, there is no surprise that these communities allow extensive use of fill in the floodplain. Unincorporated areas of Harris County historically have large amounts of fill parcels, but recent improvements in the fill requirements have led to a reduction in the number of fill permits granted. The city of Pearland continues to expand and with a large percentage of the land in the floodplain, that explains the number of fill permits granted within this period. There are other areas in the Fort Bend County of the watershed towards the western end that also have large amounts of floodplains, with relatively few developments that are expected to fill if fill regulations are lax and the pressure to develop in this area continue.

Fourth, the univariate analysis of fill shows that fill parcels are clustered up to about 700 meters. This shows that clusters of fill occur in the watershed with fill occurring mostly at the subdivision level. More importantly, the bi-variate analysis shows significant clustering of fill relative to floodclaim locations. Since we can be 95% confident that the clustering of fill relative to floodclaim is not by chance, important questions on the role of fill in exacerbating flood damages need to be considered. The Ripley's k analysis indicates that flood claims cluster relative to distances of about 2,300 meters away from fill locations. The distance between fill locations and flood damages continue to provide additional details that adjacency of fill parcels to other non-fill parcels can give rise to additional flood damages over time. A further analysis of the difference between fill and non-fill parcels will examine whether there is a significant difference between them in terms of on-site flood damages.

6. EXPLAINING THE EFFECT OF FILL ON FLOOD DAMAGES

As described in Section 4, the PSM procedure showed the treatment effect of fill. On the average, the use of fill on parcels lead to a 23% reduction in flood loss in the clear creek watershed. Additional measures are also necessary using a second-order analysis of spatial regression models and control for temporal variations. This section discusses the results of the spatial autoregressive model in examining the difference between fill and non-fill properties in relation to flood loss. Additional control variables in the model are also be examined to identify their impact on flood damages.

6.1 Modelled Result for a Spatial Autoregressive (SAR) model

The multivariate regression model is statistically significant ($p<0.00001$) while the independent variables explained 66% of the variance in flood loss from the pooled sample in the watershed, with an r-square of 0.6605. Table 6.1 represents the results of the regression model. Fill is negative and significant at $p<0.001$ level two-tailed which supports *Hypothesis 1* that on the average, holding other variables constant, fill parcels will experience significantly lower amounts of flood damage than non-fill parcels. Other parcel-level characteristics also show significant differences with respects to flood damages. The value of the building relative to flood damage was also significant at $p<0.05$ and the model show that holding other variables constant, higher building values will lead to larger dollar-amounts of property loss. The area of a building also shows a significant negative relationship with flood loss at $p<0.001$ indicating that larger buildings experience significantly lower amount of property loss from flooding. Building age is not a significant predictor of flood loss, where $p>0.05$.

Parcel proximity variables show mixed results in relation to flood loss. For example, wetland distance does not significantly predict flood loss ($p>0.05$). Surprisingly, distance to compensatory storage like retention ponds have a positive impact on flood damages, however, this effect is not significant ($p<0.05$) and does not support *Hypothesis 11*. Distance to the stream is statistically significant at $p<0.05$ which also supports *Hypothesis 10* and indicates that properties farther from stream locations will experience significantly lower amount of flood loss, holding other variables constant. Distance to the edge of the floodplain is also significant at $p<0.05$ which supports *Hypothesis 8* with the expected negative relationship and indicates that parcels farther from the edge of the SFHA experience significantly lower amount of flood loss.

Other natural environment factors also show significant relationships. Precipitation is a significant predictor of flood loss at $p<0.001$ with a positive relationship that supports *Hypothesis 12* and indicates that parcels experiencing higher amounts of precipitation incur significantly higher amounts of flood losses. The slope of the parcel also shows significant relationship at $p<0.05$ and supports *Hypothesis 7*, showing that steeper parcels experience significantly lower amount of flood damages. Finally, as expected the CRS activity relating to fill also have a negative relationship with flood losses at $p<0.001$, supporting *Hypothesis 2* and indicating that parcels in communities with higher CRS scores for fill requirements experience significantly lower amount of flood losses.

Table 6.1 SAR Result for Total Damage

	Model 1			Model 2		
Log Damage	Coeff	Std.Err	Z	Coeff	Std.Err	Z
Fill	-0.0755	0.01744	-4.33245***			
Building Value (log)	0.01034	0.00607	1.70356	0.0113928	0.006260	1.81985
Building Area	-0.00005	0.00001	-4.41562***	-0.0000515	0.000012	-4.4104***
Building age	-0.00587	0.00198	-2.95495**	-0.0058395	0.002001	-2.91861**
Wetland Distance	-0.00001	0.00000	-1.66328	-0.0000099	0.000006	-1.64533
Stream Distance	-0.00006	0.00002	-3.40227***	-0.0000539	0.000017	-3.21739**
Pond Distance	0.000001	0.00001	0.166991	0.0000020	0.000008	0.25144
Floodplain Distance	-0.00010	0.000005	-2.03443*	-0.0000098	0.000005	-1.98787*
Precipitation Avg	0.021025	0.00455	4.61596***	0.0215529	0.004615	4.67004***
Slope Average	0.006226	0.00775	0.803065	0.0066787	0.007783	0.85816
CRS Activity 430	-0.001104	0.00018	-5.99316***	-0.0011182	0.000185	-6.04554***
Fill Type						
Property				-0.0818697	0.018721	-4.37307***
Described				-0.0614223	0.040997	-1.49822
Portion				-0.0458783	0.047215	-0.97170
Structure				-0.0555821	0.052053	-1.06781
Damage Year						
2001	6.90000	0.15431	44.7126***	6.89962	0.1543	44.70870***
2008	5.67495	0.06814	83.2810***	5.67514	0.0681	83.27760***
2009	8.20269	0.27431	29.9028***	8.19939	0.2743	29.88230***
Constant	-0.77865	0.25726	-3.02665**	-0.8197	0.2633	-3.11295***
Rho	0.314789	0.00913	34.45960***	0.31466	0.0091	34.44430***
	N= 6059 R^2= 0.743			N= 6059 R^2= 0.661		

Notes: *p <0.05; **p <0.01; ***p <0.001

6.2 Regression Results for Structure and Content loss

This section summarizes the results of the fully specified model in the analysis for building and content loss individually with the summary of significant variables and their coefficients shown in table 6.2. For building structure as the independent variable, fill parcels on the average have about 7% less damage from flooding than non-fill parcels ($p<0.001$) while content is only reduced by about 4% ($p<0.05$). Stream distance and pond distance are also statistically significant control variables for structure damage ($p<0.001$), however only stream distance ($p<0.05$) is statistically significant for content damage. While CRS score is significant ($p<0.001$) for structure damage, CRS is not a statistically significant predictor of content damage, holding other variables constant.

Table 6.2 Results for Building and Content Loss

	Log Structure			Log Content		
	Coeff	Std.Err	Z	Coeff	Std.Err	Z
Fill	-0.07333	0.016981	-4.31831***	-0.0413466	0.0165356	-2.500470*
Building Value (log)	0.01005	0.005911	1.70010	0.0033255	0.0057550	0.5778400
Building Area	-0.000049	0.000011	-4.40564***	-0.0000269	0.0000109	-2.4750100*
Building age	-0.005614	0.001932	-2.90585**	-0.0039784	0.0018811	-2.1149500*
Wetland Distance	-0.000010	0.000006	-1.69808	-0.0000072	0.0000057	-1.2624500
Stream Distance	-0.000054	0.000016	-3.35214***	-0.0000326	0.0000157	-2.0768900*
Pond Distance	0.000002	0.000008	0.205508	0.0000004	0.0000075	0.0541902
Floodplain Distance	-0.000009	0.000005	-2.02305**	-0.0000026	0.0000045	-0.5665970
Precipitation Avg	0.020354	0.004433	4.59149***	0.0089321	0.0043162	2.0694600*
Slope Average	0.006007	0.007545	0.79614	-0.0049434	0.0073392	-0.6735590
CRS Activity 430	-0.001076	0.000179	-6.00569***	-0.0002459	0.0001743	-1.4105900
Damage Year						
2001	6.723690	0.150276	44.74240***	4.3584000	0.1447240	30.1152000***
2008	5.520710	0.066353	83.20240***	2.7015300	0.0626892	43.0940000***
2009	8.046100	0.266971	30.13850***	4.4983900	0.2599700	17.3035000***
Constant	-0.754246	0.250377	-3.01244***	-0.2985830	0.2438060	-1.2246800***
Rho	0.322102	0.009066	35.52690***	0.3734970	0.0112349	33.2443000***
	N= 6059 R^2= 0.746			N= 6059 R^2= 0.495		

Notes: *p <0.05; **p <0.01; ***p <0.001

6.3 Summary of Regression Results

The results of all the regression models represent the expected relationships between the independent and dependent variables, while the r-square values indicate that they explain the variation in the dependent variable. First and most importantly, the expected relationship between fill and flood damage is shown in the regression model with the expected negative sign of the coefficient. Additionally, fill is also significantly related to both structure and content damage from flooding even after examining them separately in different regression models. These relationships were also highly significant as expected and supported *Hypothesis 1* of this research.

Second, fill permit types have varying impacts on flood damages. Specifically, all permit types except fill with structure alone are statistically related to flood damages from the distance model, with property and described fill being highly significant. In the model, only property with the entire parcels with fill experience a significant reduction in flood damages. The results supported *Hypothesis 6* of this research.

Third, other parcel-level control variables such as building area and building age also show a significant relationship with flood damages while all the parcel-level variables including building value show a significant relationship with flood damages. A surprising relationship born out in the model is that building age and amount of property damage from flood claims are not significantly related. As expected, buildings with larger square footage experience significantly lesser damages from flooding. This supported *Hypothesis 3, 4,* and *5* of this research.

Fourth, some of the proximity variables are also significant predictors of flood damage. Specifically, stream distance and floodplain distance showed the expected negative relationship with flood damages, while stream and wetland distance does not show statistically significant results. The results of the regression indicate that distance of the parcel to the closest wetland permit is not a significant predictor of flood damages, although the expected negative relationship can be seen in the model. The model does not indicate that compensatory storage proximity is statistically related to flood damages. These results support *Hypothesis 8 and 10,* while *Hypothesis 9 and 11* of this research is not supported.

Finally, other control variables indicate the expected relationship with flood damages. For example, the planning component of fill, i.e. the CRS activity related to fill restrictions indicate that parcels in communities with higher restrictions on fill experience significantly lower amounts of flood damages. Precipitation also had the expected relationship with flood damages, with parcels experiencing higher annual precipitation averages experiencing significantly higher amounts of flood damages. As seen from the model, slope is not a statistically significant. The result supports *Hypothesis 2 and 12* of this research.

7. DISCUSSION

In this section, I discuss the results of the previous analysis by specifically addressing the exploratory and explanatory data analysis. Additional policy implications of the findings are also presented in this section.

7.1 Discussion of Exploratory Analysis

The results of the exploratory analysis of fill in the Clear Creek watershed reveal several findings that are worthy of discussion. First, fill permits reduced in most communities in the watershed towards the end of the study period. Over 80% of the approved fill permits occurred during the first half of the study duration between 2000 to 2007. The reduction in the number of granted permits is understandable considering that some communities within the watershed are already saturated with residential development, coupled with the restrictions of building within the floodplain in other communities. There also exists a culture of using fill in floodplains at the initial development stages in many communities (Bollens et al. 1988).

Another observation is in terms of percentage of floodplain area relative to the number of fill permits granted. Harris County has about 29% of its land within the floodplain in the watershed and records the second largest number of fill permits in the watershed. This is understandable because there is a lower amount of land available for housing construction, leading to dependence on the land in the floodplain. Even communities with a lower percentage of floodplain area in the watershed still record high amount of fill permits. For example, the city of Pearland records the highest amount of fill permits in the watershed but has only 18% of its land in the floodplain.

Communities that have higher amounts of fill permits also seem to have larger property square footage, meaning that not only do they allow large number of developments in the floodplain, the surface area covered by these developments are also large, leading to larger amounts of land removed from the floodplain. The LOMR-F dataset does not account for the amount of compensatory storage provided by individual parcels that have been filled, and this makes it difficult to balance the amount of land that has been removed from the floodplain compared to the amount of flood detention that has now been provided.

Third, there is a general tendency for the number of fill permits to rise after major flood events. For example, two major flood events occurred in the watershed during the study period, tropical storm Allison in 2001 and hurricane Ike in 2008. Immediately following major flood events like Allison, I noticed a drop in the number of permits granted in the following year. However, there was a subsequent steady increase in the number of permits granted. In fact, the number of permits granted after Allison reached its peak in 2007 with over 1,000 permits granted in one year alone in the Clear Creek watershed. Previous research also found that after major storm events, number of wetland permits, and floodplain development continue to rise (Reja et al. 2017), usually an indication of a recovery-based approach in many communities.

Fourth, the city of Pearland has the highest number of fill permits compared to the other communities in the study area, accounting for almost 40% of the fill used in the entire watershed. This finding is also surprising since this community has a similar percentage of floodplain area compared to the other communities (except Harris county unincorporated areas, and Seabrook which is a coastal community). The number of fill permits in addition to the average area of the residential structures indicates an extensive use of fill in this area. The city of Pearland is the fastest growing city in the Houston area (see Pearland Economic Development Corporation, 2012) with a population growth of 142% and housing unit growth of 139% between 2000 and 2010. Other cities within the watershed such as League City, Houston, and Friendswood also have high population and housing unit growth percentages, which explains the large number of fill permits in those communities.

Permit types also cluster at different levels as shown by the Knox analysis in the previous section. Parcels with the entire property filled account for the largest number of permits in the study area and have a random distance of about 268 meters. Additional spatial observation of fill clusters shows that multiple pockets of parcels within different subdivisions cluster around each other. Specifically, the spatial-temporal analysis indicates that the fill parcels are spatially and temporally clustered, meaning that they are close in both distance and time, indicating a continuous use of fill within a particular time frame. The Ripley's k analysis also explains that the clustering of fill permits reaches its peak at about 800 meters, indicating a relative closeness in the distribution of fill in the watershed. The rapid increase in fill permits after tropical storm Allison is likely the cause for this spatial and temporal dimension in the watershed. This implies that floodplain development accompanied by some form of mitigation measures is expected to rise after a major storm event.

The bi-variate analysis which addresses the adjacent effect of fill on non-fill properties is also worth considering. The clusters of flood damage using kernel density show that these damages are clustered spatially around filled parcels. The Ripley's-k analysis also shows that the clusters of flood damages by up to 800 meters around fill parcels is not by chance, indicating significant correlations between fill clusters and flood claim clusters in the study area.

7.2 Discussion of Explanatory Analysis

The result of this research as shown in section 5 led to supporting 8 out of the 12 hypotheses proposed. There are several other characteristics and relationships in the model that worth further consideration, especially those related to fill, compensatory storage, and other proximity variables.

In summary, for the primary independent variable of fill, the effect size shows a statistically significant difference between flood damages for fill and non-fill properties. The final regression model indicates that, on the average, fill properties record approximately 8% fewer flood damages than non-fill parcels. From this result, although the difference between fill and non-fill parcels is statistically significant, an 8% difference in property damages is not likely to drive policy changes and encourage the use of fill in the watershed. The mean flood damage to the pooled sample properties in the watershed is about $924 over the study period. When properties fill, they only mitigate about 8% of that damage which is about $74 and is statistically significant based on the spatial autoregressive model.

In the initial regression model, fill parcels record approximately 23% fewer amount of flood damages than non-fill parcels. That difference reduces to about 8% when the model controls for temporal variations. The effectiveness of fill in mitigating losses is expected to reduce over time as additional buildings are constructed in the flood zone including other changes in the built environment. This implies that even though fill significantly reduces flood damages based on the current study, there is a need to evaluate the protection that fill will offer under worse environmental conditions in the future.

Comparing the average BFE before and after filling for some communities shows that in general, less than 2 feet of freeboard is achieved when parcels fill. Using fill slightly raises the building above BFE which makes the property susceptible to damages that may be experienced by other non-fill properties in the floodplain. This explains what has been previously asserted, that homeowners and developers request LOMR-F certificates not for mitigating properties from flooding but to avoid paying flood insurance. Although this research did not collect survey data on why properties use fill, additional findings may further highlight why developers chose this method of flood mitigation.

The result also shows that the extent of fill in floodplains significantly impact flood damages. As seen in model 2, only fill occurring on entire parcels show a higher effect size compared to the other types of fill. Scale comes to the fore here and the results seem to support using fill contiguously over large areas. Some subdivisions in the study area have large amounts of parcels that have been filled and the result show that these are the parcels that have significantly lower amount of flood damages.

Although the results indicate that larger amounts of fill offer better protection from flood damages, the associated adverse impacts are also worth considering. As shown in the results of the exploratory analysis, the clusters of fill locations in correlation with clusters of flood damages does not occur by chance. Although the regression model suggests using fill for a large surface area to achieve better flood damage reduction, the exploratory analysis indicates that this act further directs the flood damages to other locations. Analyzing the benefits to fill parcels compared to the cost to non-fill parcels is worth further consideration in future studies.

For the effect of compensatory storage on flood damages, the results in the model is somewhat surprising as it shows that parcels in proximity to compensatory storage sites such as detention ponds do not have significantly lower amounts of flood damages. As expected, the relationship in the models shows that parcels farther from detention ponds have more flood damages, but this is not statistically significant. The non-significance of this result raises pertinent issues on the effectiveness of compensatory storage provisions, especially since the enforcement of these in floodplains is difficult to measure.

A possible reason for the nonsignificant result may be because detention ponds do not perform the same natural functions which floodplains serve in mitigating flood damages. The most effective flood attenuation function is to allow natural floodplains to compensate for excess floodwaters, limiting the impact on development (FEMA 2013).

This means that compensating for flood waters through detention ponds will not be as effective as the functions that natural floodplains provide. It is important to note that detention ponds in this research are based on the pond classification of the National Hydrography Dataset which are standing bodies of water. This classification may not cover small detention ponds whose waters are dry at the time of data collection. Including small and dry detention ponds in future research may lead to significant results and contribute to discussions on the size and hydrological characteristics of detention ponds that are used near fill subdivisions.

Compensatory storage in the floodplain is similar to building a new wetland to replace a naturally occurring wetland which has been altered. In their study of wetland alteration permits in Texas and Florida, Brody et al. (2008a) noted that although new wetlands are built to replace altered ones, there is a spatial mismatch in the functions that the new wetlands perform. Similarly, compensatory storage in floodplains cannot provide the natural floodplain function for storing flood waters (FEMA 2013). In light of this, the model in this dissertaion shows that there is a similar spatial mismatch between naturally occuring floodplains and newly constructed detention ponds. When detention ponds exceed their capacity to hold flood water, which is often not the same with the floodplain, the proximity of these ponds to properties which are mostly feet away from the ponds can make them susceptible to flood damages.

The model also shows that proximity to section 404 wetland permits do not show statistically significant impact on flood damage at the parcel level. This result is expected because wetland alteration permits occur in different forms and have varying impacts on flood damages (Brody et al, 2007a). What the results shows is that at the parcel level, proximity to wetland permits in general does not significantly impact flood damages. The negative coefficient observed in the result shows that parcels farther from wetland permits experience less flood damages. The Clear Creek watershed is saturated with wetland alteration permits that involve small scale residential development which have been found to exacerbate urban flooding.

7.3 Fill Policy Recommendations

The relationship between fill and flood damages as shown in this research has highlighted some important insight into fill as a flood mitigation measure as well as possible policy implications. The mixed results of fill mitigating property damages and redirecting damages to other areas require serious attention through structural and non-structural policy recommendations. As filling parcels accumulate over time in the study area, and as shown in the regression model, the effectiveness of fill in mitigating losses continue to decline. The results in this research benefits policies that can be implemented at the jurisdictional level as well as regional considerations, both of which are highlighted below.

7.3.1 Recommendations at the Jurisdictional Level

Since local jurisdictions are primarily responsible for enforcing fill requirements in the floodplain, it is critical that fill policy recommendations are addressed at this local level. For example, Harris County in the past issued a high number of permits, but that number declined after several higher restrictions are placed for residential development and the use of fill in their floodplains. Other communities, on the other hand, such as Pearland and League City continue to approve fill in the floodplain and lax requirements for floodplain development. Examining the number of fill permits granted for each community in the study area shows that stricter requirements are needed.

Several actions are necessary to either restrict the use of fill in the floodplain or allow fill in congruence with other measures that will mitigate the adverse impact of fill on surrounding areas. First, to ensure that fill mitigates flooding as intended, stricter measures should be enforced if fill is permitted in the floodplain. This can be achieved by requiring additional freeboard beyond the BFE. When parcels are significantly higher than BFE, realistic levels of protection is offered thereby leading to even more significant reduction in flood damages. Additional levels of protection are also offered to protect the building from rising flood levels due to sea level rise and increase in precipitation events.

Second, local communities should avoid using fill when adverse impacts are expected to other non-fill locations. Since a regression model indicates that compensatory storage does not significantly reduce the impact of flooding, higher engineering standards that examine the flood attenuation function of retention ponds should be considered. This include analyzing the location of detention ponds and determine whether the floodwaters from the filled floodplain are directed to the new detention pond that has been provided. Additional engineering methods should address the volume of detention ponds rather than an overly simplistic placement of shallow detention ponds equivalent to the amount of fill used, since their mitigation functions cannot be adequately determined.

Third, while the CRS reward communities that have stricter fill and floodplain requirements with lesser insurance premiums, penalties should be placed on communities that do not permit adequate compensatory storage provisions, since this can lead to adverse impacts on non-fill areas. This should be accounted for in the weighing structure of the CRS program. Local communities can impose a tax penalty on properties within subdivisions that cause adverse impact to other areas.

Fourth, rather than focus on a one-size-fits-all approach and dumping fill in the floodplain before development, a synergistic approach of floodplain management should be adopted. Brody and Atoba (2018) proposed a framework that local jurisdictions can adopt by combining avoidance, resistance, acceptance, and awareness as a measure of flood risk reduction. Fill is a form of vertical avoidance, however, combining this with horizontal avoidance which involves locating properties farther from the floodplain and wetlands is a better approach to flood mitigation and an example of a synergy of mitigation measures. Other horizontal avoidance techniques include acquiring multiple parcels around floodplains or preventing development on certain part of a parcel in exchange for tax benefits (Beatley 1994).

7.3.2 Recommendations at the watershed Level (Regional Watershed Planning)

Communities within a watershed will benefit from an integrated regional planning approach which addresses problems at the regional scale. The watershed should be treated as a ‘basin’ and collective system (Walker & Salt 2006), which can be achieved through a comprehensive regional environmental planning governance initiative to address fill and other related floodplain development strategies within watershed. This can be achieved through collaboration of local communities within the region (Thibert 2015). When communities collaborate, they can address the spatial mismatch of fill and compensatory storage provisions and avoid cross-jurisdictional adverse impacts within the waterhsed.

In addressing flooding at the watershed scale, the no adverse impact (NAI) approach being pursued by the Resilient Chicago program (see Sauvageot, 2015) will greatly benefit the watershed. The NAI is important because not only does it advocate for preventing adverse impact of floodplain development, it proposes that properties that can be potentially affected by floodplain development and fill be informed so that they can take appropriate mitigation measures. Preventing adverse impact requires a synergistic and collaborative approach with members of neighboring communities within the watershed system.

Additionally, some communities have a ‘zero-rise policy where there is no fill allowed unless there is an additional purchase of adjacent easements to make way for residual flooding, and compensatory flood storage. Other communities also have additional freeboard requirements of 1 or 2 foot when fill is used (Birkland et al. 2003, Burby 2001). However, while adopting this strategy of the adjacent easements, additional engineering may be required since this research shows that proximity of a parcel to a retention/detention pond does not significantly reduce flood damages. Detailed engineering design on flow patterns and proximity to streams should also be considered when designing compensatory storage provisions in the floodplain.

Regional governance is another strategy that can be adapted to prevent adverse impacts and reduce the pressure to use fill in floodplain development. Considering the pressure of residential development in the watershed, and its impact on the number of fill used in the floodplain, monitoring the growth of communities is essential. For example, Smart Growth can be practiced and include principles like reducing outward growth through urban growth boundaries, increasing residential densities, mixed land uses, walkable societies, impact fees, public transit, neighborhood revitalization, affordable housing, etc. (Downs 2005; Song & Knaap 2004).

In addition to regional governance, Cross/multiscale regionalism can help address regional problems at spatial and temporal scales. As shown in the results, we see the spatial and temporal significance of filling floodplains and how they are clustered both in space and time, thereby showing the importance of addressing these scales in evaluating the effectiveness of fill. Systems that address cross-scale and cross-level scale issues are more successful in identifying the problem and seeking ecologically sound solutions (Cash et al. 2006). Ignoring these problems at multiple scales will evidently lead to an increase in cumulative flood damages in the clear creek watershed.

8. CONCLUSIONS

8.1 Research Summary

This dissertation research has quantitatively addressed the impact of fill on flood damages and confirmed that fill is a significant indicator of lower amounts of flood damages. This conclusion is reached after statistically controlling for parcel, built environment, and proximity variables, in relation to flood damages. The result also indicates that the extent of the parcel that fill covers statistically impacts the amount of flood damages to the fill parcel in comparison to a non-fill parcel. Additionally, my research found that proximity to retention ponds does not statistically reduce flood damages at the parcel level. Exploratory space-time analysis also shows that clusters of flood damages occur near clusters of fill, addressing the anecdotal claim that fill can lead to adverse impacts for non-fill properties. The result in this dissertation is based on a 15-year analysis of a pooled fill and non-fill parcel selection in the Clear Creek watershed.

A total of 8 out of 12 hypotheses were confirmed using a spatial autoregressive model for a distance-based weight matrix with flood damages as the dependent variable. Seven hypotheses were confirmed with structure damage as the dependent variable while five hypotheses were confirmed with content damage as the dependent variable. The confirmed hypotheses followed the expected sign and relationship with flood damages.

8.2 Limitations

The first major limitation of this research is that NFIP flood claims are used as a proxy for flood damages. The flood claims data represent building and contents loss for claims filed under the NFIP, which only reflects insured flood losses and doesn't account for uninsured losses or losses occurring outside the floodplain. This kind of loss can only be estimated using flood loss estimation models that have sophisticated hydrological and built environment parameters. A major concern with this dataset is that NFIP losses are underestimated and do not include indirect losses from flood events, and the cost of temporary relocation. Additionally, the maximum claim for residential properties under the NFIP policy is a cap of $250,000 per property, which sometimes do not cover the full replacement cost of property damages during extreme flood events.

Despite the limitation of flood claims data, previous research has still been able to use this data to conclude that past flood claims are usually the best predictor of future losses. Additional research can be conducted to reflect losses for uninsured losses through flood loss estimation methodologies. Although flood insurance outside the floodplain is voluntary, some homeowners still purchase flood insurance and file claims when they are affected by flood events. This research ensures that all NFIP flood claims both within and outside the floodplains are accounted for although the actual damages from flood events may be underestimated due to flood insurance policy requirements by NFIP.

Second, measurement error from surveyors that record new elevation based on fill is a major limitation of fill data, as these are not accounted for in the elevation certificate grant; however, this is the best available method of measuring fill since there are no available spatial-temporal digital elevation datasets where change in elevation can be captured. Finally, in matching fill parcels with non-fill parcels, the effectiveness of the matching procedure is predicated on the reliability and sensitivity boundaries of the PSM method selected.

Third, in this research, the rate of subsidence is not accounted for. Due to the complexity in measuring subsidence, the study assumes that during the 15-year period of examining fill in the area, subsidence rate is constant across all parcels, but is not accounted for. This is because there is little subsidence variation for the entire watershed. Subsidence is the reduction in ground elevation due to the heavy withdrawal of groundwater (FEMA 2013; Chen, 2015). The scope of this research, however, does not allow for studies on the extent of subsidence in the model. Previous research on flooding has not addressed subsidence issues, but subsidence becomes very important in this research since it deals with change in elevation. However, since the extent of land elevation change is not examined on a ratio scale, the extent of subsidence will not be needed in the model.

A major problem that could occur from violating this assumption is if significant changes in subsidence have occurred during the study period. The study area falls within areas where significant groundwater depletion has occurred due to increasing population and increase in industrial activities. Fill areas are also susceptible to increased risk of subsidence (FEMA 2001). This research cannot determine if subsidence level from filled parcels will significantly impact inundation and subsequently the dependent variable which is insured flood claims. Determining subsidence also requires additional technical modeling requirements that are beyond the scope of this dissertation.

8.3 Future Research

This research contributes to both the theory of urban flood mitigation and planning, and the practice of floodplain management, but there are still improvements that can be carried out to the research in future. First, there is a need to improve the resolution of the parcel-level fill dataset collected to account for specific details including the amount of fill, type of fill and the new elevation after fill relative to BFE to be included into the regression model. This ensures that we understand the impact of the extent of parcel-level mitigation on flood damages.

Second, additional measures are needed to ensure the measurement of adjacent damages by improving the spatial and temporal resolution of flood damages to adjacent parcels. This will be more effective when considered at the subdivision or neighborhood scale to provide a better understanding of how adjacent losses are felt in surrounding areas. This includes identifying specific mitigation measures available or not available to the affected neighborhoods rather than the single requirement of whether the parcel/subdivision is filled or not. Understanding the mitigation measures used by other properties will ensure accounting for other variables that prevent adjacent damages other than fill.

Finally, future research should also expand the scale to include entire communities raised above BFE or coastal communities where fill is used extensively. This includes accounting for subsidence rate for large areas and sees the risk levels of these communities after a specified duration. The expanded filled site should also examine the direction of flow of storm water and where they are directed to identify if they are responsible for adjacent damages to other areas.

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APPENDIX A

Pearson’s Product-Moment Correlation Matrix

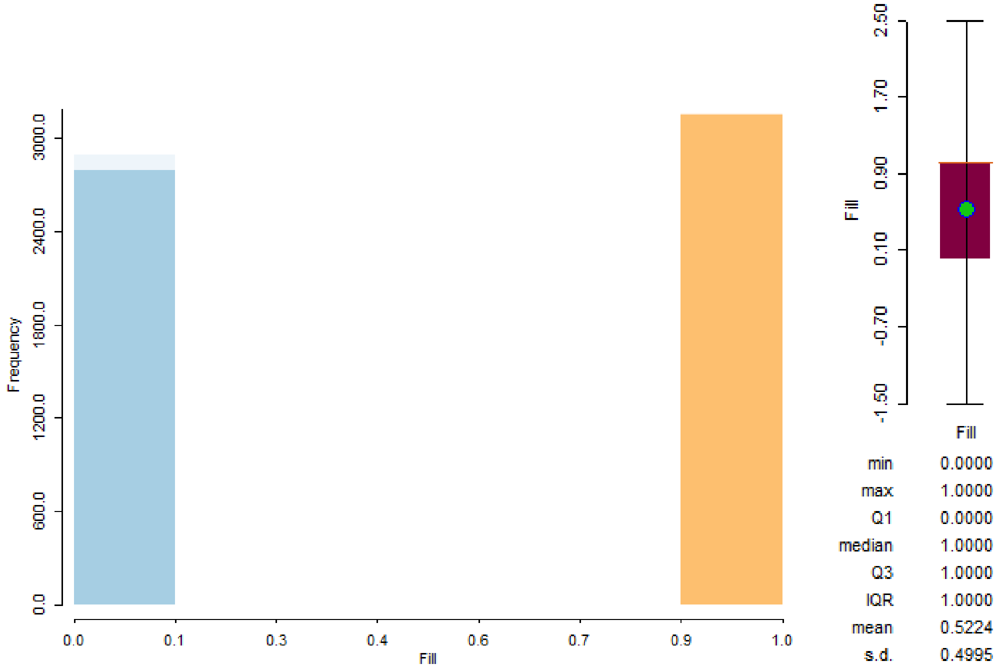
	Damage	Fill	Building value	Building area	Building age	Wetland distance	Stream distance	Pond distance
Damage	1							
Fill	-0.0881	1						
Building value	0.0135	-0.0579	1					
Building area	-0.0077	-0.0481	0.5706	1				
Building age	0.0034	-0.0462	0.3484	0.1847	1			
Wetland distance	-0.0857	-0.0368	0.0475	0.0482	-0.0437	1		
Stream distance	-0.0697	-0.0062	0.0141	-0.0818	0.1814	0.0057	1	
Pond distance	-0.0222	0.0109	0.0839	0.0506	0.1873	0.1531	-0.0093	1

	Floodplain distance	Precipitation	Slope	CRS	Described	Portion	Structure	Property
Floodplain distance	1							
Precipitation	-0.047	1						
Slope	-0.1457	0.0416	1					
CRS	0.1177	0.3512	-0.0895	1				
Described	-0.089	0.0947	-0.0356	0.1303	1			
Portion	-0.0929	-0.1064	-0.0474	-0.1582	-0.0485	1		
Structure	0.1972	-0.0935	-0.0006	-0.1611	-0.0427	-0.0374	1	
Property	-0.0359	0.0053	0.0222	0.0404	-0.1911	-0.1674	-0.1473	1

APPENDIX B

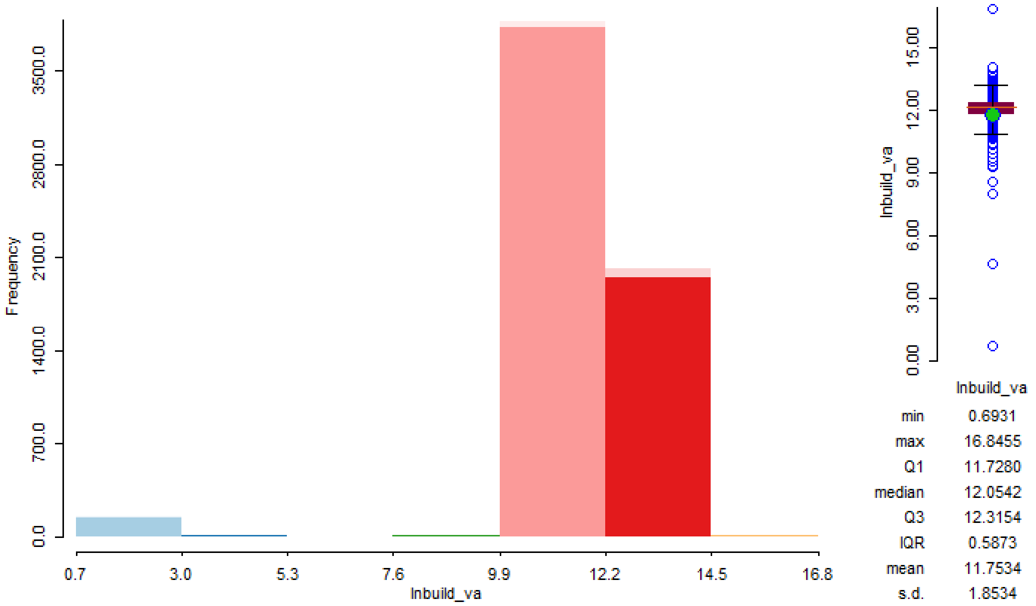
Histograms and Box Plots

Parcel Variables

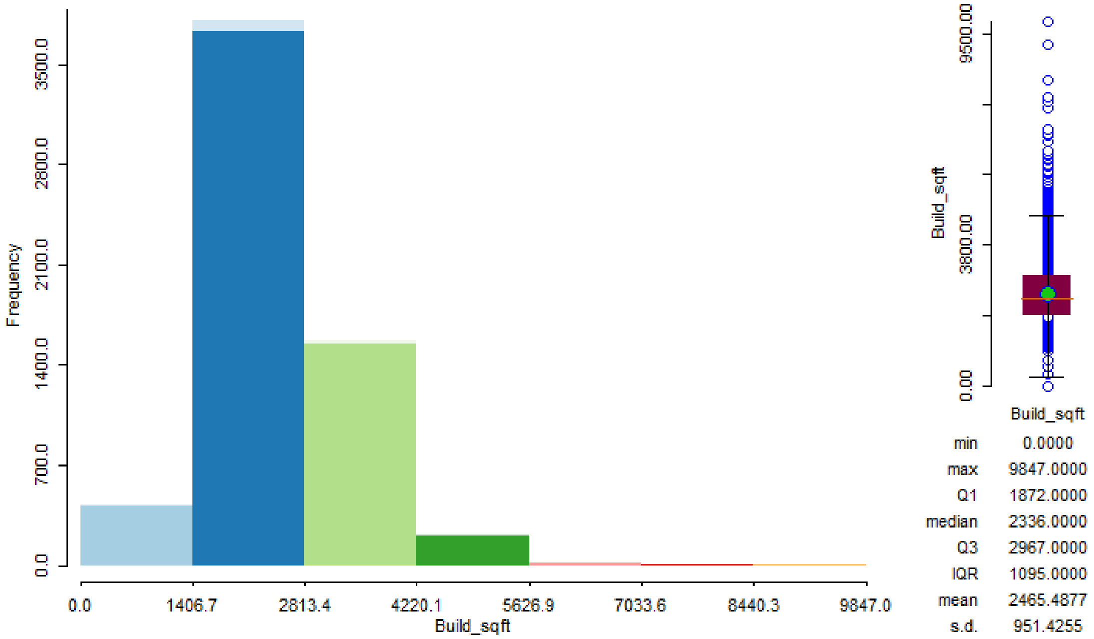


	Fill
min	0.0000
max	1.0000
Q1	0.0000
median	1.0000
Q3	1.0000
IQR	1.0000
mean	0.5224
s.d.	0.4995

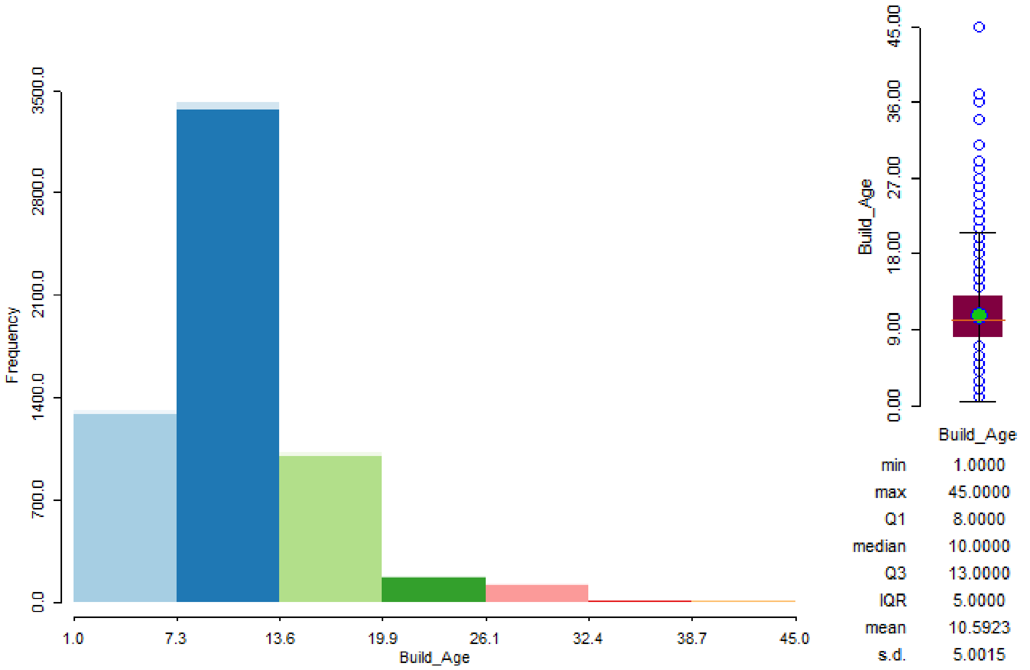
(a) Fill



(b) Building Value (log)

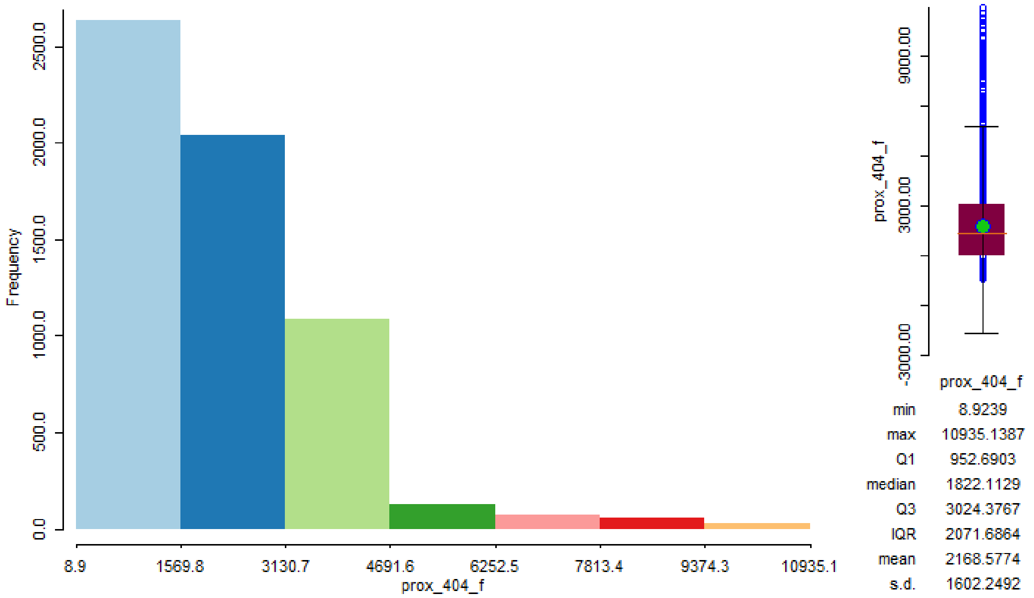


(c) Building Area

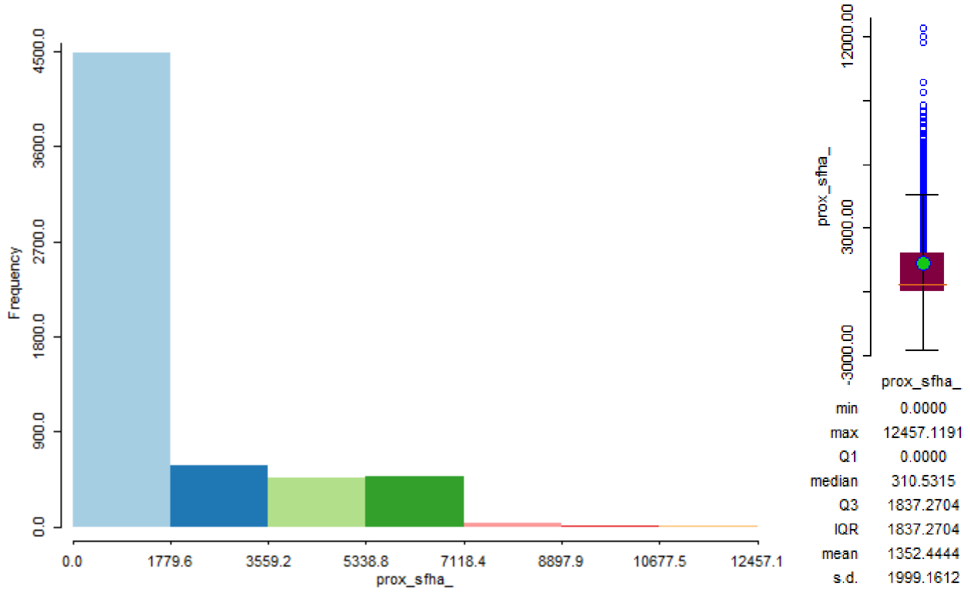


(d) Building Age

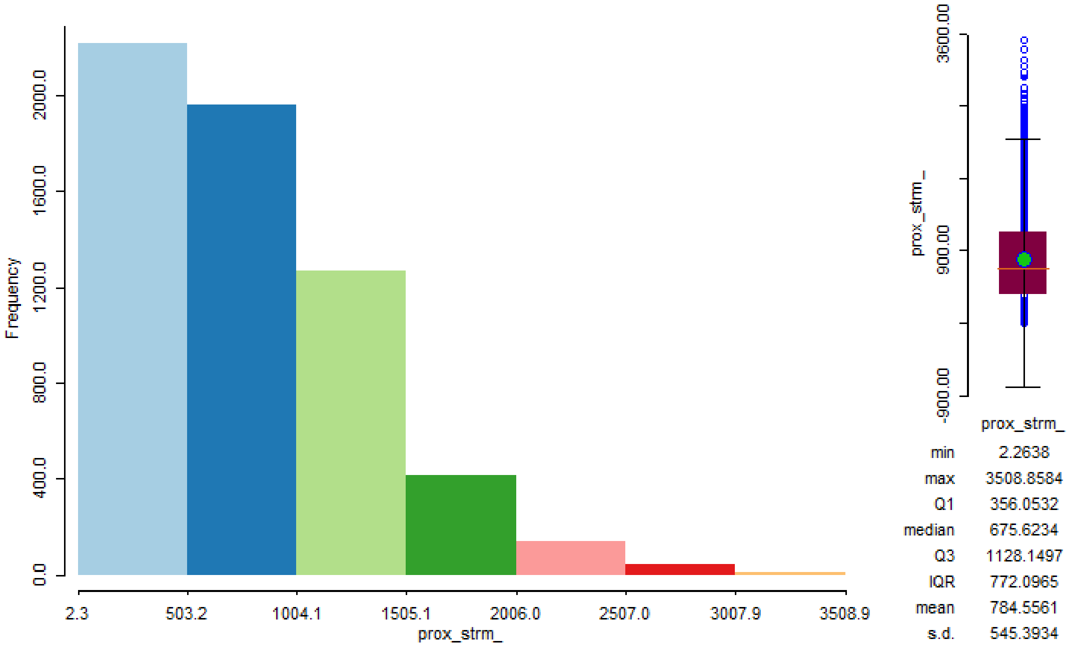
Proximity Variables



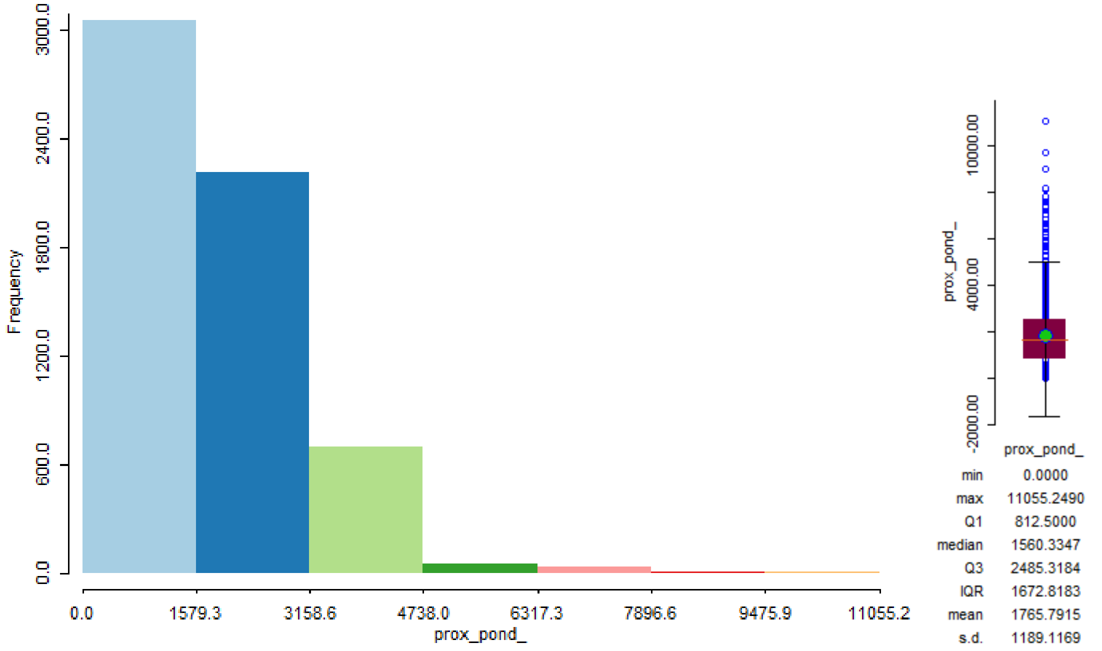
(a) Distance to Wetland Permits



(b) Distance to 100-yr Floodplain



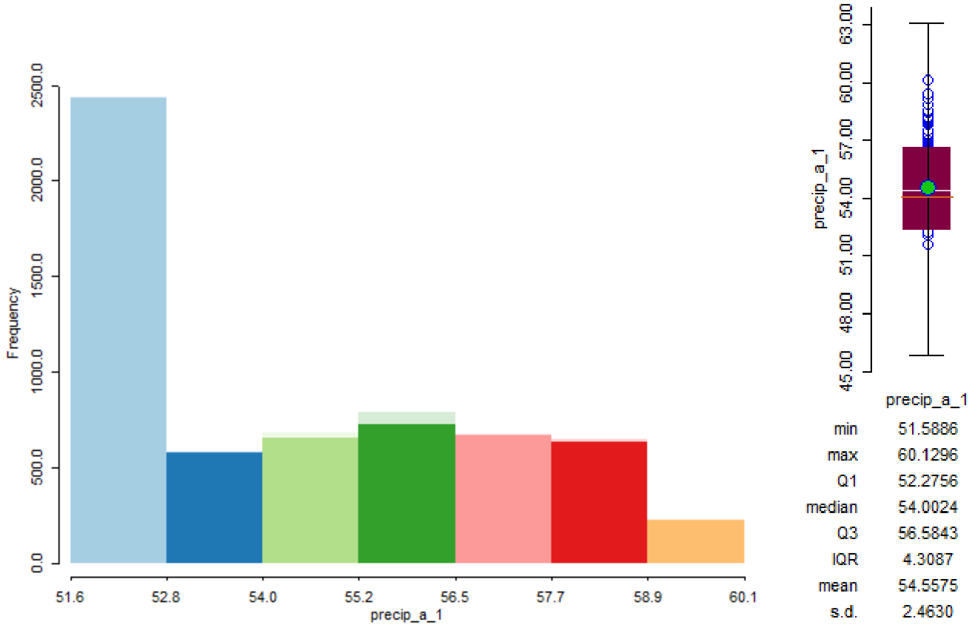
(c) Distance to Stream



	prox_pond_
min	0.0000
max	11055.2490
Q1	812.5000
median	1560.3347
Q3	2485.3184
IQR	1672.8183
mean	1765.7915
s.d.	1189.1169

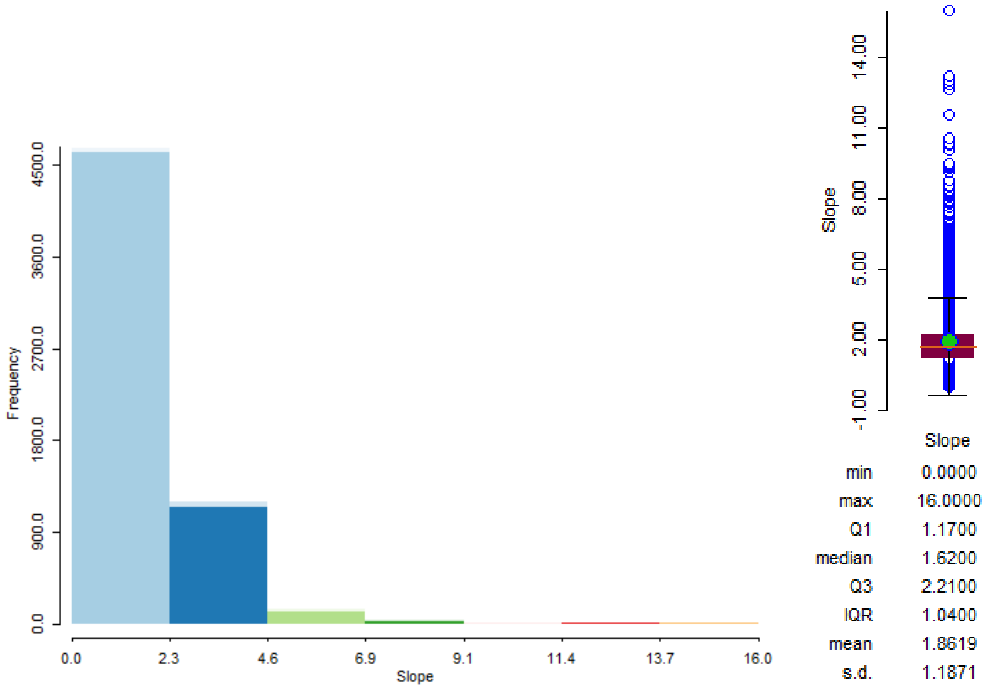
(d) Distance to Pond

Other Control Variables



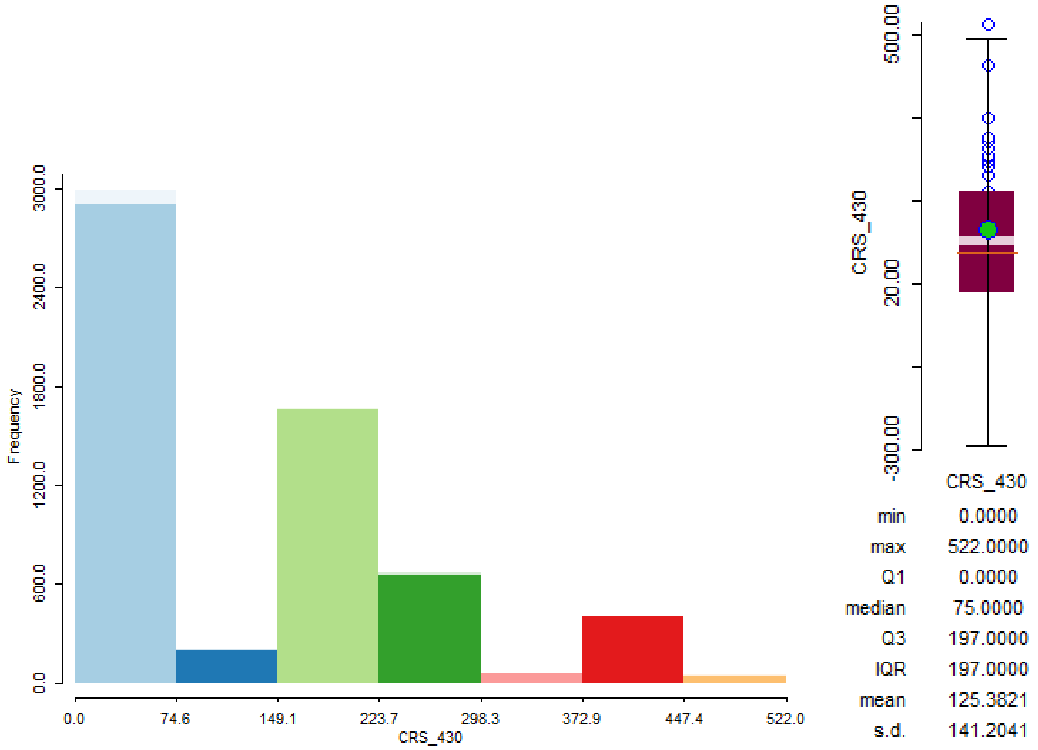
	precip_a_1
min	51.5886
max	60.1296
Q1	52.2756
median	54.0024
Q3	56.5843
IQR	4.3087
mean	54.5575
s.d.	2.4630

(a) Precipitation Average



	Slope
min	0.0000
max	16.0000
Q1	1.1700
median	1.6200
Q3	2.2100
IQR	1.0400
mean	1.8619
s.d.	1.1871

(b) Slope



	CRS_430
min	0.0000
max	522.0000
Q1	0.0000
median	75.0000
Q3	197.0000
IQR	197.0000
mean	125.3821
s.d.	141.2041

(c) CRS Score for fill and floodplain requirements

APPENDIX C

Fill Images

(a) Example of fill Subdivision in the study area with Compensatory Storage. Background Image reprinted from Google Earth Pro (2017).

(b) Example of fill Subdivision in the study area without Compensatory Storage Background Image reprinted from Google Earth Pro (2017).