HUMAN-STREAM CORRIDOR INTERACTIONS AND FLOOD RESILIENCE

A Dissertation

by

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ABSTRACT

Flood damages in the United States continue to increase despite large investments to control stormwater. The rate at which flood damages are increasing significantly outpaces precipitation trends leaving societal trends largely to blame. Population growth and development within flood vulnerable areas such as floodplains and coastal regions is a large driver of the rising cost of floods. Not only does building in risky areas increase the likelihood of damage, but it also displaces and fragments natural habitats such as wetlands that provide flood attenuation as an ecosystem service. Efforts to mitigate flood damage have historically favored resistance based strategies. However the damages avoided through the use of flood control infrastructure (FCI) are often offset by their tendency to attract development into the stream corridor and increase downstream flood risk. The outcome of resistance based strategies to flooding, some have argued, has resulted in a loss of flood resilience. Despite such knowledge there have been no studies that have examined how these human-stream corridor interactions effect flood risk systematically. This study addresses this by using cross sectional regression models to isolate the influence of natural habitat modifications, FCI, and open space preservation on insured flood loss from 2006-2010 within the stream corridors of 273 developed watersheds along the Gulf of Mexico. Results indicate that stream hardening and the fragmentation of natural habitat significantly increase flood damage within the stream corridor, whereas efforts to preserve open space translate into significant savings in terms of damages avoided. These findings support the treatment of stream corridors as complex socio-ecological systems consisting of dynamic human-environment interactions. Instead of attempting to eliminate flood disturbances with costly resistance based infrastructure, cities should instead focus on flood resilience that leverages existing ecological systems and non-structural, avoidance based mitigation approaches to prevent flood damage.

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NOMENCLATURE

AREA_MN	Mean Area
BFE	Base Flood Elevation
C-CAP	Coastal Change Analysis Program
CONTIG	Contiguity Index
CRMA	Climate Resilience Mitigation Activities
CRS	Community Rating System
DEM	Digital Elevation Model
DFIRM	Digital Flood Insurance Rate Map
EPA	Environmental Protection Agency
FCI	Flood Control Infrastructure
FEMA	Federal Emergency Management Agency
GYRATE_AM	Area-Weighted Mean Radius of Gyration
HMA	Hazard Mitigation Assistance
HMGP	Hazard Mitigation Grant Program
HUC	Hydrologic Unit Code
KSAT	Saturated Hydraulic Conductivity
LCT	Land Cover Type
LM	Lagrange Multiplier
LPI	Largest Patch Index
LULC	Land Use / Land Cover
LZ	Low-Density Zoning
MAUP	Modifiable Area Unit Problem
MUD	Municipal Utility District
NED	National Elevation Dataset
NFHL	National Flood Hazard Layer
NFIP	National Flood Insurance Program
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration

OLS	Ordinary Least Squares
OSP	Open Space Preservation
PLAND	Percent of Land
PRISM	Parameter-elevation Regressions on Independent Slopes Model
SSURGO	Soil Survey Geographic Database
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VIF	Variance Inflation Factor

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1. INTRODUCTION

1.1 The Problem

Floods are one of most prevalent and damaging natural hazards in the United States (US) (Birkland et al. 2003; Conrad et al. 1998; Kolber 1999). The common response to flood events in the US is to fortify the coastline and harden streams and rivers in an attempt to protect vulnerable communities from the adverse impacts of future storms (Brody et al. 2015). However, property losses from flooding continue to increase (Brody et al. 2011), despite large-scale investments in resistance-based approaches to flooding. Even more troubling is that precipitation and streamflow have decreased since the 1970s (Patterson et al. 2012) in the region most adversely impacted by floods: the southeastern US (Brody et al. 2011). This pattern suggests that there are non-climatic drivers of flood damage. One of the largest contributors to increasing damages is the amount of development occurring in flood prone areas (Changnon 2003; Pielke Jr and Downton 2000). However, this trend is also driven by the loss of natural, flood attenuating habitat (Akanbi et al. 1999; Opperman et al. 2009), changes in watershed hydrology as a result of flood control infrastructure (FCI) (Criss and Shock 2001) and the spread of impervious surfaces (Shuster et al. 2005).

Underlying these drivers of increasing flood damage is a failure to consider how the human-stream corridor system will respond to specific interventions. For example, cities fail to acknowledge that FCI often leads to a greater density of development in the floodplain as a result of people perceiving it as being safe creating a greater potential for catastrophic loss if and when the FCI fails (Burby 2006). Moreover, new developments of require new FCI to mitigate flooding at the level of the site with little consideration for how the increased water conveyance efficiency will impact downstream communities (Greco and Larsen 2014). Even less attention is given to the costs of losing ecosystem services like flood attenuation because of floodplain development and FCI. The entire landscape can shift in response to these interventions often resulting in a fragmented habitat pattern that is disconnected from its natural disturbance regime (King et al. 2009;

Opperman et al. 2010; Poff et al. 1997). In short, the human-stream corridor system is a complex system that does not respond to interventions in a linear way. Not recognizing this locks the system into a trajectory of increasing resistance at the expense of flood resilience (Liao 2012).

1.2 Research Purpose and Objectives

The influence of habitat loss, FCI, and development on watershed hydrology and flood damage have all been studied. However, very few, if any studies have addressed these simultaneously. Assessing one of these without controlling for the influence of the other will likely result in a misinterpretation of their effect on flood damage. This study intends to address this gap by examining the influence of stream corridor habitat modification, FCI, and open space preservation efforts on historical flood damage along the Gulf of Mexico. Specifically, this study will address the following research questions: 1) does natural habitat composition and configuration at the stream corridor scale influence flood loss?; 2) what are the effects of controlling greater proportions of the natural drainage network with FCI?; and 3) how have efforts to preserve floodplain habitat influenced flood loss?

To answer these questions, this dissertation provides a review of the literature on how specific human interventions within the stream corridor influence insured flood loss. Metrics were identified and applied to conceptualize each of these interventions and hypothesize their effect on flood damage. Regression analysis was then used to isolate their effect on insured flood damage. Results provide a better understanding of how human-stream corridor interactions within developed watersheds influence flood risk within the context of socio-ecological resilience. The study highlights that historical, single-objective efforts to minimize flood damage have neglected development, hydrological, and ecological responses often resulting in unanticipated and undesirable outcomes. The findings illustrate the importance of leveraging multi-objective policies and land use strategies to increase flood resilience.

There are multiple reasons why these interactions were chosen at a conceptual level. Natural habitat within the stream corridor can mitigate flood risk by slowing, absorbing, and storing stormwater. Increasing the area and connectivity of natural habitat can increase its capacity to do so, and can also be an indicator of floodplain encroachment, ecological integrity, and the presence of a natural disturbance regime. FCI, such as channelization, increases stormwater conveyance efficiency by moving water more quickly away from a development thereby minimizing flood risk of the adjacent communities. However, FCI can also enhance flood risk by increasing the velocities and flood heights for downstream communities and can also attract more development into the floodplain by lowering flood risk perception and increasing the amount of developable land. Finally, efforts to preserve open space within the floodplain can decrease flood damage directly by minimizing development within vulnerable areas and indirectly through the protection of ecologically valuable land and the use of land use and growth management plans. To date, there has been little to no research conducted that has not only operationalized these interactions but also tested their combined effect on actual historical flood loss.

1.3 Dissertation Structure

This dissertation is structured in the following manner. This first section introduces the issue of flooding and flood resilience in the US. The second section provides a review of the literature with subsections focusing on studies that have examined the influence of habitat loss and fragmentation, flood control infrastructure, and avoidance based strategies on flood risk. The section ends with a discussion on previous research that this study is related to, expected results, limitations, and knowledge gaps. The third section provides and overview of the research framework, which includes a conceptual model, overview of dependent, independent and control variables, and presents the research hypotheses. The fourth section presents the research methodology, which includes information on the study area and sample selection, how variables were conceptualized and measured, model selection and diagnostics, and known validity threads. Section five presents the results from the analysis and provides a summary of how the variables behaved within the regression model. Intercorrelations between variables and estimated dollar savings for specific variables are also presented. The sixth section provides a discussion of the results, provides example stream corridors from the study sample to illustrate key discussion points, and discusses implications for policy, planning, and the application of results that land use and environmental planning efforts. Finally, the last section of the dissertation provides concluding thoughts and suggestions for future research.

2. LITERATURE REVIEW

A few areas of literature must first be acknowledged to better understand and conceptualize this research proposal. Although broken down into several sections, the commonality between them all is how humans have transformed and manipulated stream corridors in an attempt to reduce and mitigate the effects of flooding. The sections include a history of stream corridor habitat loss and its effect on flooding, the paradigm of flood control as a major of driver of habitat loss and flood vulnerability, and the current trend towards non-structural forms of flood mitigation. The chapter concludes with a brief summary of previous research findings and identified gaps in the literature.

2.1 Stream Corridor Habitat Loss and Flooding

Synthesis

The stream corridor is a spatial element of watersheds consisting of mostly floodplain habitat that provide a suite of ecosystem services with the most valuable being flood attenuation. Human floodplain encroachment and riverine flood control projects have significantly altered this landscape resulting in large losses of natural habitat such as wetlands and riparian forests. The loss of these valuable habitats have resulted in: 1) a decrease in the natural stormwater storage capacity; 2) an increase in imperviousness along with a concomitant decrease in roughness; and 3) an increase in habitat fragmentation. Previous studies have argued that the increase in flood damage, particularly within the floodplain, are in large part driven by these ecological modifications which increase stormwater runoff, velocity, and peak flows.

Stream Corridor Habitat Loss in the United States

The stream corridor is a spatial element at the watershed and landscape scales that commonly consists of a matrix of riparian (i.e. streamside) forest and shrub cover and wetlands. Broadly speaking, the stream corridor consists of three major elements: the stream channel, floodplain, and transitional upland fringe (Bernard and Tuttle 1998).

Stream corridors support high levels of biodiversity (Tockner and Stanford 2002) and provide a disproportionate amount of ecosystem services. In their review of the world's ecosystem services, Costanza and others (1997) found that floodplains were ranked second, behind only estuaries, in terms of dollar value per-hectare.

Despite their benefits, there is cause for concern about the state of stream corridor habitats in the U.S. and the potential loss of ecosystem services (Charron et al. 2008; Sweeney et al. 2004). Only 2% of the original forested riparian habitat remains in the western U.S. (Todd and Elmore 1997), in large part due to structural mitigation and water control (Lytle and Merritt 2004). Elsewhere, Swift (1984) found that stream channel modification, vegetation clearing and wetland drainage were responsible for nearly 200,000 miles of waterway modification in the U.S., which is roughly 20% of the Nation's one million stream miles. In central and southeastern portions of the U.S., riparian buffers have suffered extensive losses over the past 150 years due to intensive agricultural development (Jones et al. 1999) and urbanization (Morgan II et al. 2007). Below the confluence of the Ohio River, less than 20% of the historic extent remains of the floodplain forests along this Mississippi River (Llewellyn et al. 1996), as a result of river flow regulation and land use. In their review of natural floodplain extent, Tockner and Stanford (2002) note that floodplains are the most threatened ecosystem worldwide and claim that they will disappear faster than any other wetland type. The widespread degradation of riparian ecosystem services has led to an increase in the number of riparian and stream corridor restoration projects across the U.S. (Bernhardt et al. 2005).

Flood Mitigation as an Ecosystem Service

Despite only representing less than 2% of Earth's terrestrial land surface area, floodplains provide approximately 25% of all non-marine ecosystem service benefits, with the regulation of flood water providing the most value (Akanbi et al. 1999). Riparian ecosystems and associated plant species are critical elements of maintaining stream hydrologic characteristics (Mahoney and Rood 1998; Stromberg 1998). One of the more valuable services that riparian buffers provide is the dissipation of energy associated with flood events by obstructing highwater streamflow and allowing for greater ground retention and infiltration (Swanson et al. 1982).

Healthy floodplain habitats typically form dense woodlands that slow the downstream passage of the flood peak, resulting in a lower but longer duration flood events (Thomas and Nisbet 2007). Living vegetation and woody debris reduces channel conveyance by acting as resistance elements that obstruct or divert overland and subsurface water flow (Anderson et al. 2006; Tabacchi et al. 2000). Several numerical investigations have demonstrated that increasing channel roughness will attenuate peak discharge at catchment outlets and delays the arrival of the hydrograph (Rutherfurd et al. 1996; Wolff and Burges 1994; Woltemade and Potter 1994). More recent one-dimensional hydraulic modeling studies have corroborated this effect, but note that the impact of roughness on streamflow is moderated by the magnitude of the floods, with smaller floods being more sensitive to vegetation condition than larger floods (Anderson et al. 2006). Thomas and Nisbet (2007) modeled the influence of reforesting 2.2 km of streams with riparian forests and found that it would slow overland flow by 50%, increase flood storage volume by 71%, and delay peak flow by 140 minutes. In short, forested floodplains reduce the size of peak flows and therefore flood risk by desynchronizing subcatchment stormflow contributions (Thomas and Nisbet 2007).

The literature clearly shows the flood mitigating influence of wetlands. A comprehensive review of the role of wetland in the hydrological cycle by Bullock and Acreman (2003) conclude that wetlands are significant modulators of the water cycle with most studies (23 of 28) showing that floodplain wetlands reduce or delay floods, particularly for downstream communities. Wetlands have frequently been referenced as ecological solutions to reduce runoff and decrease downstream flood risk. These habitats slow down and temporarily store stormwater away from rivers, thereby reducing and delaying destructive peak flows. A recent study conducted by Javaheri and Babbar-Sebens (2014) used a coupled hydrologic-hydraulic model to investigate the impact of wetlands on flooding and found that they could reduce peak flow by 20-41%, reduce flood area by 55%, and decrease stormwater velocity by 13%. Observations of actual floods by Michener et al. (1998) that occurred in Georgia during 1994 and 1997 showed that much of the potential economic damage was ameliorated by large tracts of intact riparian areas.

Studies examining the impact of removing stream corridor habitat have also illustrated their value in terms of flood attenuation. Empirical research conducted by Brody et al. (2008) found that the loss of wetlands across 37 counties in Texas significantly increased the observed amount of insured flood damage from floods, with evidence that wetlands found within the floodplain being more valuable than those outside of the floodplain (Highfield and Brody 2006). Similarly, an analysis by Brody et al. (2014) found that forested areas and wetlands significantly attenuated flood damage with palustrine wetlands being the second most powerful predictor. Proportional losses of wetlands have been shown to decrease watershed storage and increase flood peaks. For example, Ogawa and Male (1986) found that encroachment of wetlands, particularly mainstem floodplain wetlands, significantly increased peak flows. Others have illustrated that small wetlands losses (< 10%) can have major effects on flood flows (Johnston et al. 1990).

Evidence of the flood mitigation value of natural habitat can also be found within studies that examine the effect of converting natural habitat into development. Most of these studies have illustrated that the conversion of natural landscapes (such as wetlands) to accommodate development undermines the hydrological processes of watersheds to absorb, store, and slowly release water. Many empirical studies and observational evidence indicate that increased imperviousness increases surface runoff (Carter 1961; Tourbier and Westmacott 1981). For example, White and Greer (2006) found that as impervious surfaces increased from 9 to 37% within the Pensaquitos Creek watershed in southern California, total runoff amplified by nearly 200% over their study period (1973-2000). This spread of impervious surfaces frequently occurs in ecologically sensitive areas near streams. Brody, Davis, et al. (2008) in their study found that these impervious surfaces were characterized by low intensity, sprawling development which were driving the increase in wetland alteration permits along the Gulf of Mexico.

Importance of Stream Corridor Landscape Configuration

Landscape heterogeneity is crucial for numerous ecological processes such as nutrient dynamics, energy flow and movement of organisms and materials (Foley et al. 2005; Kareiva et al. 2007; Turner et al. 2001). Biodiversity is affected when the landscape is reconfigured by anthropogenic disturbances such as agriculture and urban development, which compromises the capacity for landscapes to deliver ecosystem goods and services (Assessment and others 2005; Tscharntke et al. 2005). The ecosystem services provided by floodplains are especially susceptible to landscape changes (Kepner et al. 2012), which can affect water quantity by altering ecohydrological processes (Brauman et al. 2007) and hydrologic flow (Qiu and Turner 2015). Many of the studies discussed above that examine the impact of impervious surface or habitat loss focus primarily on the effects of landscape composition (i.e. proportion of land cover) rather than configuration (i.e. spatial arrangement of cover types). However, empirical and theoretical evidence indicates that landscape configuration (e.g., connectivity, proximity, contagion, etc.) may mediate the transport of water across the landscape, thereby influencing hydrologic services such as flood attenuation (Alberti et al. 2007; Gergel 2005; Soranno et al. 1996; Weller et al. 1998, 2011).

Ziegler et al. (2006) argues that landscapes can be viewed as a mosaic of surfaces differing in the propensity to generate overland flow, which is caused when rainfall rates exceed the surface's storage capacity. The degree to which habitats can buffer overland flow depends on the frequency at which those habitats are located below upslope overland flow source areas. As habitat fragmentation increases so too does the likelihood that overland flow will reach the drainage network unimpeded (Ziegler et al. 2004). Overland flow that does not encounter pervious sinks before encountering the hydrologic network will have the greatest impact on streamflow (Ferreira et al. 2016). Corroborating this was a study conducted by Pappas et al. (2008) which found that impervious surfaces located in low-lying, downslope areas adjacent to the stream network delivered runoff more quickly and in greater amounts than areas with impervious surfaces located in upslope areas.

Land cover surfaces that generate large amounts of overland flow, such as impervious surfaces, tend to coalesce in urbanizing watersheds leading to more runoff and damaging flood events. Connected overland flow areas facilitate the formation of long flow paths that concentrate surface runoff and compromise the effectiveness of downslope buffers. Small, disconnected riparian buffers are often insufficient for attenuating excessive overland flow from large storms when several flowpaths converge (Ziegler et al. 2004). As a result, many have argued that wider riparian buffers are required in increasingly urbanizing watersheds to maintain desired functionality (Barton et al. 1985). Other studies that have examined the effect of urban development patterns on flood damage have found that low-intensity development tends to amplify surface runoff more so than developments with higher imperviousness by spreading impervious surfaces over larger areas. Although somewhat counterintuitive from an impervious surface perspective, the thought here is that low-intensity developments tend to fragment hydrological systems particularly within sensitive flood-prone areas (Brody et al. 2015).

Examining the biophysical characteristics of habitat patches in landscapes with varying degrees of fragmentation can also help explain how habitat configuration influences rainwater movement through the landscape. Vegetation within fragmented forests as a result of land cover conversion typically have different physical characteristics than the replacement vegetation at least initially (e.g. root mass/depth/turnover, total biomass, leaf area index, leaf morphology) (Ziegler et al. 2004). Therefore, it could be argued that the mechanisms and pathways that partition rainwater (i.e. canopy interception, infiltration, and water ponding) differ on replacement land covers as compared to undisturbed forests (Bruijnzeel 2000; Giambelluca 2002; Zimmermann et al. 2006). Moreover, reduced soil infiltrability on converted land has been found to occur (Malmer and Grip 1990), leading to even greater increases in overland flow.

Stream corridor habitat, like floodplain forests, are particularly sensitive to fragmentation. Previous studies have found that habitat fragmentation of floodplain forests alters the regional mix of community types, with increasing fragmentation leading to the establishment of dry zone, younger seral stage community types (Rudis 1995). The likely underlying explanation for this process is that flood control infrastructure is often accompanied by land clearing and drainage (Turner et al. 1981). The removal of forest cover changes the floodplain's seasonal water table creating a cascading effect on surface litter decomposition, species regeneration with a simultaneous increase in solar radiation and wind exposure. Mature stands of floodplain forests could regenerate and stabilize if left undisturbed, however increased road access and persistent drainage improvements suggests a continuing human-mediated disturbance pattern (Rudis 1995).

Fragmentation of stream corridor habitat also increases the potential for invasive species that cannot withstand flood disturbance, cannot slow overland flow as effectively, or recover as quickly after a disturbance has occurred leaving surrounding and downstream development more vulnerable to flood damage (Birkland et al. 2003). Thus, fragmented stream corridors consisting of small and fragmented floodplain habitat that are disconnected from the drainage network may be a byproduct of a poorly functioning ecosystem that is less capable of providing critical ecosystem services like flood attenuation. In order to maintain this important societal service riparian habitat must be able to withstand flood and anthropogenic disturbances. One of the key criteria for the persistence of riparian ecosystems is connectivity, which maintains the biological connections between otherwise fragmented patches and thus promotes recruitment (Gillies and Clair 2008). Riparian ecosystems will become increasingly vulnerable to disturbances as fragmentation increases, which could ultimately push the ecosystem across an irreparable threshold.

One of the few empirically verified configuration metrics that influence the capacity of stream corridor habitats to attenuate peak flow is habitat size. Recent studies have found that wetland patch size influence their functional role. For example, Cohen and Brown (2007) used a dynamic system model to compare stormwater management of an undisturbed hierarchical drainage network of treatment wetlands. What they found was that sediments were removed by small upland wetlands and water flow was attenuated by large secondary wetlands. Other studies have illustrated that larger, downstream main-stem wetlands have greater capacities to offset peak flows than smaller upstream tributary wetlands (Ogawa and Male 1986).

2.2 The Flood Control Infrastructure Paradigm

Synthesis

The U.S. has historically relied on flood control infrastructure (FCI), such as channelization and levees, to protect communities from riverine flooding. The investments in such practices has not only limited physical losses, but economic losses as well. For example, the U.S. Army Corps of engineers estimated that flood damages between 1991 and 2001 totaled nearly $45 billion, however, damage estimates without FCI would have increased this total by an additional $200 billion. Cost savings calculations of FCI, however, often fail to account for many of its costs. First, storms can exceed the design capacity of the structural mitigation resulting in more damage to occur than if the FCI had not been installed in the first place. Second, FCI can lead to a false sense of security that often results in an increase of development in flood prone areas. Third, the multi-functional value provided by natural stream corridor habitat is overlooked by the single purpose of minimizing flood damage resulting in large scale ecological deterioration. Finally, the increase in conveyance efficiency provided by FCI often results in an increase in flood risk for downstream communities. Despite these costs cities in the U.S. continue to rely on FCI because it is assumed that urbanized floodplains only have two options: retreat or control. Retreat is seen as being politically infeasible and expensive resulting in a continuation of FCI installation. The outcome of this trend, or paradigm, is the erosion of flood resilience through the creation of inundation intolerant floodplains where even small floods can cause widespread damage.

Flood Control Infrastructure in the United States

Flood control in the U.S. has historically relied on structural public works to manage floods (Gruntfest and Wohl 2000; May and Williams 2012; May 1996). These strategies involve the use of levees, floodwalls, dams, channelization, and straightening of river channels to control both the direction and velocity of floodwater. The demand for flood control infrastructure (FCI) stemmed from an increase in floodplain development coupled with periodic inundation from large storms. A product of this cycle were a multitude of Flood Control Acts (1917, 1927, 1928, 1936, 1938, and 1944) (Tobin 1995) almost all of which showed a bias towards structural measures that aimed to eliminate flood problems (Johnston 1992). Much of the infrastructure built during this time is still in use today.

The amount of funds invested in FCI since the passage of these Flood Control Acts has been significant. From the 1940s on, the U.S. Army Corps of Engineers (USACE) spent over $100 billion on structural flood control projects (Stein et al. 2000). Some of the most expensive forms of FCI have been built fairly recently and include large-scale structures (e.g. seawalls, and gates) to protect inland communities from storm surge. An examples of this is New Orleans' $14.5 billion flood control system that was built in response to Hurricane Katrina in 2005.

FCI proliferated across the U.S. during the 20th century as a result of Federal policies and funds. There are now over 25,000 miles of levees, floodwalls, embankments, and dikes throughout the U.S. (Johnston 1992). Providing protection up to the 100-year flood to an estimated 5,000 square miles and 1,000 communities (Johnston and Monday 1994). The number of dams at least 6 feet in height exceeded 75,000 by the end of the 20th century (of Engineers 1996), impounding at least 62,500 m^3 of water leaving only 2 percent of the nation's rivers unaffected with 18 percent under the waters of reservoirs (Graf 2001).

The obvious goal of FCI is to prevent, or at least minimize, flood damage from occurring by keeping floodwaters away from buildings and structural assets. Calculating the cost savings from such investments is a complicated task and is often met with contention. However, analyses have shown that these structures have provided a degree of protection. Damage avoided from inland flood events has been estimated by USACE to be as high as $19 billion for the Midwest flood of 1993 (Burby et al. 1999), and they claim to have prevented a total of $706 billion in damage while only spending $120 billion on FCI during the 20th century (of Engineers 2009).

One of the most common forms of FCI within urban drainage systems are open channels. Although there are multiple ways to design open channels, the most widely implemented form also happens to be the most destructive. This channel design consists of replacing the entire river channel and much of the floodplain with a smooth trapezoidal-shaped concrete conveyance structure with walls high enough to contain design flows (Greco and Larsen 2014). These structures are built with the single objective of maximizing conveyance efficiency. To do so, the design of open channels seeks to maximize open channel flow by increasing stormwater velocity and minimizing in-channel roughness caused by things like trees and boulders (Dunne and Leopold 1978).

Other research has indicated the intimate relationships between riverine hydrological dynamics and riparian plant species establishment and survival (Scott et al. 1997; Shafroth et al. 1998). As hydrological dynamics shift so too do the composition and distribution of riparian species because they have adapted to what is referred to as a “natural flow regime” (Poff et al. 1997). Thus, the spatial pattern of riparian habitat will be disrupted as different forms of structural mitigation are applied within a watershed to regulate the flow of water (Hupp and Osterkamp 1996; Scott et al. 1996).

Undesirable Consequences of Flood Control Infrastructure

One the most commonly cited undesirable consequences of FCI is the fact that flood losses continue to mount, despite efforts to control rivers (Michener and Haeuber 1998). An assessment of flood damage from the first 20 years and the last 20 years of the twentieth century show an increase in annual flood loss from $1.76 billion to $4.4 billion (NOAA 2000). In general, the data has shown increasing damages from low frequency, catastrophic flood events that have overwhelmed flood control structures inundating communities located in flood prone areas (Conrad et al. 1998; Kolber 1999). A review of the literature shows that there are several reasons that help explain the trend and include: 1) increase of instream flow velocity and greater flooding downstream; 2) a decrease in flood risk perception due to a decrease in flood frequency; 3) increased development (and imperviousness) in previously unprotected areas; 4) an increasing reliance on FCI; and 5) a loss in the functionality of hydrological ecosystems. All of these taken together erode the resilience of cities to catastrophic floods when the FCI either fails or encounters a storm that it was not designed to withstand. Liao (2014) furthers this argument by explaining that FCI locks the "human-river system" into a perpetual state of increasing control, precluding the ability for cities to adapt to small scale, periodic flood events. It is for these reasons that structural approaches to prevent flood damage has been repeatedly criticized (Mount 1995; Philippi 1996; Smits et al. 2006; White and others 1945).

A common assumption is that engineered structures can prevent if not eliminate riverine flooding (Tobin 1995). Flood control projects can drastically alter the geomorphology of rivers often resulting in stream flow characteristics that decrease flooding locally (Lehner et al. 2011). However, FCI has the concomitant effect of exacerbating flooding downstream. FCI typically raises the level of the river by constricting the waterway and the floodplain resulting in faster moving water and larger peak flows downstream (Birkland et al. 2003). An analysis of historical gauge data along with Missouri and Mississippi rivers found that flood stages had increased 2 to 4 meters during the 20th century at constant discharge owing much of this effect to FCI, particularly channelization and levees. The same study found no such trend in similar rivers with little to no FCI (Criss and Shock 2001). To put it another way, the potential energy of peak flood water increases proportionally with channel restriction at the watershed scale. The correlation between potential energy and flood damage, although undocumented at this scale, seems inescapable.

Further undermining the assumption that FCI prevents flood damage is that it has also been shown to increase, if not promote, development within previously flood prone areas. This trend leads to higher potential losses and has been referred to as the levee or escalator effect (Parker 1995; Tobin 1995). In short, these concepts illustrate that communities expand onto floodplain lands after they have been protected by some sort of flood control structure, placing more property at risk. Two underlying concepts have been blamed for this phenomenon: a decrease in flood risk perception and the elimination of the requirement to purchase flood insurance in protected areas. One of the primary objectives of the National Flood Insurance Program (NFIP) is to prevent development within the floodplain. However, houses protected by certain types of FCI are considered “out of the floodplain” thereby indirectly encouraging development by waiving the requirement to purchase flood insurance for homeowners with federally backed mortgages (Montz and Tobin 2008), which some have referred to as the safe development paradox (Burby 2006). Others have argued river dynamics are largely unnoticed as a result of confining water between levees or behind dams or within channels. In doing so, this removes one of the primary drivers that influence an individual’s risk perception: previous experience with flooding. As the interval between experienced storms increases, the less likely previous experience will influence purchase behavior (Kriesel and Landry 2004). In short, the reduced frequency of small scale, high probability flood events increases the severity of large scale, low probability flood events by increasing development in flood prone areas via a false sense of security and a flood insurance shortcoming.

An important positive feedback emerges when FCI is installed, which often requires more FCI to protect the development that it may have indirectly (or directly) attracted, leading to the creation of cities that are highly resistance but not resilient to floods. Some have argued that the increasing rate of floodplain urbanization as a result of this feedback mechanism is the primary driver for the increasing flood losses (Changnon 2003). Resilience theory suggests that flood resistance can undermine flood resilience (Holling and Meffe 1996) by placing the city within the state of either dry and stable or inundated and disastrous. In this scenario, flooding is a result of FCI failure with little flexibility for adapting to shifting boundary conditions (Pahl-Wostl 2006).

Increased resistance to flooding via FCI can result in dramatic changes in a watershed's flow regime. Often times flood control projects will shorten, narrow, and straighten river systems, severing the main channel from their floodplains (Lehner et al. 2011). As a consequence floodplain habitats no longer are subjected to natural flood pulses that are necessary for their survival ultimately leading to a loss of flood attenuating habitat such as wetlands and riparian forests. Multiple examples of this trend have been illustrated by historical flood events. One example can be found in the Mississippi Basin, where one of the most severe flood events in U.S. history occurred during 1993. Gosselink et al. (1981) calculated that the forested riparian wetlands adjacent to the Mississippi during pre-settlement times had the capacity to store approximately 60 days of river discharge. However, the subsequent removal of wetlands via channelization, leveeing, and drainage reduced the storage capacity to 12 days. Daily et al. (1997) attributes much of the severity of the 1993 flood (the most severe flood in U.S. history at the time) to the loss of this ecosystem service. Key ecological patterns and processes that are essential for floodplain ecosystems are not considered in conventional flood control channel design (Greco and Larsen 2014) and the loss of their functionality is rarely, if ever, included when calculating FCI cost savings.

2.3 The Non-Structural Approach to Flood Loss

Synthesis

In contrast to FCI are nonstructural forms of flood mitigation such as land use and zoning regulations, land acquisition, open space preservation, and environmental restoration programs that may prove to be more effective and sustainable (Gruntfest and Wohl 2000). Complementing the nonstructural approach is the restoration of the natural functions of rivers and floodplains by undoing preexisting structural works. This approach has gained ground more recently as a result of largescale losses of stream corridor habitat and the ecosystem services they provide as well as the increasing recognition of the limitations of FCI. Many of these sustainable flood mitigation alternatives argue that the regeneration and reclamation of natural habitat can perform the role of flood attenuation while simultaneously providing many other ecosystem services. Supporting this approach was a recent assessment of different scenarios of flood control systems by Greco and Larsen (2014) who found specific ecological principles (e.g. wider and rougher streams) that could accommodate the 200-year flood and meet other conservation efforts, which they refer to as multifunctional flood control.

Non-Structural Flood Mitigation through Land Use Management and Policy

Traditional forms of non-structural flood mitigation include land use management and policies that guide development away from flood-prone areas such as floodplains and river bottoms (Beatley 2009). Specific land use policies have often been cited as a particularly effective form of flood hazard mitigation (Berke and French 1994; Berke 1996; Burby and others 1991; Burby et al. 1999; Sheaffer et al. 1976). These practices have included wetland preservation, wildlife habitat creation, recreational and open space requirements, and, to a limited extent, promoting low intensity agriculture (Birkland et al. 2003). However, one of the best ways to improve land use policies is to make them more spatially targeted such as place-based land use regulations like clustering of development, conservation overlay zones, and transfer of development rights (Highfield et al. 2014). The incorporation of environmental overlay zones and land use restrictions on residential development in flood hazard areas can complement land acquisition efforts. Any land use policies that proactively prevents development from occurring within the floodplain exposes fewer lives and property to flood risk while also simultaneously protecting natural habitat and the integrity of the hydrological system (Birkland et al. 2003; Whipple Jr 1998). Other non-structural policies that could complement hazard mitigation plans include public education and training, taxation and fiscal incentives, flood warning systems, relocation of structures, and directed public infrastructure investments (Olshansky and Kartez 1998).

Land use management policies have often been difficult to implement despite their promise as a cost-effective hazard mitigation tool. One of the main reasons why limiting development in floodplains is disregarded is because local governments often ignore proactive measures until a problem has surfaced. This has been referred to as the “land use paradox” which essentially illustrates that local governments have a difficult time valuing land use approaches to flood mitigation until a problem is evident (Burby and French 1981). Land use policies are either ineffective or too expensive once the problem has become entrenched. Other issues include the fragmented nature of local governments and that their boundaries are not aligned with ecological zones, a confounding plurality of competing local preferences, economic development needs, and a belief among landowners that property rights are absolute (Birkland et al. 2003).

Strategies to overcome the difficulties of non-structural mitigation at the local scale include the National Flood Insurance Program’s (NFIP) Community Rating System (CRS). The CRS is the most comprehensive national program for incentivizing local communities to implement primarily non-structural flood mitigation techniques, and was created by FEMA to encourage communities to exceed the NFIP’s minimum standards for floodplain management. Communities that participate earn points for various flood mitigation activities in exchange for federal flood insurance premium discounts, ranging from 5 to 45 percent. The non-structural orientation of the CRS program is categorized into four “series” containing 18 mitigation “activities”. Credit points are assigned to participating CRS communities based on the degree to which different flood mitigation activities are implemented, but not all activities carry the same amount of points (FEMA 2013). Cost savings are not limited to premium reductions alone, but can also be witnessed in terms of avoided flood damages. Studies of the CRS program have shown its overall effectiveness in reducing flood loss as well. For example, a state-wide study in Florida found that a change in CRS class equaled, on average, a $303,525 decrease in the amount of damage per flood (Brody et al. 2007). A parallel analysis on the Texas coast showed that an increase in CRS class translated into a $38,989 reduction in the average property damage per flood (Brody, Zahran, et al. 2008).

More recent studies have examined the ability of specific CRS mitigation activities at offsetting historical flood loss. A national study conducted by Highfield and Brody (2012) found that open space protection (i.e. CRS Activity 420) was one of the most effective in reducing observed losses. Open space protection is considered a key element of an avoidance based approach to reducing flood risk that involves relocating, moving, or steering development away from vulnerable areas while simultaneously increasing the ecological functionality of floodplains. Implementing open space preservation can involve a wide range of techniques including "buy-outs", purchase of development rights, conservation easements, and regulatory and inventive-based land use policies. Highfield and Brody (2012) found that the dollar savings of a one-point increase in the activity for preserving open space in the floodplain was equal to, on average, $3,532 per community/per year. Considering the average amount of points accrued for open space protection among communities in the study sample, the total savings per year for this activity was equivalent to, approximately $591,436. This finding was further corroborated with a more recent study by Brody and Highfield (2013) that found that if communities within their national sample would have saved nearly a million dollars per year if they were to maximize their point totals for open space protection.

Reducing Flood Risk by Restoring Floodplains

The undesirable consequences of FCI, coupled with the increasing recognition that riverine habitats provide critical ecosystem services, has generated largescale interest in restoring floodplains as part of an integrated planning and management approach to flood risk reduction (Opperman et al. 2009; Thorp et al. 2010). Much of this initial interest in river restoration emerged in response to the environmental degradation and unwise occupation of floodplains caused by dams. This triggered a shift away from promoting flow stability through command and control forms of river management towards a flood hazard management program based on ecological resilience by fostering natural flow regimes. As a result, the U.S. witnessed the removal of defunct and underutilized dams, changes in operating rules of dams to mimic natural flood pulses, and the re-engineering of structures to increase downstream naturalness (Graf 2001).

Other forms of FCI removal have more recently been implemented. The primary objective of these interventions is similar to that of dam removal: to restore the natural functionality of floodplains. To accomplish this objective, floodplain habitat, like wetlands and riparian forests, must be reconnected (i.e. exposed) to periodic inundation from rivers which can only be accomplished through the strategic removal of FCI like levees and concrete channels (Opperman et al. 2009). In doing so, this regenerates the ecological processes that sustain floodplain habitat and increases the natural storage capacity of floodplains thereby alleviating downstream flooding. Although large scale reconnection of floodplains is fairly uncommon in the U.S., it is not unprecedented. In California, the Yolo Bypass was created to divert water away from Sacramento by reconnecting the Sacramento River with a 24,000 ha floodplain (Kelley 1998). With this bypass in place, the City was able to convey three times as much flood control storage volume in all Sacramento basin reservoirs into the floodplain during a storm in 1986 when the local flood control system was operating near maximum capacity (USACE 1999). Heavy investments in additional FCI would have been required to prevent large scale damage to Sacramento had the bypass not been in place.

More recently, the Dutch have pioneered an integrated form of river basin management referred to as the “Room for the River Program”. This plan emerged after decades of controlling rivers with large civil engineering projects resulted in significant population growth in floodplains that was becoming increasingly vulnerable to higher peak discharges and sea level rise (Klijn et al. 2004). This control paradigm came under scrutiny in 1995 when the Rhine and Meuse Rivers breached their dykes causing the evacuation of a quarter million people (Zevenbergen et al. 2015). The Dutch came to the conclusion that nature cannot be controlled and that they must seek alternative methods for managing flood risk. This realization started the transition away from fighting against the water and towards working with the water (Rijke et al. 2012). The central element of this new philosophy was enhancing the river’s discharge capacity by enlarging the floodplain area through, for example, flood bypasses, excavation of floodplains, dike relocation and lowering of groynes (Klijn et al. 2004). Key to the success of this program was its multilevel governance design covering a broad range of stakeholders that leveraged centralized and decentralized decision-making processes, which helped to achieve a multitude of objectives such as flood reduction, transport capacity, recreation, ecosystem regeneration, water supply, and water quality (van den Brink 2009).

Key ecological design parameters and concepts must be implemented otherwise multifunctional flood defenses will not be able to fully leverage the flood mitigating benefits of natural floodplain habitats. Opperman et al. (2010) synthesized the concepts from previous literature of what makes floodplains ecologically functional and found that there are three basic elements: (1) hydrologic connectivity between the river and the floodplain, (2) a variable hydrograph that reflects seasonal precipitation patterns, and (3) sufficient spatial scale to encompass dynamic processes for floodplain benefits to accrue to a meaningful scale. More recent studies have argued that adopting a regenerative design paradigm coupled with reconciliation ecology is necessary to sustain productive river systems (Greco and Larsen 2014). Regenerative design for multifunctional flood defense is a process-based river restoration method that encourages floodplain forest regeneration by designing flood control channels with high Manning's *n* roughness coefficients and wide floodplains to increase channel conveyance (Beechie et al. 2010). These concepts are rooted in the Flood Pulse Concept which argues that floodplains and large rivers should be viewed as interacting components of a single system. In their article, Opperman et al. (2010) take it a step further by bringing together floodplain geomorphology and riparian landscape ecology to illustrate how vegetative communities develop in response to a natural disturbance regimes over time. The key point in their article from a landscape configuration perspective is that larger, more contiguous patches of floodplain habitat may be required to match the scale of the disturbance regime, which maintains internal recolonization sources or what Pickett and Thompson (1978) refer to as 'minimum dynamic area'. In short, flood resilient human development should design around the geomorphological and hydrological characteristics that dictate the processes that create healthy riparian systems.

2.4 Previous Research and Expected Results

This study builds off of two previously peer reviewed articles. The first examines the impact of land use/land cover (LULC) characteristics on insured flood losses within a coastal watershed in southeast Texas. This study used empirical models to calculate the influence of different LULCs within a 0.5 mile buffer of 7,900 properties claiming insured flood losses from 1999-2009 (Brody et al. 2014). This research found that:

- The pattern of development significantly influences the amount of adjacent flood losses. More specifically, clustered development have the greatest effect on reducing flood damage whereas sprawling, low-density development experienced significantly more flood loss.
- Palustrine wetlands, a key constituent of stream corridors, were the second most powerful LULC variable in mitigating flood damage. However, estuarine wetlands did not have a statistically significant effect on reducing flood loss likely because they are a coastal ecosystem and may not effectively suppress surge.
- Other natural land cover types, particularly grasslands and forests, also significantly reduced flood losses throughout the study area.

The second study examines the influence of LULC on flood losses along the Gulf of Mexico from 1999 to 2009. This particular study expands on the previous one by including 2,692 watersheds that have a wide variety of land use configurations, socio-demographics, and geographic characteristics. It also advances the previous research by scaling up the unit of analysis to the watershed, utilizes new statistical procedures to account for temporal factors, and also examines flood losses across different floodplain hazard area designations. Many findings within this article helped define the direction and scope of this study. The finding of particular interest is that a percent increase in palustrine wetlands is equivalent to, on average, a $13,975 reduction in insured flood losses per year, per watershed.

These two studies provide a strong theoretical, conceptual, and methodological background for this proposed study. The second one in particular is useful because it provides a dataset that already has many of the same control variables aggregated to the same unit of analysis. It is clear that specific types and compositions of LULC provide significant reductions in insured flood damage. However, these studies still leave many questions unanswered, particularly with regard landscape characteristics and flood control infrastructure, which this study attempts to answer.

Given the findings from these two studies along with the insights from the literature review it is expected that this study will find significant influences of stream corridor habitat and FCI on insured flood losses. More specifically, it is expected that previous findings regarding palustrine wetlands and forests will be corroborated. That is, increasing the percent area of these two land covers will decrease insured flood losses within the floodplain. If specific land cover types, like floodplain forests, do significantly decrease flooding, then composition (i.e. percent area) will have the largest influence. However, it is also expected that land cover configuration (i.e. connectivity) will also have a statistically significant impact on insured flood loss, but will be secondary to composition. In other words, a floodplain composed of 20% palustrine wetlands will have fewer insured flood losses than a floodplain with 10% palustrine wetlands because it will be able to attenuate flood water more effectively. However, if both of the floodplains had an equivalent amount of palustrine wetlands but one was more connected, then the effect of habitat connectivity on reducing flood loss may not be as large but significant nonetheless. More contiguous patches of wetlands and forests likely attenuate flood water more effectively, which is why it is hypothesized that they will help mitigate flood loss. However, the connectivity of floodplain habitat may also be an indicator of several watershed level characteristics: 1) greater physical and biological integrity; 2) a more natural and periodic flood regime; 3) more clustered urban areas; and 4) stronger floodplain development restrictions.

Hypothesizing the magnitude of effect that FCI has on insured flood loss is difficult because of a lack of studies that have examined the relationship between flood risk and flood control. However, the effect of FCI on insured flood loss within the floodplain is hypothesized to increase or remain unchanged with increasing FCI. As discussed in the literature review, FCI does reduce flood loss locally. However, the cost savings of FCI are hypothesized to be offset by its displacement of flood attenuating natural habitat, attraction of development into flood prone areas, propensity to increase downstream flood risk by increasing storm water velocity and peak flows, and tendency to lower flood risk perception. How much of the potential benefits of FCI are offset by these factors will largely determine the magnitude of the effect of FCI on insured flood losses within the floodplain.

2.5 Limitations and Gaps in the Literature

The literature indicates that flood risk cannot be eliminated entirely. Previous attempts at minimizing flood risk through the use of flood control infrastructure have neglected the reciprocal links within the human-stream corridor system. The outcome of these single objective approaches to flood mitigation has resulted in large-scale deterioration of floodplain ecosystems, the loss of flood risk perception, and increased development in flood prone areas. This trend has triggered a shift from working against the river towards working with the river. Emerging from this shift is the new science of socio-hydrology (Sivapalan et al. 2012) that conceptualizes settled floodplains as deeply intertwined human-flood systems (Baldassarre et al. 2013). Planning policies, insurance programs, and urban designs in coastal areas that do not adequately recognize this are likely to continue undermining flood resilience in favor of flood resistance.

Although there have been promising management schemes in California and the Netherlands that have taken on river management in a more integrative approach, there are still large gaps in the underlying knowledge base. In general, there is a lack of understanding pertaining to the link between landscape pattern and the provisioning of ecosystem services or hydrological processes at any scale (Laurance et al. 1998; Ziegler et al. 2004, 2006). Part of the problem is that there is a lack of empirical data, tools, and guiding principles to design multifunctional green infrastructure (Lovell and Taylor 2013). Studies that have documented the provisioning of riparian or wetland ecosystem services often do so in isolation of the influences of flood control infrastructure, without considering the spatial configuration of the landscape, and with limited data on how to measure benefits of specific strategies in real dollar amounts. It is difficult to understand, much less communicate, how these multifunctional flood defenses or floodplain restoration projects will pay off in the long run without a scientifically rigorous empirical valuation. Investigations are needed that provide a quantitative understanding of how FCI and stream corridor habitat influence flood damage for science-based urban land use decisions.

That said, interest in reforestation projects as a means of reducing flood risk has been around for a while. However, the ability of forests to reduce the severity of major floods and whether the consequences of these events is due to the loss of natural land cover continues to be a highly contentious topic (Laurance 2007). A study in North Carolina found no relationship between human-induced land cover changes and flood severity from 1930 to 2000 (Lecce and Kotecki 2008). The perception that natural habitats can mitigate flooding has significant implications for land use management and planning. Recent large flood events in China, Bangladesh, and Columbia have led to large investments in reforestation with little evidence of their ability to reduce the impacts of flooding (Hofer 2005; Mogollón et al. 2016; Trac et al. 2007). However, these analyses fail to acknowledge that damaged ecosystems pass through a reorganization phase and that different ecosystem components return to “normal” conditions at different rates. It could be argued that these studies have not allowed a sufficient enough time to pass to allow for the benefits of ecosystem services to start to accrue (Michener and Haeuber 1998).

Finally, the ability to achieve a natural disturbance regime might be prohibitively difficult in highly-modified urban landscapes, especially when space is limited. If so, this would undermine the ability to restore the ecological functionality of floodplains (Hubbart et al. 2011). Achieving some ideal pre-settlement river regime is likely impossible meaning that most restoration efforts will have to include a mixture of artificial and natural systems (Schmidt et al. 1998). However, there has been progress with the naturalization of river discharges by changing the operating rules of dams to more closely mimic natural flows (Michener and Haeuber 1998). Others have argued that the concept of reconciliation ecology can be used to find ways to re-engineer human landscapes to include more ecological functionality in novel and analogous ways (Lundholm and Richardson 2010).

3. RESEARCH FRAMEWORK

The literature review illustrates that human interactions with the stream corridor have been predicated on control. However, the benefits of control (e.g. increased water conveyance) may be outweighed by its costs (e.g. floodplain encroachment and habitat loss). As a result, many communities are considering alternative forms of flood mitigation based on non-structural mitigation activities (e.g. wetland preservation and floodplain avoidance). Although interest in natural floodplain functionality as a means of flood mitigation has increased, there has been a lack of study examining three predominant human-stream corridor interactions: natural habitat modification, flood control infrastructure, and open space preservation efforts. Measuring the impact of one of these activities without controlling for the others may not provide an adequate representation of their effect on mitigating actual flood damage.

Figure 1, below, illustrates the link between the variables of interest (i.e. stream corridor habitat and FCI) and insured flood loss within the 500-year floodplain. A central element of the model is the positive feedback loop between increasing floodplain development and increasing flood control infrastructure (FCI). Local flood loss decreases because of increasing FCI, creating a false sense of safety (i.e. safe development paradox) leading to more floodplain development, which in turn requires more FCI. This process produces two outcomes of relevance for this study: stream corridor habitat loss and increased flood water velocity. The loss and fragmentation of stream corridor habitat diminishes the floodplain's ability to provide flood mitigation as an ecosystem service. The increased speed at which floodwater moves through the watershed (i.e. increased conveyance efficiency) produces larger downstream peak flows. When combined, these three processes (i.e. increased floodplain development, loss of stream corridor habitat, and increased peak flows) are hypothesized to severely offset the local flood mitigation value of FCI at the watershed scale.

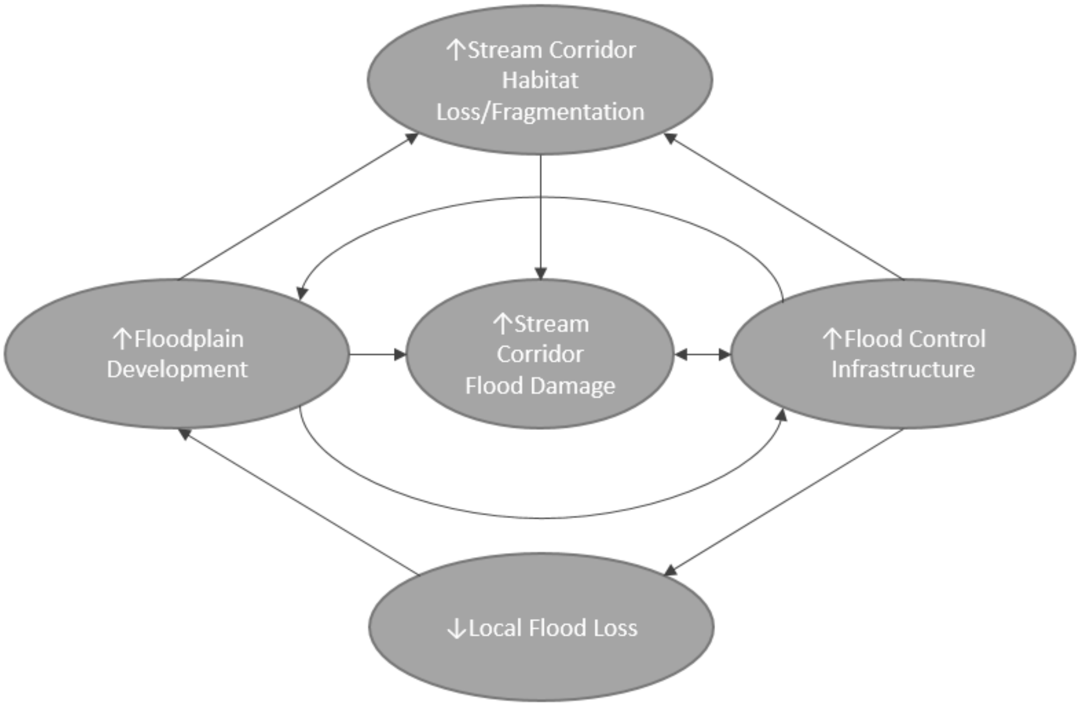

Figure 1. Human-Stream Corridor System

Using the human-stream corridor system illustration as a guide, I developed a conceptual model to highlight the relationship between insured flood loss and three variables of interest: 1) natural habitat modification, 2) flood control infrastructure, and 3) floodplain open space preservation (see: Figure 2). Statistical relationships between the independent variables of interest and insured flood loss are examined while controlling for several socioeconomic and biophysical controls. The orange boxes highlight the variables of interest, and their hypothesized relationship with insured flood loss within the stream corridor. A central element of the conceptual model is watershed hydrology, which can be thought of as streamflow velocity and peak flows. Increased peak flows and stormwater velocities increase the likelihood of flooding resulting in insured flood loss.

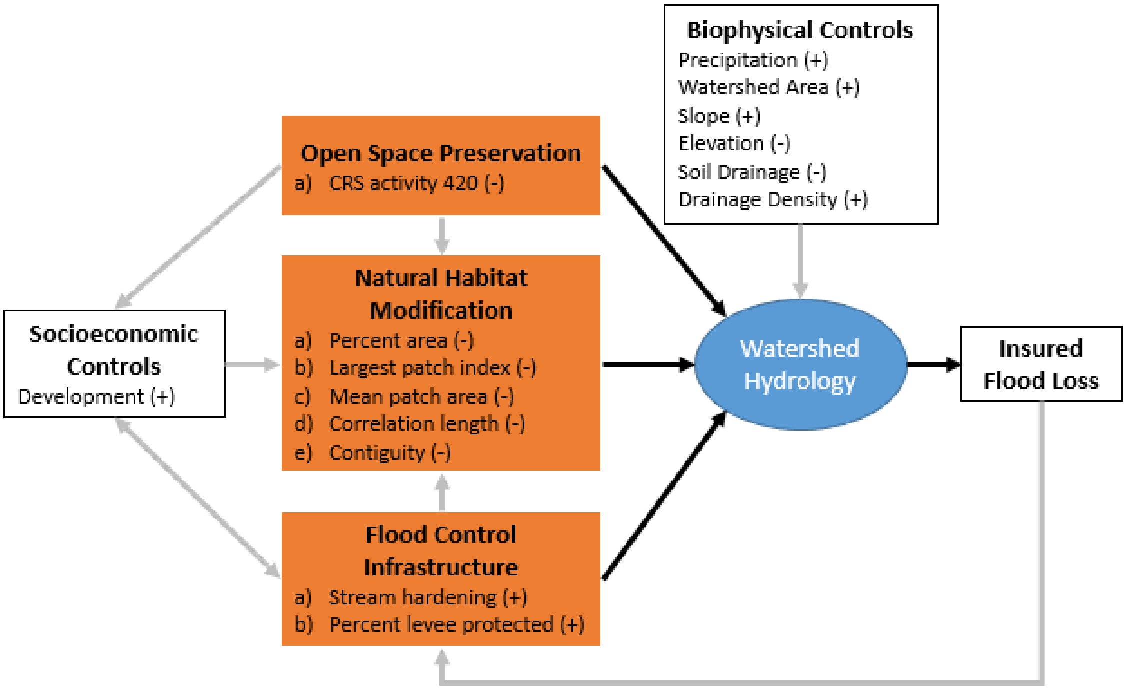

Figure 2. Conceptual Model

3.1 Dependent Variable

Flood damage, the dependent variable for the study, was measured as the dollar amount (contents plus building damage) of claims paid per household under the National Flood Insurance Program (NFIP). The NFIP is administered through the Federal Emergency Management Agency (FEMA) to provide flood insurance to residents and businesses. Structures located within the 100-year floodplain with a federally backed mortgage are required to purchase flood insurance. Although insured loss does not capture all flood-related damages, the saturation of NFIP policies in the study area is among the highest in the nation. Flood insurance is so prevalent within the study area that insurance uptake outside of the floodplain has been found to account for nearly half of the policies. Moreover, flood claims are geocoded to the parcel level allowing for the flexibility to aggregate damage to a particular scale of interest. These characteristics make insured flood loss a good proxy for overall damage.

3.2 Independent Variables

Floodplain Habitat Modification

Stream corridor habitat loss and modification can occur in a multitude of ways. Habitat loss occurs when habitat is either physically removed or slowly deteriorates because the natural disturbance regime that it depends on has been modified. Stream corridor habitat is removed typically as a result of human floodplain encroachment. This process can include urbanization within the floodplain and/or agricultural expansion. Anthropogenic occupation of floodplains typically requires the unpredictable nature of the natural flow regime to be more stabilized, predictable, and controlled. A more predictable flow regime provides a sense of security for development and the provisioning of water to crops when demand is high. All of these activities result in an overall loss of natural floodplain habitat, which can be measured as total area lost.

The percent of a land cover type (PLAND) can be used to estimate the influence of natural floodplain land cover on flood damage. PLAND is a measure of landscape composition and refers to the proportional abundance of a land cover type (LCT) within a landscape. Previous research conducted in the same study area by Brody et al. (2015) showed that watersheds with high proportions of palustrine wetlands experience less insured flood loss. Leitão et al. (2012) argue that PLAND is a fundamental aspect of landscape structure and is one of the single most important variables when describing landscapes. Much of its usefulness comes from its ease of calculation and straightforward and intuitive interpretation.

Although total area is a strong predictor of ecosystem provisioning like flood attenuation, it is equally as important to understand the spatial characteristics (i.e. configuration) of LCTs. Stream corridor habitat fragmentation is indicative of sprawling residential development occurring on land that had originally been left as open space or low impact uses (Brody et al. 2013). These types of developments require more infrastructure, such as roads and parking lots, thereby generating larger total areas of impervious surfaces (Brody et al. 2006). Moreover, ex-urban, fringe developments are more likely to occur within the floodplain (Shuster et al. 2005) where the impervious surfaces can act as direct conduits to the drainage network resulting in large increases in the magnitudes and frequencies of peak flows (Marsh and Marsh 1995).

The configuration of LCTs can be calculated using landscape metrics, which are frequently used by ecologists and conservation biologists (Ferreira and Botequilha-Leitão 2006). In particular, landscape metrics can be used to quantify the spatial patterns of landscapes to help better understand the status of ecosystem structure and function. In river systems, fragmentation implies that the functionality of the stream corridor has been impaired. Size, shape, and connectivity of stream corridor habitat all have an effect on the functionality of floodplain ecosystems. However, it is difficult to be prescriptive about the ideal patterns of habitat within the floodplain. Static riparian buffer widths do not sufficiently take into account the dynamic nature of riverine ecosystems both spatially and temporally. Moreover, the inherent variability and changeability of riparian ecosystems precludes the development of a comprehensive standard for the degree of habitat connectivity required to provide critical ecosystem services (Hughes 2003). Given the complexity and variability of floodplain ecosystems a suite of fragmentation metrics were selected as a starting point for measuring floodplain habitat composition and configuration, which include: largest patch index, mean patch area, correlation length, and contiguity.

Largest Patch Index (LPI) builds on PLAND by measuring the percent coverage of the largest patch in the watershed. LPI is a simple measure of landscape dominance of a particular land cover type. Larger, more continuous patches of natural floodplain habitat may be indicative of a stream corridor with a more natural flood pulse as a result of less FCI. Moreover, a single, large patch of natural habitat may likely be a key driver in flood attenuation at the watershed scale. Like PLAND it is simple to calculate and intuitive to interpret. It is expected that increasing LPI will reduce flood damage within the floodplain.

Mean patch area (AREA_MN) is simply the average patch size for a particular LCT. Area is a measure of landscape composition in that it indicates features associated with abundance without considering placement or location. This metric is considered a fundamental aspect of landscape structure and function, and is often a starting point for examining patch characteristics (Leitao et al., 2006). As discussed in the literature review, larger, more intact stream corridor habitat have a strong influence on mitigating damaging floods, with patch size having a direct impact on wetland functional roles.

Correlation length, also known as area weighted mean radius of gyration (GYRATE_AM), is a measure of how far across the landscape a patch extends its reach, or, put another way, the mean distance between each patch cell and the patch centroid. Generally, the more elongated or far-reaching the patch is across a watershed, the greater the radius of gyration. This metric is particularly useful for capturing elongated landscapes such as stream corridors. When aggregated at the class level using an area-weighted mean it provides a measure of landscape continuity or extensiveness, and has been found to be a good measure of overall habitat connectivity (Keitt et al. 1997). More recent studies have found this measure to be useful for measuring the physical continuity of forest patches across landscapes (Echeverria et al. 2006).

Contiguity index (CONTIG) assesses the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index of patch boundary configuration and patch shape. It differs from in GYRATE_AM in that it puts more weight on interior patch grid cells than perimeter grid cells, or, put another way, it weights orthogonally contiguous grid cells more heavily than diagonally contiguous grid cells. An interior patch grid cell is a single grid cell of a habitat patch that is entirely surrounded by habitat grid cells of the same class type. To give an example, a narrow patch with few interior grid cells will have a smaller contiguity index than a patch of the same exact area with more interior grid cells. In short, large contiguous patches result in larger contiguity index values.

Flood Control Infrastructure

Increased risk of flooding is typically met with infrastructure used to control or alter streamflow. This often results in a complex network of flood control structures that includes dams, levees, channelization, weirs, etc., which, when combined, can completely manipulate a basin’s hydrology. These structures have become so commonplace that over 75,000 dams measuring at least six feet now impound portions of every watershed in the U.S. (Graf 2006). These structures are built either to increase conveyance (i.e. moving water more efficiently away from development) (Greco and Larsen 2014) or increase residence time (i.e. increase the amount of water stored on the landscape) (Guenni et al. 2005).

Two common forms of FCI along the Gulf of Mexico include channelization and leveeing. Channelization is a form of channel engineering that is undertaken for flood control, navigation, drainage improvement, and reduction of channel migration potential. The outcome of channelization are rivers and streams that have more uniform channel cross-sections, steeper stream gradients, and reduced average pool depths. This type of modification often results in the following: increase stream velocities, eliminates channel-forming flood pulses; and increases erosion and sediment load. These modifications can result in higher stream flows during storm events, potentially increasing the risk of flooding (USEPA 2007).

Levees are embankment or shaped mounds built to reduce flooding by preventing storm flows from spreading into the floodplains. They are typically designed as longitudinal structures along rivers with the dual purpose of keeping stormwater within the channel and reducing the impacts of upstream channelization and channel modification (USEPA 2007). Although beneficial in terms of flood reduction levees do have negative consequences. One of which is an increase in flow by forcing water through a more confined area leading to increased velocity, erosion, and flood damage particularly in downstream locations (Bernard and Tuttle 1998). Finally, stream corridor habitats like riparian wetlands that depend on seasonal flooding are negatively affected by levees because they prevent naturally occurring flood pulses.

Open Space Protection

Open space protection within the floodplain is a key avoidance strategy for flood mitigation (Beatley 2009) for multiple reasons. The primary one is that it eliminates the opportunity for loss by removing people and structures from flood-prone areas. Riparian buffer zones and setbacks are common strategies employed within comprehensive plans that allow for natural flood pulses and fluctuations of riverine systems to occur and prevents damages to structures that would have occurred had they been placed closer to the stream. As a result, many have started to view this strategy as a horizontal equivalent of freeboard (i.e. elevation above base flood) (Medlock 2008). The second one, is that the protection of ecologically valuable habitat within the floodplain, as discussed in the literature review, increases the water storage capacity of the landscape thereby reducing flooding of surrounding and downstream developments. Finally, open space protection is usually implemented as part of a larger land-use and growth management plan. This could include the clustering of development within areas that are less flood prone or the use of low-density zoning that lowers the concentration of development in high risk areas by increasing the minimum lot size requirements. Open space protection often implies management by a specific institution such as a public agency or non-profit organization that can coordinate efforts and leverage external funds to enhance the functionality of the protected area. Measuring the degree by which communities protect floodplain open space can get at potential flood risk reduction that land cover imagery alone may not capture. One of the few available metrics that can be used to measure the degree of open space preservation that can be compared across communities and watersheds is the number of credits accrued for activity 420 within the Communities Rating System (CRS). Further discussion regarding the specifics of this activity are discussed within the concept measurement section.

3.3 Control Variables

Biophysical Controls

The first natural factor to take into consideration is associated with the watershed (or drainage basin). Although there are a multitude of basin characteristics that can affect various components of the stream hydrograph, this study will focus on those that specifically influence peak discharge, which is the primary measure used to define the magnitude of a flood event (Matthai 1990). At the watershed scale there are four primary geological factors that affect peak discharge: precipitation, basin area, soil drainage characteristics, slope, and stream network density.

Precipitation is the primary driver of the hydrological cycle. Studies that have focused on the impact on specific storms on peak flows have focused on two general structural properties of precipitation events: exterior and interior characteristics. The former is related to the depth and duration of precipitation, while the latter explains the spatial and temporal distribution of precipitation intensities throughout a storm cycle (Bras 1990). Although these concepts are important for measuring event specific impacts they are difficult to operationalize at the watershed scale over longer periods of time.

More recent research at the watershed scale has found other rainfall specific measurements that drive peak discharge and damaging flood events (particularly flash floods). These measures include antecedent rainfall (AR) and accumulated antecedent rainfall (AAR). AR represents the amount of rain the days immediately prior to a rain fall event, whereas AAR corresponds to total accumulated rainfall over a longer period. At the watershed scale these measures are primarily a function of the number of days a precipitation event exceeds a threshold (which can be defined using percentiles) (Ávila et al. 2015). In short, the greater the number of days above a given rainfall threshold the greater the likelihood for a flash flood event to occur.

The amount of rainfall converted to overland flow and ultimately streamflow is first influenced by soil characteristics. The amount of water that soil can retain is a primarily a function of texture and saturated hydraulic conductivity (i.e. the ease with which the pores of a saturated soil permit water movement) (Saxton and Shiau 1990). Calculating the amount of rain converted to overland flow as a result of soil characteristics is complex, but can be broadly summarized by the Soil Conservation Service's drainage class designation within their soil survey (SSURGO). This measure captures both soil texture and hydraulic conductivity.

The degree to which overland flow is then converted to damage peak flows, in terms of watershed geomorphological conditions, is driven in large part by the size of the basin and density of the drainage network. Drainage area has been found to be the most significant factor affecting flood magnitude (Matthai 1990). In general, the larger the contributing area the higher the peak flow from a given storm event. In some instances basin shape may play a large role in determining how particular characteristics of the hydrograph respond to a storm event (e.g. lag time) (Saxton and Shiau 1990). Many measures of basin shape have been developed to help explain basin hydrology, however, basin area has been found to have strong correlations with peak discharge and flood damage along the Gulf of Mexico coast (Baker 1977; Brody et al. 2015; S. Brody et al. 2011). The second component of basin geomorphology that influences peak flows is drainage density. In short, the literature has shown that peak flow increases proportionally with drainage density as a result of increased hydrological efficiency (Gregory and Walling 1968; Saxton and Shiau 1990).

Finally, the topography not only dictates the delineation of a watershed, but also has a strong influence on stream flow. The slopes of a watershed affect both the time of concentration and the amount of surface depression storage. The effect of basin slope can either augment or counteract the effect of basin shape and size. In general, steeper slopes have been found to reduce concentration time resulting in sharper and higher peak flows (Matthai 1990).

Socioeconomic Controls

Anthropogenic disturbances in watershed landscapes can significantly influence the hydrologic cycle. These impacts include reduction and changes to natural habitat, increases in impervious surfaces, alteration of the natural storage features and stream characteristics, and poor development decisions.

Human development creates impervious surfaces that prevent precipitation and overland flow from being absorbed by the landscape. Urbanization increases the expanse of concrete and other impervious surfaces through the creation of streets, parking lots, and other built structures all of which reduce the infiltration of water. Studies have found that relatively small changes in imperviousness can result in dramatic ecosystem changes. Others have argues that impervious surfaces can be used as a key environmental indicator. More importantly, imperviousness and runoff are directly correlated. To illustrate this effect, Schueler (1994) calculated that total runoff for a one-acre parking lot is about 16 time that produces by an undeveloped meadow. This effect, many have argued, turns what would have been a non-flood event into flashy, rapidly moving peak flows (Jennings and Jarnagin 2002; Sauer et al. 1983) influencing not only immediately surrounding areas but downstream as well (Michener and Haeuber 1998).

The problem of imperviousness is further compounded by fact that it typically replaces land cover types that have a greater capacity to retain water. Converting naturally permeable surfaces to less permeable or impermeable surfaces dramatically alters the hydrologic characteristics of watershed (Shuster et al. 2005). Moreover, increased watershed area that has been converted to an impervious surface may signal a decline in the ecological integrity of terrestrial and aquatic biological communities (Arnold Jr and Gibbons 1996). Lastly, and probably most importantly, the process of urbanization often places greater proportions of communities at risk of flooding by locating new developments in hazardous areas (Changnon 2003). This was further confirmed by Pielke Jr and Downton (2000) that found that precipitation alone could not explain the rising trend in national flood damages, but rather that societal trends were largely to blame.

3.4 Hypotheses

Previously reviewed literature has illustrated that the conversion of natural habitat to impervious surfaces via development can intensify flood damage. Researchers within the hazard mitigation and urban planning field have argued that efforts to control rivers and streams to prevent flood damage have actually increased the potential for catastrophic losses. The mechanisms that might help explain this outcome would be: (1) increased development in the floodplain; (2) loss of critical ecological habitat; and (3) increased downstream peak flows. Despite such knowledge there has not been any research connecting these human-stream corridor interactions together. This study is broken down into three overarching hypotheses:

1. The total amount of insured flood loss will significantly increase in stream corridors with more habitat loss and fragmentation.
    a. Increases in percent area of natural stream corridor land cover will significantly decrease insured flood loss within the stream corridor.
    b. Increases in the largest patch index of natural stream corridor land cover will significantly decrease insured flood loss within the stream corridor.
    c. Increases in mean patch area of natural stream corridor land cover will significantly decrease insured flood loss within the stream corridor.
    d. Increases in the correlation length of natural stream corridor land cover will significantly decrease insured flood loss within the stream corridor.
    e. Increases in the mean contiguity index of natural stream corridor land cover will significantly decrease insured flood loss within the stream corridor.

2. The total amount of insured flood loss within stream corridor will increase as the proportion of drainage length modified by flood control increases.
    a. Increases in the proportion of the drainage network that is channelized will significantly increase flood damage within the stream corridor.

   b. Increases in the proportion of the stream corridor that is leveed will significantly increase flood damage within the stream corridor.

3. Increasing efforts to protect stream corridor open space will significantly reduce flood loss.
   a. Increases in the number of credits associated with Community Rating System’s open space preservation activity (i.e. activity 420) will significantly decrease insured flood loss within the stream corridor.

4. METHODS

4.1 Study Area

The study consists of stream corridors within 2,690 12th order watersheds (based on the USGS Hydrological Unit Code (HUC)) that encompass the 144 counties and parishes along the Gulf of Mexico as identified by the National Oceanic and Atmospheric Administration (NOAA) (Crosset 2005). This area stretches from the Florida Keys to the Southern tip of Texas, and includes watersheds from the following six states: Florida, Georgia, Alabama, Mississippi, Louisiana, and Texas. Watersheds were included if they met the following criteria: 1) intersects on of the NOAA-designated coastal watersheds; and 2) 500-year floodplain data is available for the entire watershed (Figure 3).

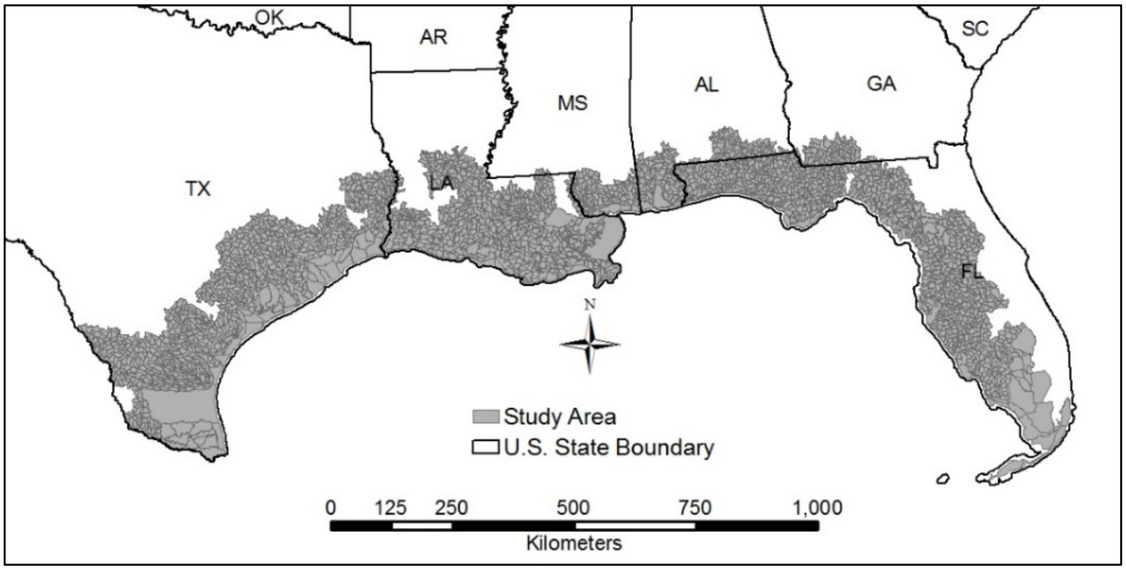

Figure 3. Study Area

This Gulf of Mexico coast is an ideal region in which to examine the relationship between riparian habitat change and insured flood loss for several reasons. First, over a third of the area lies within the 500-year floodplain, making development extremely vulnerable to flood damage. For example, S. D. Brody et al. (2011) found that communities within this area suffered the largest amount of insured property damage in the U.S. from 1996-2007. Second, the Gulf coast has a legacy of rapid population growth and associated land use change, much of which has displaced natural habitat. For example, Harris County and Hillsborough were 2 of the top 10 jurisdiction in the nation from 1996-2001 for land conversion for development (NOAA 2008). Third, large scale riparian habitat loss, facilitated by channelization and drainage, has occurred throughout this region with some areas experiencing a decline in bottomland hardwoods by over 95% (Fredrickson 1979; Swift 1984).

The watershed scale is ideal because it captures the level at which landscape patterns are likely to affect ecohydrological processes and hydrologic services (Strayer et al. 2003). Moreover, a watershed approach that considers the entire wetland and stream corridor system has been recommended by the U.S. Army Corps of Engineers (USACE). As a result, any findings within this study supporting a particular approach for flood mitigation will be in congruence with federal guidelines (USACE 2002). In 2008, the Environmental Protection Agency (EPA) and the USACE developed new guidelines for how to implement compensatory mitigation for the unavoidable impacts to that nation's wetlands and streams. Within these guidelines, the USACE requires that mitigation must occur within the same watershed as the impact to increase the likelihood of replacing lost functions considering habitat diversity, connectivity, land use trends, and compatibility with adjacent uses (USACE 2008). As a result, many state and federal agencies are implementing restoration initiatives within watersheds with HUC codes ranging between 11 and 14 digits with larger HUC codes representing smaller watersheds (Bernard and Tuttle 1998).

The stream corridor is the unit of analysis, which is made up almost entirely by the FEMA 500-year floodplain plus levee protected areas. Using the 500-year floodplain as a proxy for the stream corridor is justified for the following reasons: 1) it encompasses the largest spatial component of the stream corridor; 2) it captures the scale of the disturbance regime; 3) it is aligned with a nationally standardized flood frequency; and 4) it contains the area in which homeowners with federally backed mortgages are required to purchase flood insurance. The 500-year floodplain encompasses two of the three major stream corridor elements: 1) the stream channel; and 2) the floodplain. The 500-year floodplain fails to capture the third component of the stream corridor, which is referred to as the transitional upland fringe or the transitional area between the floodplain and the surrounding landscape. This area will be excluded from this analysis as it is relatively small in comparison to the 500-year floodplain and difficult to define. Next, the floodplain encompasses the scale at which the flood-pulse concept operates. This is critical as it captures the dynamic interaction between water and land on which stream corridor habitat depend (Bernard and Tuttle 1998). Moreover, it makes stronger conceptual sense to align the effect FCI, habitat loss and fragmentation, and open space protection to the scale of the disturbance regime because that is the process these activities are attempting to influence. Finally, the 500-year floodplain contains and consists primarily of the 100-year floodplain, which is where homeowners are required to purchase flood insurance if they have a federally-backed mortgage making insured flood loss a good proxy for total flood-related damages.

It should be clarified that the 500-year floodplain was chosen over the 100-year delineation because: 1) it captures many of the claims that are immediately adjacent to the 100-year floodplain boundary and 2) it minimizes the effect of floodplain shape on the calculation of the landscape metrics. A study conducted in the same area found that although claims within the 100-year boundary are roughly four times higher than those outside the floodplain, it still failed to capture 40% of the damage (Brody et al. 2015). A parallel study within one of the most flood vulnerable watersheds in the region calculated that the average distance for claims outside the 100-year floodplain was approximately 420 m with a clear inverse distance relationship between the claim amount and distance from the floodplain (Brody et al. 2012). And although residents outside the 100-year floodplain but within the 500-year floodplain are not required to purchase flood insurance, it has been found that proximity to the 100-year floodplain is a significant driver of policy uptake (Brody et al. 2016). As a result, it can still be argued that damage within the 500-year floodplain is still a good proxy for overall flood-related damages. Finally, the 500-year floodplain provides a standardized way to buffer the 100-year floodplain thereby reducing the edge and shape effect of the 100-year floodplain on the calculation of the landscape metrics.

Lastly, it should be noted that levee protected areas were included within the final designation of the stream corridor. This was done because areas protected by FEMA accredited levees are considered outside the floodplain despite only requiring protection to the 100-year event. The NFIP designates these areas as having moderate flood risk, and strongly recommends the purchase of flood insurance. Moreover, including these areas provides spatial continuity of the stream corridor within watersheds with levee protected areas.

Sample Selection

To capture the effect of floodplain habitat and FCI on insured flood loss, this study excluded stream corridors that: 1) were not located in urbanized watersheds and 2) did not experience flood loss between 2006 and 2010. This was done because interest in restoring floodplain habitat and/or replacing or complementing FCI with natural habitat (i.e. green infrastructure) is concerned with protecting existing development and offsetting the hydrological effects of increasing urbanization. A recent literature review of the effects of urbanization on watershed hydrology in the southern U.S. by O’Driscoll et al. (2010) found significant increases in stream peak flows with increases in total impervious area as small as 6% at the watershed scale. Therefore, this study only included watersheds with at least 5% total impervious area. Of the remaining watersheds only those with at least one flood insurance claim with a non-zero damage amount within the floodplain were assessed in order to capture potential exposure to flood damage. Figure 4 displays the 275 watersheds that contain the floodplains that fit these criteria.

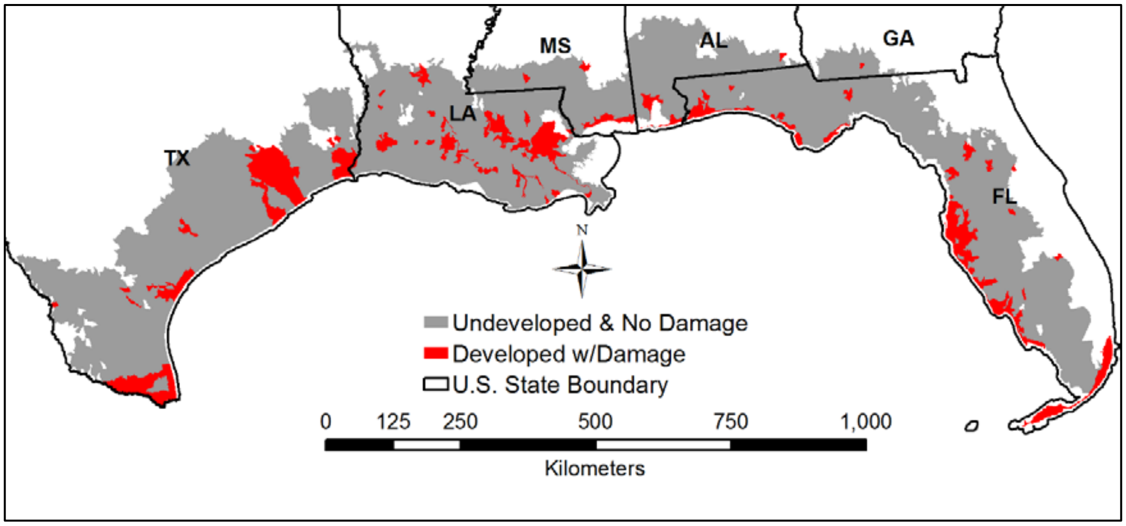

Figure 4. Watersheds within the study area that are developed and experience insured flood loss

The delineation of the 500-year floodplain within each watershed was derived from FEMA's National Flood Hazard Layer (NFHL) and FEMA's Q3 data. The NFHL is a national database that is comprised of digital flood insurance rate maps (DFIRMs), which represent the best available data of flood hazard areas and associated floodwater surface elevations. FEMA's Q3 data was used in areas where DFIRMs were unavailable. The Q3 database was developed in the 1990s by digitizing existing hard-copy FIRMs that were prepared using older techniques. As a result, the Q3 database is not as accurate as the NFHL database, but contains the only existing vectorized flood zone data for these areas. The 500-year floodplains were then combined with the levee protected areas that include FEMA and U.S. Army Corps of Engineers (USACE) designated levee protected areas.

A Quick History of Human-Stream Corridor Interactions in the Southeastern United States

In the southeastern U.S., floodplain ecosystems consist predominantly of bottomland hardwood (Fredrickson and Kaminski 2005) and swamp forests (Conner et al. 2001). This area once supported the largest expanse of forested wetlands in the U.S. (Stanturf et al. 2000) that stretched from coastal Texas to Florida along broad, flat alluvial floodplains (Rudis 1995; Wharton et al. 1982). The composition of these floodplain communities are strongly influenced by riverine hydrology (Wharton et al. 1982), and the vegetation have adapted to grow in periodically inundated or saturated soils (Conner et al. 2001).

The fertile floodplains of the southeast have been used for agriculture and silviculture (Quarterman 1957; Wharton et al. 1982), both of which have resulted in significant losses of native floodplain habitat (King et al. 2009). Floodplain forests were one of the first ecosystems to be converted to agriculture by Native Americans, and were among the first to be logged by early colonists in the Southern United States (Cowdrey 1996; Pinchot and Ashe 1897). Most of these floodplain forests have now been harvested for timber one to several times (Heavrin and others 1981).

Estimates have shown that only half of the original floodplain forests remained by the 1930s (Conner et al. 2001) in large part as the result of federally incentivized wetland drainage under the Swamp Land Act of 1850 (Stanturf et al. 2000). The increasing demand for more agricultural land in the latter half of the 20th century quickly consumed much of the highest and best drained sites. This stimulated the development of flood control projects to free up more agricultural areas by isolating river movement, draining swamps, and encouraging forest clearing in lower, wetter sites (Stanturf et al. 2000; Sternitzke 1976). As a result, conversion to agriculture increased rapidly during the 1960s and 1970s further accelerating forest clearing and reducing floodplain habitat (Sternitzke 1976).

At the same time the federal government was investing in large scale flood control infrastructure in response to significant flood loss events as part of the Flood

Control Act of 1936. As a result, stream leveeing and channelization proliferated across the southeastern U.S. (Ntelekos et al. 2010). These engineered solutions to flooding rendered previously uninhabitable areas suitable for human occupation, causing new building and settlements to encroach into floodplains (Tobin 1995). Urban and agricultural expansion into floodplains resulted in a loss of more than 68,000 ha per year in south-central U.S. between 1940 and 1980, eliminating nearly half of the forested wetland regionally with some areas witnessing a decrease by as much as 80 percent (Messina and Conner 1997). Not only was composition altered, but so too was the composition of these forests. A study of floodplain forest fragmentation by Rudis (1995) found few large and many small forest fragments across Texas, Mississippi, and Louisiana.

4.2 Concept Measurement

Dependent Variable: Flood Damage

The dependent variable, insured flood loss, is from FEMA's National Flood Insurance Program's (NFIP) claims dataset. Total insured flood loss from 2006 to 2010 that fell within the stream corridor was calculated for each watershed. This variable was then log transformed to better approximate a normal distribution. The mean damage per stream corridor over the 5 year period was $7.6 million and ranged from $117 to $940 million. Total flood damage for the entire study period was approximately $2 billion.

Independent Variables: Land Cover Metrics

NOAA's Coastal Change Analysis Program (C-CAP) Regional land cover data will be used to determine the degree of habitat loss and fragmentation for each watershed's stream corridor for the year 2006. Table 1 illustrates how the C-CAP land cover classes will be aggregated into an anthropogenically disturbed, natural, and water classifications. Combining the classes into these simplified groups was done because floodplain habitats are within a dynamic environment that forms a complex habitat mosaic. Assessing only one of the natural land cover types would ignore the surrounding land cover types resulting in significantly different landscape fragmentation metric calculations. For examples, a forested riparian area could contain several isolate patches of wetlands. Assessing the wetlands independently of the forested region would result in an interpretation that the area is more fragmented that it is in actuality. Moreover, aggregating improves classification accuracy by limiting confusion between similar land cover classes (Wickham et al. 2013).

Table 1. Original and reclassified C-CAP land cover types.

C-CAP	**Reclassified**
Developed , High Intensity Developed, Medium Intensity Developed, Low Intensity Developed Open Space	Anthropogenic Disturbance
Barren Land	
Cultivated Crops Pasture/Hay	
Grassland Herbaceous	Natural
Deciduous Forest Evergreen Forest Mixed Forest	
Scrub/Shrub	
Palustrine Forested Wetland Palustrine Scrub/Shrub Wetland Palustrine Emergent Wetland	
Estuarine Forested Wetland Estuarine Scrub/Shrub Wetland Estuarine Emergent Wetland	
Open Water Palustrine Aquatic Bed Estuarine Aquatic Bed Unconsolidated Shore	Water and Submerged Lands

The anthropogenically disturbed class includes all intensities of development (high, medium, low, and open space developed) as well as barren land and agricultural land cover types (i.e. cultivated crops and pasture/hay). The intensities of development correspond with certain thresholds of development with high ranging from 80-100%, medium ranging from 50-79%, low ranging from 21-49%, and developed open space ranging from 1-20%. Barren land, within the study area, often consists of graveled areas and bedrock, which are often in areas heavily influenced by human activity such as mining, gravel roads, and areas cleared for new construction. The agricultural land cover types consist of cultivated crops intensely managed for production and pasture areas consisting of grasses planted for livestock grazing or the production of hay.

The natural land cover classification consists of 5 land cover classes: grassland, forests, scrub/shrub, palustrine wetlands, and estuarine wetlands. Grasslands are areas dominated (over 80%) by herbaceous vegetation and are not subject to intensive management such as tilling. Forests contain deciduous, evergreen, and mixed forests. Trees within these categories are over 4.8 m (16 ft) in height and account for more than 20% of the total vegetation cover. The scrub land cover type contains areas dominated by shrubs less than 5 m tall, with shrub canopy typically accounting for greater than 20% of total vegetation. This variable includes tree shrubs, young trees in an early successional stage, or trees stunted by environmental conditions. Palustrine wetlands consist of three distinct types: nontidal, scrub/shrub, and emergent dominated vegetation. In general, this type of wetland is associated with nontidal uplands composed of woody vegetation. Finally, estuarine wetlands were comprised of the same three vegetation types, but only for tidal areas. This wetland type is characterized by more deep-water tidal habitats consisting of a range of fresh-brackish-marine water chemistry and daily tidal cycles. Locations of this type of wetland include salt and brackish marshes, intertidal mudflats, bays, and coastal rivers.

Lastly, the water classification consists of open water, palustrine and estuarine aquatic beds, and unconsolidated shore. Open water is dominated by aquatic environments with less than 25% cover of vegetation or soil. The aquatic bed types are dominated by plants that grow over the surface of water, which include algal mats, detached floating mats, and rooted vascular plant assemblages. Finally, the unconsolidated shore are areas subject to frequent inundation and lack vegetation except for pioneering plants when growing conditions are favorable.

Numerous landscape and class metrics have been developed to quantify landscape composition and spatial configuration of land cover types (McGarigal 2014). A subset of these metrics were selected that may affect ecohydrological processes. Several class level fragmentation metrics describing the spatial configuration of the reclassified land cover classes will be calculated for each watershed’s stream corridor. Evidence and concepts found within the literature review were used to select the following class level fragmentation metrics to determine the spatial characteristics of natural land covers within the stream corridor: percent area, largest patch index, mean patch area, correlation length, and mean contiguity. Fragstats was used to calculate the metrics using the equations found in Table 2.

Table 2. Landscape metrics used to assess stream corridor habitat structure (adapted from McGarigal (2014))

Metric	Equation	Units	Range
Percent of Landscape	$\frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$	Percent	0 - 100
Largest Patch Index	$\frac{\max_{j=1}(a_{ij})}{A}(100)$	Percent	0 - 100
Mean Patch Area	$\frac{\sum_{j=1}^{n} a_{ij}(\frac{1}{10{,}000})}{n_i}$	Hectares	> 0, without limit
Correlation Length	$\sum_{j=1}^{n}\left[\sum_{r=1}^{z}\frac{h_{ijr}}{z}\left(\frac{a_{ij}}{\sum_{j=i}^{n} a_{ij}}\right)\right]$	Meters	≥ 0, without limit
Mean Contiguity Index	$\frac{\sum_{j=1}^{n}\frac{\left[\frac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}^{*}}\right]-1}{v-1}}{n_i}$	None	0 - 1

a_{ij} = *area (m^2) of patch ij;*
a_{ij}^{*} = *area of patch ij in terms of number of cells;*
A = *total landscape area (m^2);*
h_{ijr} = *distance (m) between cell ijr [located within patch ij] and the centroid of patch ij;*
n_i= *number of patches in the landscape of patch type i.*
z = *number of cells in patch ij;*
c_{ijr} = *contiguity value for pixel r in patch ij;*
v = *sum of the values in a 3-by-3 cell template;*

Independent Variables: Flood Control Infrastructure

This study focused on two common forms of FCI: stream channelization and levees. The United States Geological Survey's National Hydrography Dataset (NHD) provides the best available and most comprehensive drainage network and data for the United States. The NHD contains attributes classified as "canal/ditch" that are used as a proxy for stream channelization and general stream/river engineering projects. The NHD defines these attributes as artificial open waterways constructed to transport water, to convey stormwater through and from a drainage area, or to confine and conduct a periodic flow of water in such a way that concentrates flow (USGS 2009). The total length of channelized streams were then divided by the total length of the drainage network within the stream corridor to obtain a channelized proportion for each corridor.

The second FCI of interest, levees, was then calculated by combining the FEMA and U.S. Army Corps of Engineers (USACE) designated levee protected areas. Levee protected areas are included within FEMA's NFHL when the levee is certified by FEMA, which means that the structure meets current standards to provide protection from the 100-year flood (FEMA 2012). However, there are still many levee protected areas that are not certified by FEMA, which are not included within the NFHL layer. The only other nationwide source for levee protected areas is the USACE's National Levee Database (NLD), which includes the majority of the levees located within the USACE Levee Program (USACE 2017). This program consists of 2,500 levee systems many of which provide some level of flood protection below the 100-year event, and are mostly locally owned and maintained (FEMA 2012). Once these two datasets were combined, total levee area was calculated and then divided by the total area of the floodplain to obtain a proportion of levee protected area per floodplain. Levee protected areas that extended beyond the floodplain boundary resulted in percentages that exceeded 100 indicating a levee protected area that is larger than the 500-year floodplain.

Independent Variable: Open Space Protection

Although the creation of a floodplain open space protection metric using community level comprehensive plans is possible, its feasibility quickly diminishes when study areas encompass multiple states. Fortunately, the NFIP's CRS provides a standardized measure of open space protection at the community level. This measure are the points associated with Activity 420, which is referred to as open space protection within the CRS Manual. Activity 420 was created to achieve two objectives: 1) to prevent damage by keeping flood-prone lands free of developments, and 2) to protect and enhance the natural functions of floodplains. To achieve these objectives, the CRS gives more credit for activities that keep floodplains free of development by preserving it as open space. Of Activity 420's 7 elements, open space preservation (OSP) and low-density zoning (LZ) are weighted the most with 1,450 and 600 point maximums respectively. OSP provides credit for communities that keep vacant lands free of development via protection by a public agency, non-profit organization, or restrictive regulations. LZ provides credit for communities that have zoning districts that have large minimum lot size requirements (i.e. greater than 5 acres) in the floodplain. A community would exceed their 2,020 point ceiling for activity 420 by 30 points if they were to achieve these elements' maximum point allotments.

This variable was calculated by determining the amount of Activity 420 points for each community that fell within the stream corridor. Activity 420 points were then aggregated to each watershed's corridor by weighting each community's points by the amount of stream corridor area it contained.

Control Variables

Precipitation, one of the biggest predictors of flood damage, was measured as the number of days that rainfall exceeded 2.54 cm (1 in). This amount was chosen because previous studies have indicated that appreciable stormflow seldom occurs when storms produce less than 2.54 cm of rainfall (Hewlett and Doss 1984). Moreover, the 2.54 cm event is often used to differentiate "heavy" rainfall events from "light" rainfall events (Shuai and Sen 2017). Data for rainfall amounts were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group dataset. Daily counts of precipitation that exceeded the 2.54 cm storm for the study area were mapped at a scale of approximately 4 km grid cells, aggregated, and joined to the watershed unit.

Topographic features, such as elevation and slope, can also be important when predicting flood impacts. Low-lying areas along the coast tend to pool water and result in inundation. Steeper terrain can contribute to increased amounts of flood losses by increasing rainfall concentration, causing faster and higher peak flows (Stuckey 2006). The average slope and elevation of each watershed's stream corridor was calculated using a 30 meter digital elevation models (DEM) from the National Elevation Dataset

(NED). For each stream corridor, mean elevation was calculated using meters and mean slope was calculated using degrees.

The volume of infiltration is primarily a function of the underlying soils in the watershed. Flooding can be intensified in areas where soil characteristics prohibit or slow the infiltration of surface water. This study used saturated hydraulic conductivity (KSAT) found within the Natural Resources Conservation Services' Soil Survey Geographic (SSURGO) database as an indicator of soil infiltration (NRCS 2012). KSAT measures the amount of water that can flow through the soil in micrometers per second. Mean KSAT values were calculated for each watershed's stream corridor. Larger values of KSAT would indicate a greater capacity for the stream corridor to infiltrate and store water thereby reducing flood magnitudes and associated flood damages. Finally, development can prevent stormwater infiltration by increasing the amount of impervious surfaces.

Two key basin characteristics were included as controls: watershed area and stream corridor drainage density. Watershed area was calculated in square kilometers using USGS delineated 12th order watersheds. Larger watersheds drain larger regions which is expected to increase peak flows and flood damage within the floodplain. The drainage density for each watershed's stream corridor will be measured as the length of all the NHD flowlines divided by the area of the stream corridor. NHD flowlines represent the drainage network and contain perennial, intermittent, and ephemeral stream and river segments. Peak flows and associated flood damages are expected to increase as drainage density increases as a result of increased hydrological efficiency.

Finally, the number of structures was included to control for relative exposure to insured damage within the stream corridor. The number of housing units was derived from the 2010 U.S. Census block data. However, determining the number of housing units in the stream corridor is complicated for two reasons: 1) Census blocks overlap stream corridor boundaries and 2) housing units are not evenly distributed. To address these issues the use of impervious surface data was incorporated as a spatial representation of the distribution of development (i.e. housing units) within the Census blocks. Impervious surface data was obtained from the National Land Cover Database (NLCD), which is at a 30 m resolution for the year 2006 with percent impervious values ranging from 0 to 100 for each grid cell. The number of housing units for each Census block that intersected the stream corridor was calculated by weighting it by the proportion the block's imperviousness that fell within the corridor boundary and then summed by watershed. A summary of the control variables and the hypothesized effect on flood damage within the stream corridor are given in Table 3 below.

Table 3. Control variables and their hypothesized effect on insured flood loss

	Measurement	**Effect on Flooding**
Biophysical Controls		
Precipitation	# of days exceeding 2.54 cm	Positive
Soil Drainage Capacity	Saturated hydraulic conductivity	Negative
Basin Area	Area	Positive
Drainage Density	Stream length per area	Positive
Slope	Degrees	Positive
Elevation	Meters above sea level	Negative
Socioeconomic Controls		
Development	# of Household Units	Positive

4.3 Data Analysis

Multivariate regression was used to isolate the influence of habitat alterations, flood control infrastructure, and open space preservation on insured flood damage for each watershed's stream corridor after analyzing the data statistically and visually (see Table 4). Justifications for the statistical approach, model selection, and diagnostics are discussed in the next section, and is followed by the identification of known threats to validity of this study.

Table 4. Summary statistics for independent variables

Variable	Units	Mean	Std. Dev.	Min	Max
Habitat Configuration Variables					
Percent Natural	Percent	44.72	23.83	0.07	94.94
Largest Patch Index	Percent	21.85	19.98	0.04	93.10
Patch Area	Hectares	11.76	22.32	0.28	248.87
Contiguity Index	Unitless	0.21	0.06	0.08	0.63
Correlation Length	Meters	1,290.76	1,086.70	56.49	7,117.01
Flood Control Infrastructure Variables					
Channelization	Percent	24.50	23.89	0	99.93
Leveed	Percent	16.11	44.01	0	399.53
Open Space Protection Variable					
Open Space Protection	CRS Points	110.41	119.59	0	504.00
Biophysical Controls					
Precipitation	Days over 1 inch	74.73	36.59	27.71	373.75
Watershed Area	km^2	123.76	155.00	4.45	1,657.59
KSAT	µm/second	40.14	42.13	0.52	234.49
Slope	Degrees	0.53	0.36	0.01	3.57
Elevation	Meters	10.29	16.22	-1.22	137.32
Drainage Density	km/km^2	2.07	1.35	0	9.47
Socioeconomic Control					
Structures	Household units in thousands	8.77	15.79	0.03	142.81

Statistical Approach

A cross-sectional regression analysis was chosen to explain the effect of stream corridor habitat modification, flood control infrastructure, and open space preservation on insured flood loss across the study area. Stream corridor habitat modification was derived from land cover imagery collected during 2006, flood control infrastructure was obtained from a dataset that is continuously updated, and open space preservation was derived from a 2010 CRS dataset. The cross-sectional approach of this study treats the alteration of stream corridor habitat as an intervention and total insured flood damage from 2006 to 2010 as an effect. Flood control infrastructure is treated as a system state variable that changes relatively slowly over time. Treating flood control in such a way is supported because much of the large-scale infrastructure was constructed before 2006. The same could be argued for open space preservation as the points associated with this activity typically only change once every five years (FEMA 2013). Several regression diagnostics were conducted to determine whether basic regression assumptions were met and to ensure reliable results. The following sections includes information regarding model selection and regression diagnostics.

Multicollinearity & Heteroskedasticity

Landscape metrics are often highly correlated because they are measurements of a similar construct (Leitão et al. 2012). The inclusion variables with strong multicollinearity within a regression model creates estimation problems because it produces large standard errors, which makes it more difficult to achieve statistical significance. Moreover, parameter estimates become unreliable and imprecise resulting in a lack of confidence in the effect of the independent variables on the dependent variable (Treiman 2014). Although there are multiple ways to address this issue, the simplest method is to analyze collinear landscape metrics in separate models (Brody et al. 2013). This study employed this method to examine 5 different landscape metrics for natural habitat within the stream corridor, resulting in 5 different regression models.

Multicollinearity within each ordinary least squares (OLS) model was then tested by assessing the variance inflation factor (VIF) for each coefficient. In short, the variance of a coefficient becomes larger as VIF increases resulting in a loss of model precision. Belsley (1991) made note that cutoffs for VIFs can range between 7 and 10, while other sources argue that individual VIFs should not exceed 10 and that the mean VIF should not be considerably larger than 1 (Stata and others 2015). The max VIF across models was 1.86 with a mean VIF ranging from 1.37 to 1.43 (see: Table 9 in the Appendix).

Next, heteroskedasticity was tested for because its presence would violate the assumption of constant variance in the error term. More specifically, heteroskedasticity would bias the estimate of the standard error leading to incorrect significance tests and confidence intervals (Berry 1993). The Breusch-Pagan/Cook-Weisberg test for heteroskedasticity were insignificant across models indicating constant variance of the error term (see: Table 10 in the Appendix).

Spatial Autocorrelation & Model Selection

Spatial autocorrelation, or spatial dependence, occurs when there is correlation among observation that are near one another spatially. This is closely related to Tobler's first law of geography, which states, "Everything is related to everything else, but near things are more related than distant things" (Tobler 1970). Spatial dependence is common across many geographical, ecological, and social phenomena. If the spatial effects of nearby observations are not taken into account, then econometric models will produce unreliable results. More specifically, replications of the model in different areas will produce different results, but will likely have the same amount of spatial autocorrelation (i.e. unbiased but highly variable) (Loftin and Ward 1983).

If there is correlation among neighboring observations, then the actual standard error will be larger for positive values (and small for negative values) (Ward and Gleditsch 2008). That is, the standard errors are biased but the model is not. Using an unadjusted model in the presence of positive spatial autocorrelation will produce *t* values that are biased upwards as a result of underestimated variance leading to the increased likelihood of making a Type I error (i.e. falsely rejecting the null hypothesis).

One of the most common tests for spatial autocorrelation is the Global Moran's *I* test (Bivand et al. 2013). Moran's *I* measures the linear association between an attribute and a weighted average of the attribute at its neighboring locations (Moran 1950). In regression analysis the Moran's *I* test is typically conducted on the residuals because spatial autocorrelation would violate the independence assumption of the error term (Chi and Zhu 2008; Loftin and Ward 1983).

An issue that can arise when testing for spatial autocorrelation is that the specification of the spatial weights does not match the scale of interaction between the units of observation (Bivand et al. 2013). As such, special attention was given to the creation of the appropriate weights matrix for diagnosing spatial autocorrelation. First, distance-based spatial weights matrices were excluded because they require a threshold value, which is difficult to determine in the presence of strong spatial heterogeneity. This is particularly true for this study's dataset because of the clustering of urban watersheds and the irregularity of floodplain delineations. Moreover, in such datasets, large distance thresholds may include too many neighbors where observations are clustered and too few when observations are more spread out. The solution to this problem was to use a *k*-nearest neighbor structure (Anselin 2002).

Choosing the appropriate number of neighbors and spatial was informed by assessing: 1) the magnitude of the Moran's *I* and 2) model fit across neighbor designations. Moran's *I* had noticeable peaks when viewed as a correlogram at 1, 5, 7 neighborhood designations all of which were positive and significant ($p<0.000$) indicating the presence of spatial autocorrelation (see: Figure 10 in the Appendix). Moreover, the Moran's *I* test were conducted using various neighborhood weight specifications including Gaussian, bi-squared, inverse distance, and binary weights. The binary weight specification had the largest Moran's *I* statistic indicating that it better captures the nature of the spatial autocorrelation within the dataset. Spatial weights matrices were created for the fifth and seventh neighborhood designations and then tested based upon Schwartz's Bayesian Information Criterion (BIC) and the Lagrange Multiplier (LM) test. BIC is ideal because it measures the fit of the model while penalizing large models and allowing for the comparison among nonhierarchical models (Treiman 2014), whereas the LM test can be used to test for spatial dependence in the residuals of the spatial lag and spatial error models as indicator of which model might be more appropriate (Beck et al. 2006). The LM test suggested that the spatial lag model was most appropriate and the BIC indicated that the 7 nearest-neighbors was the most appropriate neighborhood structure for the spatial weights matrix (see: Table 12 and Table 13 in the Appendix).

4.4 Validity Threats

No study design is perfect and the proposed research is no exception. Although appropriate measures will be taken to arrive at an accurate conclusion it is also necessary to examine the potential validity threats that result from the proposed research design. The four types of validity threats as discussed in Shadish et al. (2002) include: statistical conclusion validity, internal validity, construct validity, and external validity.

Statistical Conclusion Validity

Statistical conclusion validity refers to the appropriate use of statistics to infer whether or not the independent and dependent variables covary. Small sample size and the violation of statistical assumptions are the two primary concerns for studies that rely on regression. Statistical power of the regression models will be high as a result of the relatively large sample size (N = 275). Moreover, particular attention was given to assuring that regression model assumptions were not violated. By not violating assumptions of statistical tests this study minimizes the likelihood of Type I and Type II errors.

Internal Validity

Internal validity refers to inferences about whether observed covariation between the independent and dependent variables reflects a causal relationship. Although this study is non-experimental, it is examining the causal relationship between a preceding moment on future flood conditions. That is, this study is examining the effect of stream corridor habitat characteristics and degree of flood control at 2006 on flood damage from 2006-2010. This design treats the habitat configuration and FCI at 2006 as an intervention that is hypothesized to have an effect on future flood loss. In doing so, this design strengthens the interpretation of the model outcomes as a cause-effect relationship.

Internal validity threats are a common issue when controlling for factors in complex human-environment systems. Modelling these types of systems and their alterations is a complex undertaking. To the extent possible, all necessary control variables will be included to reduce any spurious relationships.

Mortality issues can also be a threat to internal validity. While actual loss of respondents is not an issue with this study, the loss or new addition of flood insurance policy holders during the study period may pose methodological issues. As in many research designs the best and most representative data will be analyzed with the acknowledgement of this limitation.

Construct Validity

Construct validity refers to inferences about the higher order constructs that are represented by specific measures. That is, construct validity poses the question: do the variables measured in the study (e.g. insured flood loss, contiguity index, CRS activity 420 points, etc.) represent the constructs that the study is attempting to measure (e.g. flood damage, habitat fragmentation, and open space protection)? The main threats to construct validity include: the conceptualization of the constructs and then measurement operationalization. This first is conceptual and the latter is empirical.

The conceptualization of the constructs and how they interact within the larger system of interest are addressed within the research framework section. However, there are a few operationalization issues that should be addressed in regards to four key constructs: flood damage, flood control infrastructure, stream corridor habitat modification, and open space preservation. Error within how these measures were operationalized or estimated will bias the estimation results.

Insured flood loss is used as a construct to represent flood damage. The main source of inaccuracy for this measurement is that it does not account for uninsured flood damage. This limitation precludes capturing flood related damage to structures that were not insured by FEMA’s NFIP. Other forms of damage not captured by flood insurance include: other direct monetary costs like damage to transit infrastructure; direct non-monetary costs like mental and physical health; indirect monetary costs like the loss of income from not be able to return to work; and indirect non-monetary costs like long-term emotional impacts. As a result, insured flood loss likely underestimates actual flood damage, which may, in turn, underestimate the influence the predictors as well. That said, it can be argued that insured flood loss is a good proxy for flood damage within the study area because of a high saturation of NFIP policy uptake and is the best available dataset at the parcel level.

Next, the construct flood control infrastructure is measured as either channelization or levee protected area, which are measured using either the USGS NHD dataset or a combination of FEMA and USACE levee protected areas respectively. Neither of the measures chosen captures the magnitude of protection. That is, neither the proportionally channelized or proportionally levee protected captures the size of the storm that the FCI was engineered to withstand. Moreover, levees and canal/ditches can serve multiple functions. For example, the NHD dataset's canal/ditch feature captures all artificially manipulated stream segments many of which are used as some form of stormwater conveyance, however many of these areas were constructed for other functional roles like irrigation and waterways for watercrafts. Levees, however, are built with the singular function of excluding flooding from leveed areas, but can differ in the types of area that they protect. For example, some levees are built to protect densely populated areas whereas others are built to prevent the flooding of agricultural areas. Lastly, the FCI measures do not take into account other forms of small-scale, localized forms of structural flood mitigation like storm sewer networks and detention ponds. All of these limitations undermines the ability of these measures to fully capture the degree to which cities and communities depend on structural mitigation to prevent flood loss. The outcome of these limitations is likely similar to that of the flood damage construct in that the FCI construct measures underestimates a community's reliance on structural mitigation.

The next construct of interest is stream corridor habitat modification which is measured using five different landscape fragmentation metrics. In terms of measurement, there are two sources of potential error: spatial and thematic resolution.

When measuring landscape metrics, spatial resolution can have a significant impact. A study conducted by Wickham and Riitters (1995) found that some configurational metrics were much more sensitive to changes in pixel whereas compositional metrics were not. The metric in this study that are likely sensitive to pixel size is mean contiguity index because it is based on cell adjacency. These types of metrics will increase as resolution increases (i.e. grain size reduced) because the proportion abundance of cell adjacencies increases (Cushman and McGarigal 2008). Finally thematic resolution (i.e. the number of classes) can have a strong influence on fragmentation metrics. A systematic study of the effects of thematic resolution on fragmentation metrics conducted by Buyantuyev and Wu (2007) found that changing the number of classes of a categorical land cover map will lead to considerable differences in the values of most compositional and configurational landscape metrics. The authors argue that there is likely no ideal thematic resolution for a given study, but rather the choice of a thematic resolution should be based on theory and should be relevant to the process of interest.

The last construct of interest to mention is open space preservation which is measured using the NFIP's CRS Activity 420. The strength of this measurement compared to other potential individual plan based measures is that it is standardized enabling comparisons across the study area. Moreover, Activity 420 combines open space preservation and land use based strategies into a single measurement aimed explicitly at measuring community level attempts to increasing floodplain functionality. Despite its strengths it could be argued that Activity 420 does have limitations in terms of measurement accuracy in that it may not capture all community level actions to increase floodplain functionality. These would include any activity that could increase flood functionality but is not credited or activities that would qualify for credit but have not because it was implemented after the last CRS verification visit.

Finally, construct validity can be influenced by the operationalization of the units of observations themselves. In spatial studies this is often referred to as the Modifiable Areal Unit Problem (MAUP), which is defined as “a problem resulting from the imposition of artificial units of spatial reporting on continuous geographical phenomenon resulting in the generation of artificial spatial patterns" (Heywood 1998). The MAUP highlights two issues of concern: the scale effect and the zoning effect. The scale effect is an issue because different statistical results can occur when the same data are aggregated at different scales. The zoning affect (or aggregation effect), occurs when delineating an area at a particular scale (Openshaw and Taylor 1979). There are multiple ways to address the MAUP, however the one used the most within urban planning is to choose a zone or unit of analysis rooted in theory. In geography this is referred to as an 'object of geographical enquiry' that is at an appropriate scale and captures all the drivers of interest (Openshaw 1984). The floodplain was chosen as an ideal unit of analysis because it captures the scale of the disturbance regime (i.e. flooding) and also captures the scale of multiple disturbances of interest: floodplain habitat loss, floodplain encroachment, and riverine flood control infrastructure. Moreover, floodplain delineation is a standardized procedure and therefore avoids the ambiguity of choosing an appropriate buffer or zone.

External Validity

External validity refers to the validity of inferences about whether the relationships hold across different settings. External validity is probably the largest threat to validity posed by this research design. First, the study is delimited to a particular study area making it difficult to generalize findings to other geographic areas. Extrapolating the results to other areas would be a complex task as not all areas have the same geographical profile, environmental characteristics, and/or level of anthropogenic disturbance. Moreover, extending the results within the same area at another time may be difficult if rainfall characteristics during the current study period are anomalous.

5. RESULTS

Over the 5-year study period, the coastal watersheds of the Gulf of Mexico experienced approximately \$3.4 billion in insured flood loss, \$2.1 billion (62%) of which occurred within the stream corridors of urbanized watersheds (i.e. consisted of greater than 5% impervious surface). Put another way, nearly two thirds of the insured loss occurred on only 5% of the land area. After parsing the stream corridors by watershed boundary, the data show that the average loss per stream corridor was \$7.7 million.

The multiple regression analyses illustrate the influence of landscape configuration, flood control configuration (FCI), and open space preservation on insured flood losses, while controlling for multiple biophysical and socioeconomic variables. Table 5 shows standardized effects of each variable across the five landscape metrics. Each model explained approximately a third of the variance in the dependent variable. Table 6 shows the mean dollar effect per unit of each statistically significant variable of interest, and the total mean expected effect on annual flood damage. Mean expected effect on flood loss was calculated by multiplying the unstandardized regression coefficient by the average of each corresponding variable and the annual mean flood damage[1].

As shown in Table 5, two of the five stream corridor landscape configuration metrics result in statistically significant reductions in insured flood losses. Specifically, after controlling for biophysical and socioeconomic characteristics, a one standard deviation increase in the largest patch (LPI) and contiguity indexes reduced insured flood loss by approximately 0.122 standard deviations. When LPI and contiguity index are scaled to a 0 to 100 percent scale a 1 percent increase in each would reduce loss, on average, by \$23,000 and \$15,000 per year respectively (Table 6). The mean for LPI is approximately 22, which means that about a fifth of each stream corridor consisted of

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[1] Because of the large unit changes in the *x* variables (i.e. independent variables), this study employed the more formal $e(b * x) - 1$ approach to interpreting the coefficients from the log-level models (see Wooldridge, 2009).

one natural patch. On average, these large patches reduced insured flood loss by approximately $510,000 per year.

Table 5. Standardized beta coefficients for regression models on insured flood loss

Variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Stream Hardening	0.1097*	0.1049*	0.1173*	0.1097*	0.1306*
Leveed	-0.1358*	-0.129*	-0.1351*	-0.143*	-0.1309*
Open Space Protection	-0.0964	-0.0955	-0.1055+	-0.1212*	-0.1107+
Precipitation	0.0986*	0.0958*	0.0974*	0.1002*	0.1034*
Watershed Area	0.1114*	0.1120*	0.1095*	0.1058*	0.1194*
KSAT	-0.1048	-0.1103+	-0.1117+	-0.0770	-0.1080
Slope	0.1162*	0.1092*	0.1209*	0.1175*	0.1253*
Elevation	-0.0435	-0.0423	-0.0497	-0.0472	-0.0438
Drainage Density	-0.0674	-0.0750	-0.0906	-0.0599	-0.0982+
Structures	0.1960**	0.1821**	0.2073***	0.2073***	0.2086***
Proportion	-0.0807				
Largest Patch Index		-0.122*			
Patch Area			-0.0697		
Contiguity Index				-0.1114*	
Correlation Length					-0.036
Lag	0.5171***	0.5232***	0.5258***	0.5070***	0.5135***
Constant	5.611***	5.583***	5.310***	6.334***	5.395***
N	273	273	273	273	273
Wald chi^2	53.14***	55.29***	54.87***	50.65***	52.00***
R-squared	0.343	0.346	0.344	0.364	0.354
Adjusted R-squared	0.335	0.343	0.324	0.337	0.320

Notes: + p<0.1; * p < 0.05; ** p < 0.01; *** p < 0.001

Both flood control infrastructure (FCI) variables resulted in significant effects on insured flood loss, however, the direction of their effect depends on the specific FCI type. That is, insured flood loss was significantly reduced by levees and significantly increased by stream hardening. A one percent increase in leveed area reduces, on average, insured flood loss by $12,000 per year, whereas increasing the amount of the drainage network that is hardened by one percent would increase expected insured flood loss by $18,000 per year. Approximately 25 percent of each stream corridor's drainage network had been artificially hardened resulting in $450,000 in insured flood loss per year. Based on the standardized coefficients, leveed area was essentially tied for second along with slope in terms of the overall effect on insured flood loss. Only 64 (or 23%) of the stream corridors contained areas that were protected by a levee.

Table 6. Dollar effect per year of variables of interest that were statistically significant

Variable	**Mean Std. Beta**	**Unit**	**Per Unit Effect**	**Total Mean Effect**
Structures	0.20026	One thousand	$49,615	$435,123
Leveed	-0.13476	One percent	-$11,739	-$189,115
Largest Patch Index	-0.1220	One percent	-$23,329	-$509,739
Stream Hardening	0.11444	One percent	$18,549	$448,886
Contiguity Index	-0.1114	One percent	-$15,231	-$319,851
Open Space Protection	-0.10586	One point	-$3,404	-$375,836

Note: Variables are ranked by the magnitude of their standardized beta coefficient

Efforts to preserve open space within the floodplain (i.e. CRS Activity 420 points) resulted in statistically significant reductions in insured flood loss within the stream corridor for three out of the five. Mean savings per CRS Activity 420 point increase across all models is approximately $3,400 per year. Considering the average number of points accrued for open space protection within the stream corridors, the total savings for this activity was equivalent to, on average, approximately $380,000 per year.

Contextual control variables in the models behaved as expected in terms of directionality. Surprisingly, the strongest predictor of flood loss across all models was not precipitation, but, rather, the number of structures when comparing standardized beta coefficients. Among biophysical controls, watershed area and slope behaved as expected with positive and significant effects on insured flood loss across all models. However, elevation and drainage density behaved somewhat unexpectedly. Increasing elevation had an expected reduction in flood loss but was insignificant, whereas stream corridors with greater drainage densities unexpectedly had less insured flood loss for one of the models. Finally, as expected, increasing soil infiltration resulted in less insured flood loss, however this relationship was only significant ($p < 0.1$) for three of the five models.

Table 7 displays the intercorrelations among the dependent and independent variables that are relevant to the study's conceptual model. The relationship between structures and FCI are significant for both types corroborating the positive feedback between the two. Moreover, the relationship between structures and all fragmentation metrics are negative and significant except for correlation length illustrating that stream corridor habitat tends to become more fragmented as development increases. This relationship holds true for FCI as well, particularly channelization, which corroborates the hypothesis that stream corridor habitat is degraded as the FCI-development feedback progresses.

Table 7. Intercorrelations among all variables of interest

Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1. Insured Flood Loss								
2. Channelization	0.15							
3. Leveed								
4. Open Space Protection	-0.23	0.18	-0.19					
5. Structures	0.32	0.30	0.14					
6. Percent Natural	-0.22	-0.30	-0.15		-0.34			
7. Largest Patch Index	-0.21	-0.23			-0.27	0.82		
8. Patch Area		-0.20			-0.14	0.51	0.57	
9. Contiguity Index	-0.28	-0.23	-0.18		-0.21	0.42	0.19	0.36
10. Correlation Length						0.53	0.67	0.38

Note: Only correlations with significance levels at $p < 0.05$ are shown.

6. DISCUSSION

The results show that natural habitat fragmentation, flood control infrastructure, and open space preservation have statistically significant effects on insured flood damage within the stream corridor of developed watersheds. This small subset of land area along the Gulf of Mexico represents only 5% of the total land area yet captured nearly two thirds of the insured flood loss from 2006 to 2010. Surprisingly, precipitation, although statistically significant, was one of the weakest predictors of flood damage. Rather, four of the top five predictors were related to some form of anthropogenic disturbance two of which reflected efforts to control rivers and streams. In order of magnitude these four predictors include: 1) number of structures; 2) proportion of the stream corridor that is leveed; 3) largest patch index; and 4) stream hardening. Their effects on insured flood damage support the initial hypotheses except for leveeing, which significantly reduced flood damage. The findings support the idea of treating these areas as socio-ecological systems that consist of dynamic human-environment interactions. Flood risk mitigation efforts that overlook this will likely result in unintended and undesirable consequences. Instead of attempting to eliminate flood risk by suppressing flood disturbances with single objective infrastructure, cities and communities should focus on flood resilience by learning and adapting to flood disturbances over time.

As the study indicates, developing within the stream corridor is the largest contributor of insured flood loss. This finding corroborates previous research conducted by Pielke Jr et al. (2008) who analyzed normalized US flood damage from 1900 to 2005 in relation to hurricane landfalls and found that societal trends accounted for the exponential increase in flood damage despite no trends in hurricane frequency or intensity. Even more agreement is found within a study conducted by the same author in 2000 which found that the southeastern US was the only region that had no significant correlation between several precipitation measures and flood damage (Pielke Jr and Downton 2000). This point is significant because it highlights various perspectives of what a flood is. From a climatologists or biologists perspective a flood could simply be a hydrologic event measured in terms of discharge or peak flows, however, from a policy or risk perspective floods are often measured in terms of economic damage. Although the latter is a function of the former it is also driven by how and where development occurs. Undeveloped stream corridors that experienced relatively more rainfall events will have virtually no insured flood loss which helps explain the weak connection between precipitation and damage. It also suggests that development decisions are the primary culprit of insured flood loss, which increases the potential to reduce flood loss through land use policies.

Developing within the stream corridor not only places residents at a greater risk of flooding but it also displaces natural flood attenuating habitat and replaces it with impervious surfaces. Surface runoff increases thus leading to increased peak flows. At this point, the "escalator effect" can take effect whereby damaging peak flows justify the installation of flood control infrastructure which then results in the misconception that risk has been eliminated when residual risk still exists (Hewitt and Burton 1971; Parker 1995; Tobin 1995). The misconception of flood risk, some have argued, attracts development into the floodplain locking the system into a state of increasing control while simultaneously eroding the system's resilience to flood risk (Liao 2014; Pielke 1999). The results from this study confirm this conceptualization of flood risk. Not only is development the single largest contributor to flood damage but it is also positively correlated with stream hardening and negatively correlated with natural land cover area and connectivity both of which result in increased flood damage.

Of the two anthropogenic channel modifications, only stream hardening resulted in significantly more insured flood loss whereas leveeing had the opposite effect. There are multiple types of stream hardening that can be used for a range of purposes including flood control, navigation, drainage improvement, and reduction of channel migration potential. Physical modifications often include straightening, deepening, relocating, and minimizing roughness (i.e. removing vegetation). These types of modifications are often used in response to the hydromodifications of urbanization. In short, channelization, as a flood control measure, conveys water more efficiently downstream. Channelization decreases the risk of flooding by reducing peak flow and flood elevations, containing flood flows within channels, and routing stormwater away from developed areas (USEPA 2007). However, the risk of flooding is often merely transferred to another downstream community where stormwater velocities and peak flows increase because of the upstream structural interventions (Beatley and Manning 1997; Burby and French 1981; Owen 1981). Previous assessments that have calculated the damages avoided because of structural mitigation have overlooked this effect by focusing only on the immediately surrounding communities. However, this study, by focusing on a much larger spatial scale illustrates that stream hardening results in more flood damage likely because it not only merely transfers risk, but also attracts development into the floodplain and results in more severe flood damage when the structure is overwhelmed or fails. This study found that hardening an additional one percent of the drainage network increases insured flood damage by $18,549 within the stream corridor, which, on average, accounted for nearly a third of the total stream corridor flood damages. This corroborates previous theoretical models which argued that increasing resistance to floods undermines a community's ability accommodate change and increases the odds of catastrophic failure (Foster 1997; Godschalk 2003).

The other channel modification examined was leveeing, which, counter to the hypothesized effect, significantly reduced insured flood damage. There are a couple of reasons that could potentially explain this effect which include: 1) levees provide protection to larger precipitation events with small recurrence intervals; and 2) NFIP policies are not required behind FEMA accredited levees. FEMA accredited levees provide protection up to the 100-year event. Many of the non-accredited levees, such as those built in the 1940s and 1950s along the Mississippi, protect >70% of the floodplain up to the 50-year event (Remo et al. 2009). This level of protection exceeds that of most channelization structures. Thus, the likelihood of a levee being overwhelmed or failing is less, particularly over a short period. During the study period from 2006-2010 the local levee systems prevented flood damage from occurring because there were no storms that exceeded their capacity. This does not necessarily mean that levees increase flood resilience, because catastrophic losses occur when levees are overwhelmed or fail. Rather, the temporal scope of the analysis does not fully capture the effect of levees on flood risk. Finally, homeowners with federally-backed mortgages located behind a FEMA accredited levees are not required to purchase federal flood insurance because the levee removes them from the 100-year floodplain. If the homeowner elected to not purchase flood insurance, then any damage they experienced is effectively removed from the dataset because this analysis does not capture uninsured flood loss.

The analysis of natural land cover illustrates that the spatial configuration of undisturbed, stream corridor areas have significant influences on insured flood loss in urbanized areas along the Gulf of Mexico. In general, large, contiguous patches of natural open space are the most effective at reducing flood damage. This supports previous theoretical work by Forman (1995) who argued that sufficiently large patches are the only elements of the landscape that can protect aquifers (i.e. recharge) and interconnected stream networks, sustain viable populations of interior species, and permit a natural disturbance regime. These large blocks of habitat mitigate the impacts of floods by storing and desynchronizing floodwaters while also preserving indigenous biota (Carter et al. 1979; Taylor et al. 1990). In fact, increasing the largest patch's area by one percent reduce insured flood loss by $23,329 per year. The statistical significance of stream corridor LPI could also be attributed to the fact that elongated patches, such as those found along rivers, are more susceptible to fragmentation and are thus a strong indicator of anthropogenic disturbance (Charron et al. 2008). That is, a relatively small disturbance such as road or new development has a greater chance of dividing an elongated patch in two than a patch that is more expansive in all directions.

Stream corridors whose patches exhibited greater contiguity of natural habitat tended to experience less flood damage on average. Like LPI, larger patches will have larger contiguity values, however it differs from LPI in that it weights spatial connectedness more heavily. That is, the natural land cover raster cells will be more compact and clustered in patches that have larger CONTIG values because CONTIG weights orthogonal connections more heavily than diagonal ones. These types of patches are more likely to be found in stream corridors where anthropogenic disturbances (e.g. development and agriculture) are clustered and in areas where large tracts of land have been conserved (e.g. parks, conservation easements, etc.). Again, this corroborates foundational reserve design principles by Forman (1995) that claimed that compact patches with large core areas are more effective at maintaining ecological functionality and thus more capable of providing ecosystem services because they are less influenced by outside effects. This was empirically confirmed by this study which found that increasing the contiguity of natural stream corridor habitat by one percent reduced insured flood loss by $15,231 per year on average. Finally, landscape structure is often indicative of flows (e.g. water) within the landscape (Forman and Godron 1986; Watt 1947). Stream corridors with large, contiguous patches of natural land cover may likely be the result of an ecologically valuable disturbance regime that exhibits naturally varying flood pulses.

Findings regarding natural land cover configuration and composition align with a similar study conducted by Brody et al. (2017) who assessed the influence of natural-occurring open spaces on flood damage at the watershed scale for the same study area. Significant drivers of flood loss reduction in their study included LPI of natural land cover as well as mean radius of gyration (similar to correlation length) of forests and palustrine wetlands. Similarly, they found that the proportion of natural land cover did not have a significant on flood loss reduction, however, this metric became significant for palustrine wetlands. Taken together, these two studies imply that efforts to mitigate flood risk through the use of green infrastructure should focus on protecting large, contiguous patches of naturally occurring open spaces while preserving and restoring palustrine wetlands wherever possible. These findings corroborates design recommendations throughout the literature on maintaining biodiversity and ecosystem function (Dramstad 1996; Peck 1998).

Finally, the preservation and explicit protection of stream corridor habitat resulted in statistically significant reductions in insured flood loss. Moreover, this effect is seen even after controlling for the connectivity and amount of natural land cover within the stream corridor. This likely is an indicator of a few things that land cover data alone could not detect: 1) that the open space preserved is of greater ecological value; and 2) the spatial and physical characteristics of the development are less prone to flooding and/or minimize impact of floodplain functionality. Extra credit within CRS activity 420 is given to communities if the open space that is protected is preserved in or restored to its natural state. These types of open spaces are more likely to be actively managed by resource managers that are knowledgeable about the system requires so that it can continue to provide resources and services. Such open spaces better support floodplain functionality and will be more capable of providing natural flood control. Lastly, activity 420 provides credit for communities that implement regulatory approaches that provide incentives to developers to set aside areas as dedicated open space and to minimize impact on the natural flow regime. These efforts could include open space subdivision design, clustered development, transfers of development rights, low density zoning, planned unit developments, and prohibiting construction fill in the floodplain. Developers that employ these strategies create neighborhoods whose designs are more in congruence with natural stormwater flows and are thus spatially dissimilar than traditional neighborhood designs.

This finding illustrates that using open space protection as a land-use tool is an effective strategy for mitigating flood risk. In fact, damage experienced by communities within the stream corridor save, on average, approximately $376,000 per year as a result of open space protection, which is almost twice the savings found by Brody and Highfield (2013) in their study of the effect of activity 420 on flood loss reduction for the entire nation. This difference in savings in likely the result of examining the areas most vulnerable to flooding within the most flood damaged region of the nation. These savings may explain the increasing efforts of communities throughout the nation to acquire more activity 420 points as found by Brody and Highfield (2013). However, despite this trend, open space preservation is not well represented when compared to other mitigation strategies. Brody and Highfield (2013), found that communities with CRS open space credit are only receiving about a fifth of the total points available within this activity indicating that there is a considerable amount of room for improvement. This is likely the result of the difficulty and expense of protection open space, particularly within developed watersheds. However, the damages avoided by implementing this strategy could potentially more than offset many of the costs. For example, each stream corridor would save approximately $1.3 million per year if each of the communities within it were to maximize their point totals for open space preservation.

6.1 Human-Stream Corridor Interaction Examples

The findings from this study can be used to assess specific stream corridors of developed watersheds as examples of human-stream corridor interaction phases. As illustrated within the conceptual model, stream corridors have the tendency to fall into a state of increasing flood control often resulting in more development, less natural open space, and more flood damage. Although this study did not assess individual stream corridors over time, specific stream corridors can help better illustrate how these interactions progress over time. Moreover, assessing the specific land use policies and historical contexts of specific stream corridors may help uncover management approaches that either build or undermine flood resilience.

Four locations were selected that illustrate the various examples of human-stream corridor interactions: Crestview, FL; Bayonet Point, FL Aldine City, TX; and Brays Bayou, TX (see: Table 7). These locations were selected based on five key dimensions: total insured loss from 2006 to 2010, the percentage of natural land cover, the proportion of the drainage network that has been artificially hardened, the degree to which floodplain open space is protected (i.e. CRS Activity 420 points), and the number of structures. The encroachment of development into the stream corridor as seen in Table 7 is typically associated with increases in insured losses and stream hardening, as well as decreases in natural habitat and protected open space. The Crestview example represents an undeveloped, highly protected, and low damage scenario. Brays Bayou is on the other end of the extreme and represents a built-out stream corridor with a high degree of stream hardening, low habitat protection, and catastrophic losses. The following sections will discuss each area in more detail to better understand the characteristics of these corridors and the surrounding development.

Table 8. Selected locations that illustrate the examples of human-stream corridor interactions

Location	**Insured Loss**	**Percent Natural**	**Stream Hardening**	**Activity 420**	**Structures**
Crestview, FL	$5,011	91%	0%	367	30
Pasco County, FL	$370,373	72%	13%	308	9,055
Aldine, TX	$5,799,023	34%	51%	167	12,012
Brays Bayou, TX	$13,951,483	4%	63%	67	102,191

The Natural Stream Corridor: Crestview, Florida

The first stream corridor chosen is a natural stream corridor on the east side of Crestview, Florida. Crestview is located in the panhandle of Florida and is relatively small with a population of 20,978 (Census, 2010). The city has an elevation of 72 m (235 ft) and receives 1651 mm (65 in) of annual rainfall, which is the most of any city in Florida (http://www.cityofcrestview.org/257/History). The river that the stream corridor encompasses is the Shoal River, which, much like most of northwest Florida, consists of very little topographic relief, wide floodplains, and poor drainage (Qureshi 1978).

Development in this watershed has occurred almost entirely outside of the floodplain with only 30 structures located within the stream corridor. The lack of development in flood prone areas likely explains why this stream corridor only experienced one NFIP flood claim totaling $5,011. The absence of development within the stream corridor also precludes the need for flood control and opens up much of the area for large, contiguous patches of natural land cover which accounted for 91% of the corridor's area. As seen in figure 5, natural land cover not only covers much of the stream corridor but extends well beyond its boundary. So not only is the stream corridor free of development, but it is also buffered by natural habitat providing an extra layer of flood protection to surrounding development.

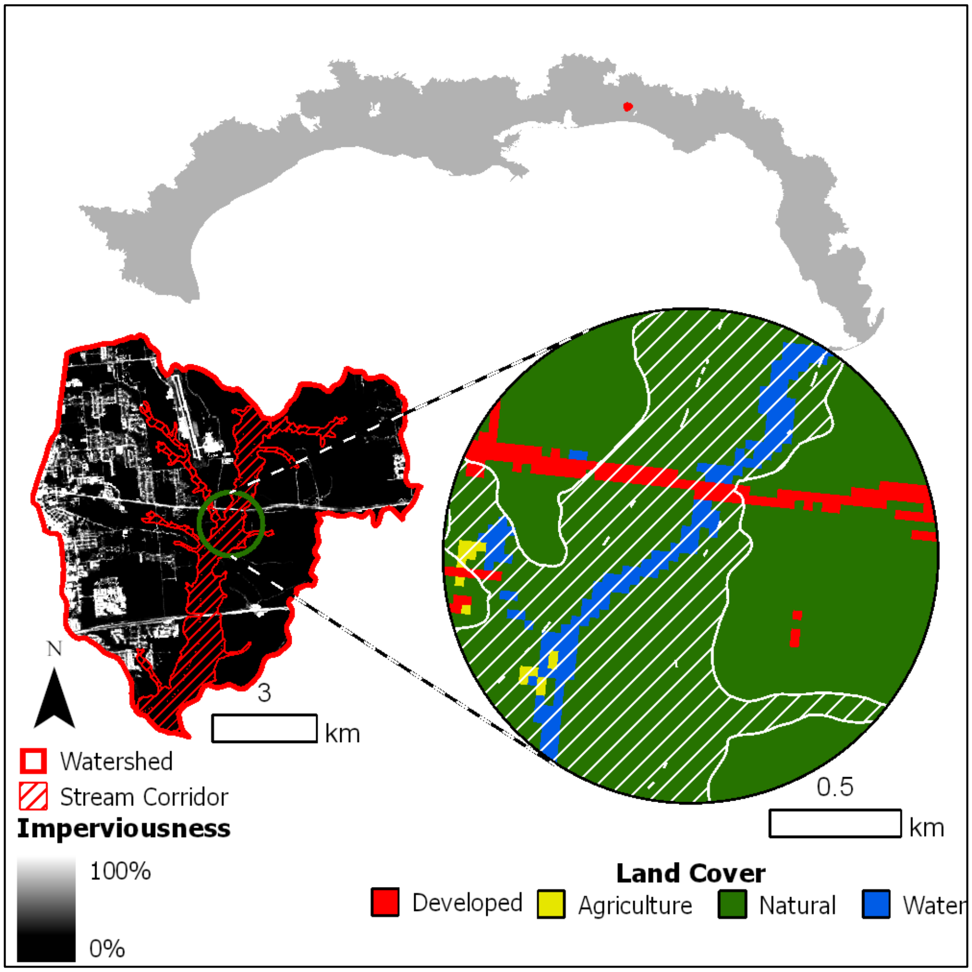

Figure 5. Crestview, Florida, stream corridor

The lack of development within the stream corridor near Crestview did not happen by chance alone, but is rather a product of strong city wide objectives, policies, and ordinances aimed at protecting critical natural resources. Crestview's comprehensive plan for 2020 has detailed land use principles with a strong focus on environmental planning. For example, the comprehensive plan states that their land development code (LDC) “should contain provisions that promote the natural functions of the topography, forests, natural areas and wetlands associated with surface waters within the city” and that “buffers will be created between development and environmentally sensitive areas, including wetlands.” Their plan also leverages economic incentives like transfer of development rights and density bonuses for developments that protect functioning wetlands within the city, which is reinforced by the requirement to cluster development on the upland portions of the development site. The inclusion of these environmental planning elements within their comprehensive plan likely had a strong influence on this corridor’s relatively high CRS Activity 420 score of 367.

The Semi-Natural Stream Corridor: Pasco County, Florida

The second stream corridor is a semi-natural corridor which is located in Pasco County, Florida. Development in this region consists mostly of sprawling suburbs and bedroom communities of Tampa which is located to the south. The geography is typical of western Florida with gently sloping terrain, numerous broad shallow lakes, and many small streams and creeks. The area near the coast consists largely of coastal swamps with very poor drainage with better drained coastal lowlands further east. Much of the development in the county has occurred on the better drained parts of the lowlands. Most of the rainfall occurs during the months of June through September with tropical storms producing the most damaging floods (Stankey 1982).

There are about 9,055 structures located within this stream corridor (Table 7) which is graphically displayed in Figure 6 that shows development encroaching into the floodplain from the surrounding areas. From 2006 to 2010 these structures experienced approximately $370,000 dollars in insured flood damage. Not only is flood control infrastructure required to support this level of development, but many of the residents will often demand it as a result of their exposure. As a result, this stream corridor has a moderate amount of stream hardening at around 12 percent. Approximately 72 percent of the land cover is natural (Table 7) with the remaining consisting of single family detached houses with its corresponding street network and surface parking. This stream corridor is likely in the beginning stages of encroachment, which have left somewhat discontiguous and moderately sized patches of natural land cover around the small streams and creeks.

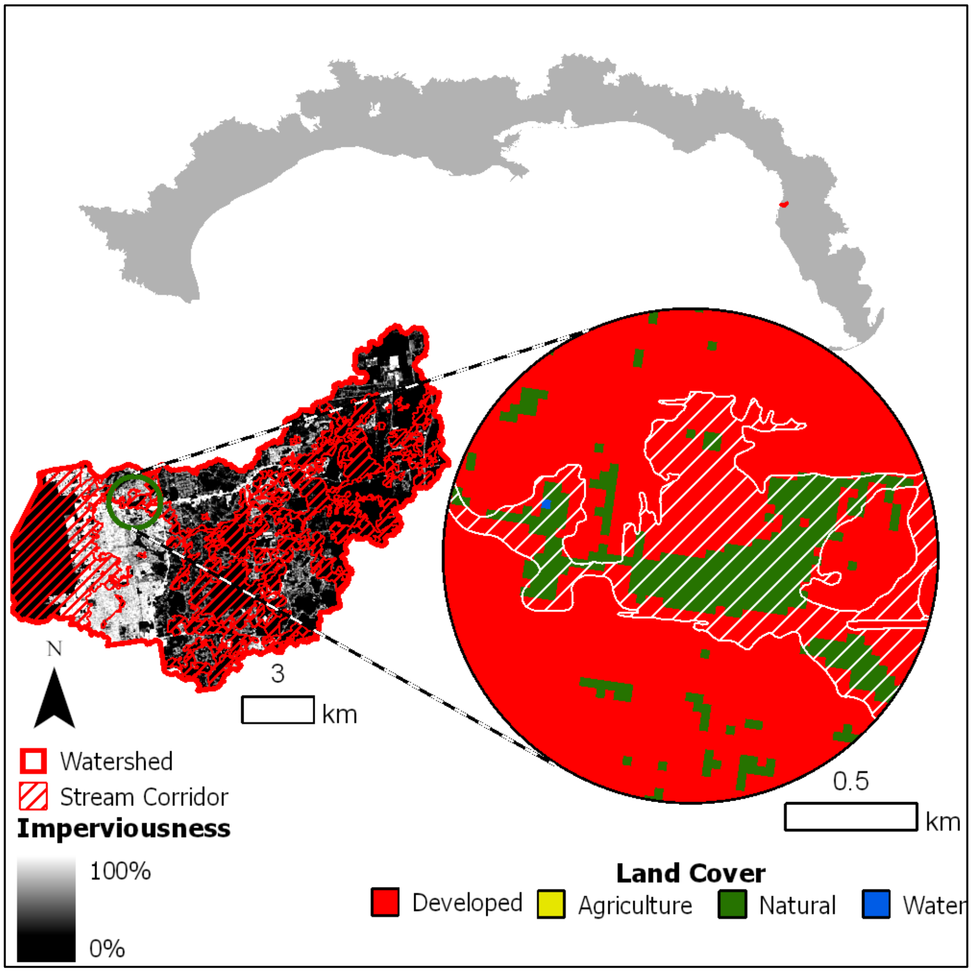

Figure 6. Pasco County, Florida, stream corridor

The land use policies in this region have enabled this type of development with fairly weak restrictions in terms of floodplain development. For example, the county's river system setback requirement within the county's 2025 comprehensive plan only requires a 15.24 m (50 ft) setback from the mean annual flood line. However, the county does restrict the use of land filling and grade changes within the 100-year floodplain, requires all subdivisions to maintain predevelopment runoff characteristics, and provides incentives clustered development. The prevention of large scale, anthropogenic based changes of the stream corridor's natural condition at the county level is likely what has preserved the small, somewhat continuous strip of natural vegetation along the streams within this stream corridor.

The Developed Stream Corridor: Aldine, Texas

The next location is a developed stream corridor located north of Houston, Texas near the city of Aldine. Aldine is part of Harris County, which is one of the most flood-damage jurisdictions in the nation. Flooding in this region is in large part due to the amount impervious surfaces as a result of sprawling development coupled little topographic relief, poorly drained soils, and episodes of heavy precipitation (Highfield et al. 2012). The city of Aldine is a fairly small community within the unincorporated region of Harris County. Water infrastructure within this region is controlled primarily by small utility districts that are 30 to 40 years old and in poor condition. The region is primarily drained by two bayous (Greens and Halls Bayou) with much of the adjacent development subject to frequent floods (WaterEngineers Inc. 2004).

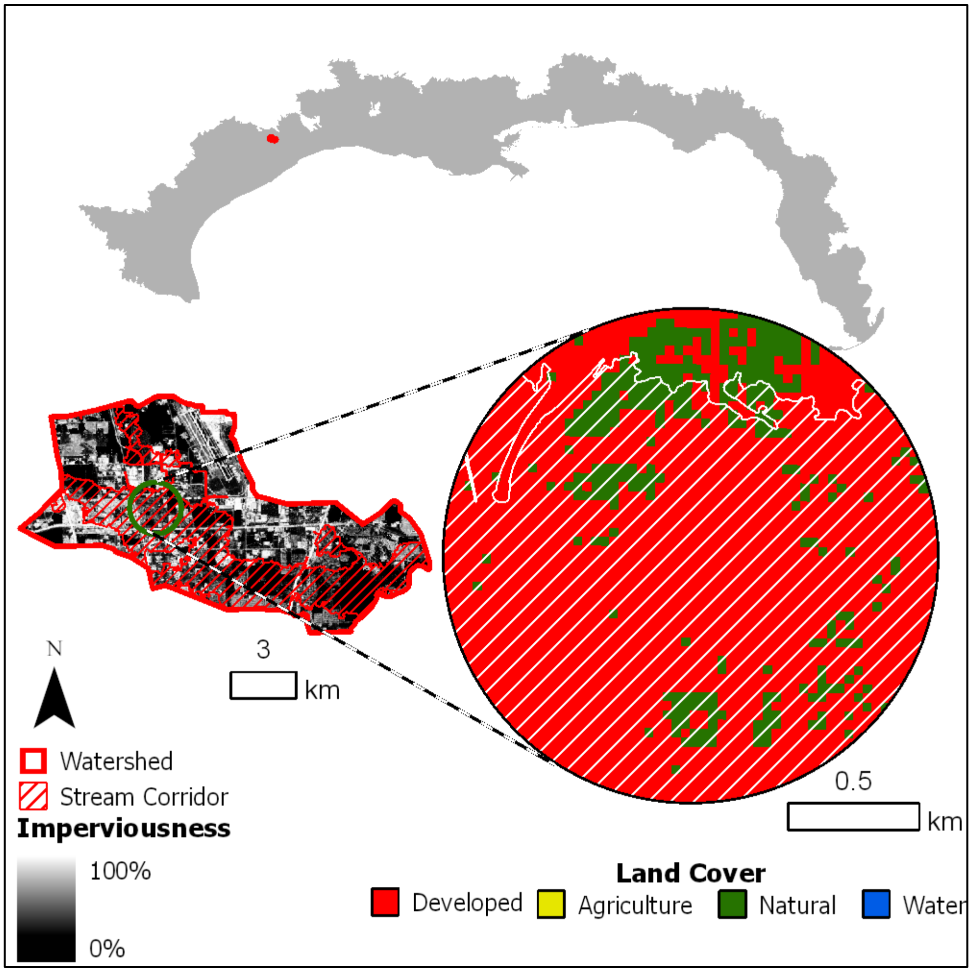

Figure 7. Aldine, Texas, stream corridor

The type of development pattern found in Aldine is illustrative of much of the sprawling, disorderly type of growth that has occurred within the unincorporated ring of land around Houston. That is, Houston is unique in that private developers can leverage municipal utility districts (MUDs) to develop land that is not proximate to any existing development by financing the installation of utility lines through the sell of tax-free revenue bonds. As a result, MUDs have been blamed, in part, for fueling Houston's leapfrog style of development because it removes many of the financial barriers to building new subdivisions (Peiser 1981). Despite their benefits, MUDs can cause many problems because the growth that they stimulate often outpaces other essential city services like police, fire, and basic social services (Qian 2010). As a result, flooding, which is a major problem in Aldine, is less of a priority and is typically dealt with in a reactionary way. For example, several areas in Aldine have resorted to using FEMA's sponsored buyout program likely because of severe repetitive flood losses or because the homes have been subjected to riverine flooding from neighboring bayous (Inc. 2004). The only other option for at risk homeowners is to rely on the installation of largescale and expensive flood control projects with the hope that their structure is removed from the floodplain.

The outcome of this development trend are communities that rely heavily on flood control infrastructure at the expense of natural habitat with the increased potential for widespread flood losses. This was evident in Aldine's stream corridor which had approximately 12,000 structures with nearly $6 million in insured flood loss from 2006 to 2010. As a result nearly two-thirds of the land area is considered developed with over half the drainage network artificially hardened (Table 7). The absence of cohesive governance and land use regulations have led to a relatively low CRS 420 score (167) with much of the natural areas consisting of small, disjointed patches as seen in Figure 7.

The Urbanized Stream Corridor: Brays Bayou, Texas

The final human-stream corridor interaction example is Brays Bayou, which is also located in the Houston area. The bayou stretches from the far western Houston and suburbs and terminates at the Houston Ship Channel. The watershed that it is located within drains highly developed and urbanized locations such as the Texas Medical Center, Rice University, and the museum district. Development that pre-dated the 1960s in this region was subject to frequent flooding when heavy rainfall events would cause the bayou to swell and overtop its banks. To address this problem the U.S. Army Corps of Engineers deepened, widened, and partially concrete-lined Brays Bayou in the early sixties. The original flood control infrastructure was designed to contain greater than a 100-year storm event. This was accomplished by increasing stormwater conveyance efficiency, which shortened the response time of the watershed and resulted in increased peak flows (Bedient et al. 2000).

What the engineers failed to consider was the future trajectory of development within this region and how that development would influence stormflow. This oversight would have costly consequences because Houston transitioned from a moderately sized city to the fourth largest in the nation during the two decades after the flood control infrastructure was installed. This growth resulted in large increases in impervious surfaces throughout the watershed, which generated more runoff and quickly overwhelmed the channel infrastructure. Within 15 years of the completion of the USACE project the bayou's design capacity shrank from greater than the 100 year storm to about a 5 to 10 year storm (Bedient et al. 2000).

Development continued to increase behind the easily overwhelmed flood control infrastructure resulting in decades of damaging storm events. Making matters worse was that many of the homes in the area were built before the implementation of FEMA's 1970 flood insurance BFE's, which allowed the homeowners to forgo the legal requirement of new construction to build to BFE levels making them susceptible to greater flood damages. With the watershed almost entirely built out, the options to avoid floodplain development or to preserve natural floodplain functionality had been removed. At this point the Brays Bayou was stuck in a trajectory of increasing flood control. In 2000, the Harris County Flood Control District (HCFCD) approved a $550 million project call 'Project Brays' to further widen and deepen the channel and construct additional detention basins. In 2015, the area experienced a 100 year event that resulted in severe overbanking along Brays despite a much of Project Brays already under completion. A recent study by Bass et al. (2016) concluded that even if Project Brays had been 100% complete that much of the development along Brays Bayou would still be exposed to substantial overbank flooding.

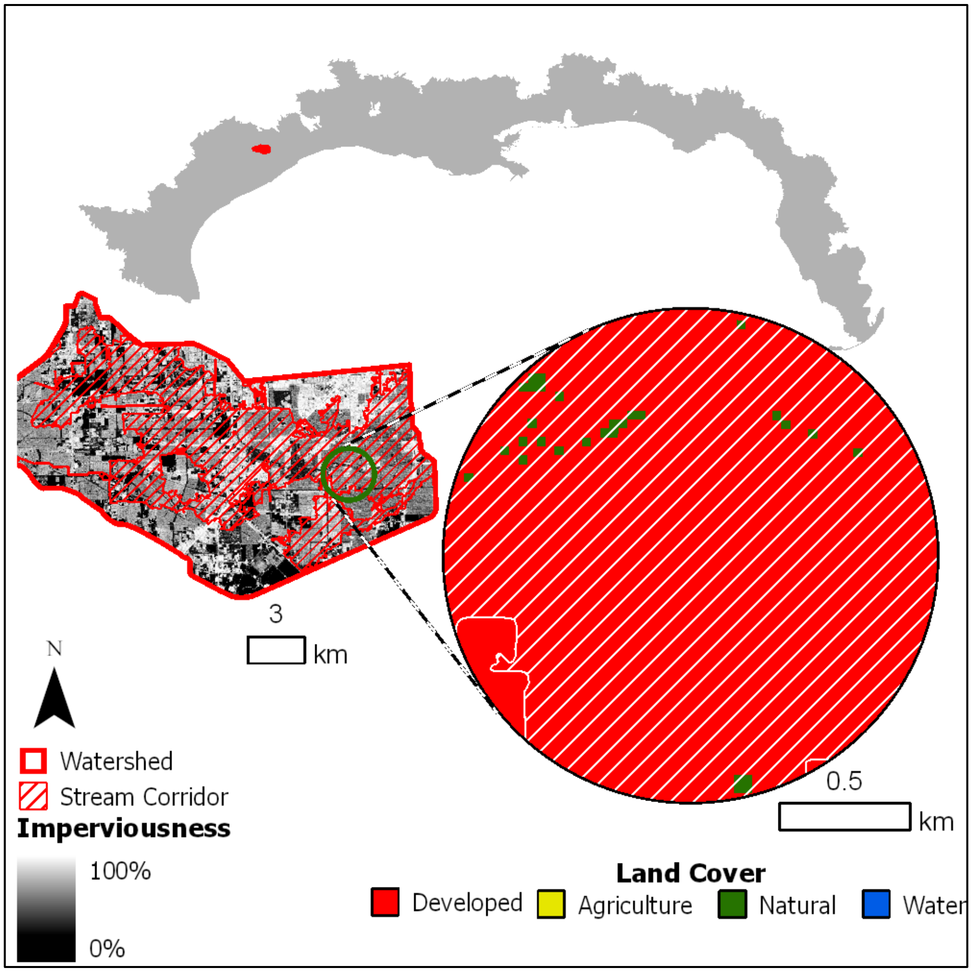

Figure 8. Brays Bayou, Texas, stream corridor

An urbanized stream corridor that is locked into a trajectory of increasing flood control like Brays Bayou eventually becomes entirely built out with very little natural land cover. Figure 8 illustrates this by highlighting an area along the bayou that is covered in development leaving only small, highly fragmented patches of natural land cover. As a whole this stream corridor is 94% developed with 63% of the drainage network artificially hardened. The positive feedback between increasing control and increasing development resulted in approximately 102,000 structures within the stream corridor. From 2006 to 2010 these homeowners experienced nearly $14 million in insured flood loss. The lack of open space and limited potential to restore floodplain functionality precludes this area from earning many CRS Activity 420 points (Table 7).

Human-Stream Corridor Evolution

The examples above illustrate the general trend of developing watersheds to increase resistance and decrease resilience to floods over time. Figure 9 below displays the stream corridor examples from developed watersheds discussed above using aerial imagery. These four examples can be viewed as phases in stream corridor urbanization within developed watersheds. The four phases would be: natural, semi-natural, developed, and urbanized. As the stream corridor progresses through these phases more flood control infrastructure (FCI) is required to not only offset rising flood damages because of increased flood risk, but to also make more land available for development. The density of development increases as stream corridor urbanization continues resulting in more imperviousness and stormwater runoff placing greater demands on the FCI. For FCI to maintain the same level of protection large investments into increasing their capacities is required. This progression is evident in the imagery. Stream corridor ‘A’ is relatively absent of FCI and development leaving a large majority of the stream corridor in its natural, forested condition. The semi-natural phase, or stream corridor ‘B’, is next. The beginnings of stream channelization can be seen in the upper right portion of the corridor allowing development to encroach into the floodplain leaving only a small buffer of vegetation. For development to continue building within the stream corridor more control and stream hardening is required, which can be seen going left to right through the middle of stream corridor ‘C’ (i.e. the developed stream corridor). Vegetation within the channel in stream corridor ‘C’ has been cleared to minimize roughness and increase stormwater conveyance. Only small, undeveloped patches of disconnected open space within the neighborhood remain. During the final phase, or the urbanized stream corridor, the drainage channels conveyance efficiency is increased by lining them with concrete. This is typically done to offset the flood damages from previous FCI that were being overwhelmed by the additional runoff from the increase in surrounding development. The concrete lined channel can be seen going left to right across the upper third of stream corridor ‘D’. Virtually all of the natural habitat has been removed and has been replaced with much more dense residential development and commercial zones. The trend through these phases is a loss of resilience to floods as indicated by the exponential increases in insured flood damage.

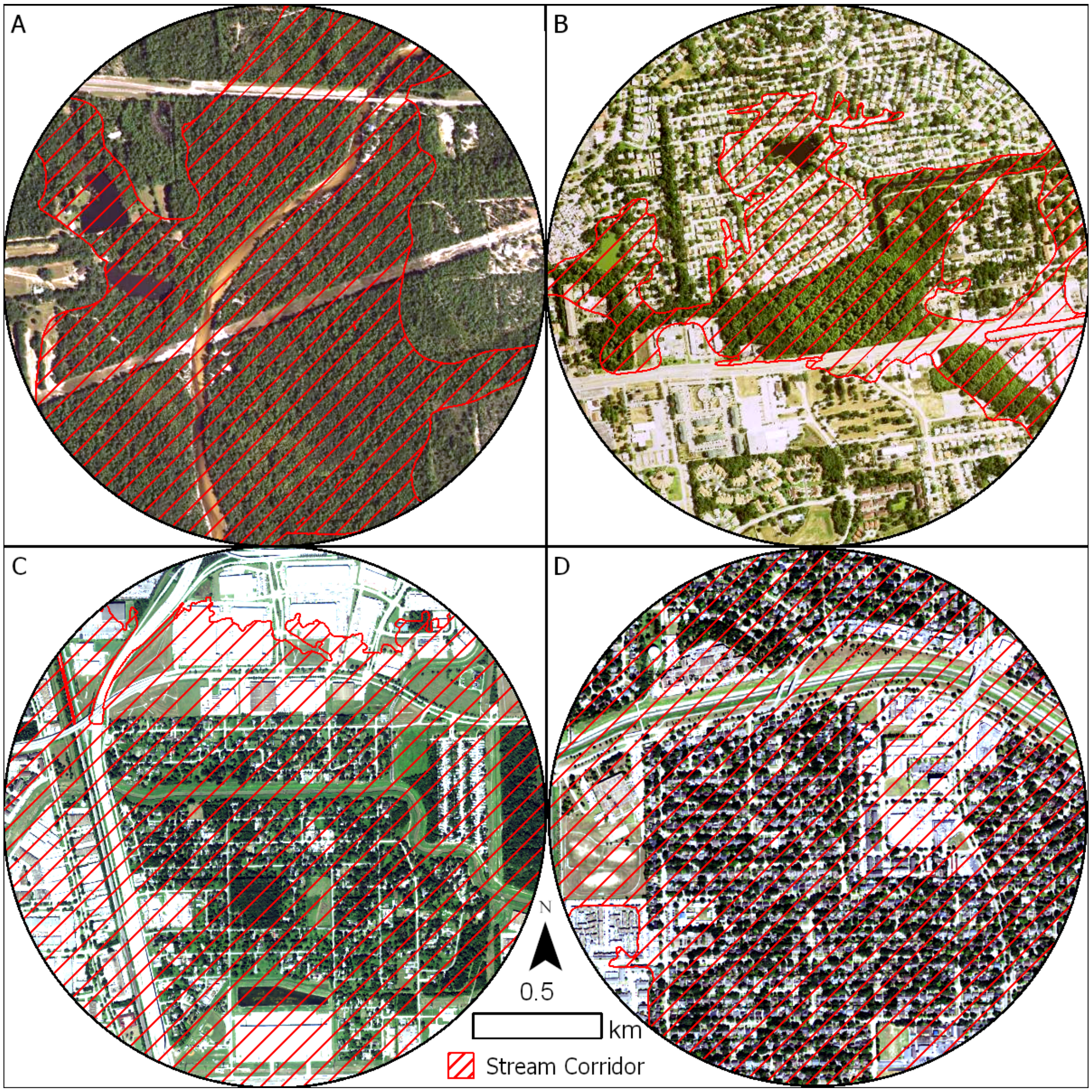

Figure 9. Aerial imagery depicting the hypothetical evolution of stream corridors over time. A) Natural; B) Semi-Natural; C) Developed; D) Urbanized

6.2 Policy, Planning, and Education

The findings and methods used in this study can be used in a multitude of ways. There are obvious implications from a policy and planning perspective that include efforts to keep stream corridors and floodplains free of development. Such efforts could compliment and include changes to state and federal policies, local land use planning, stormwater management, and site design recommendations. Many of these policy changes and recommendations will generally fall in line with more recent pushes by the ASFPM for “no adverse impacts”.

There are four overarching policy and planning objectives supported by this research: 1) prevent, remove, and relocate stream corridor development; 2) preserve large, contiguous patches of stream corridor open space; 3) discourage stream hardening; and 4) encourage open space preservation efforts. Many of these can extend and be easily incorporated within local and state government floodplain management recommendations as well as ongoing efforts at the national and local levels to reduce flood risk. One of the obvious ones includes the NFIP’s CRS activity 420, which is used to incentivize efforts to restore floodplain functionality and low impact land use decisions. Another prominent one is the Association of State Floodplain Managers’ (ASFPM) blueprint for floodplain management, referred to as “no adverse impact”, that would require communities to mitigate the impact their actions have on flood conditions of those around them (Larson and Plasencia 2001). Complimenting ASFPM’s no adverse impact strategy are FEMA’s Hazard Mitigation Assistance (HMA) programs including their buyout program, which is a cost-share approach used to acquire and remove repetitive-loss properties within the floodplain and convert them into open spaces permanently. Finally, FEMA recently released new activities eligible for HMA grants that are referred to as Climate Resilient Mitigation Activities (CRMA). The CRMA programs that are relevant to this study includes floodplain and stream restoration and methods for including ecosystem services into benefit-cost analyses. Given the variety and amount of existing policies, the focus of this section will be placed primarily on: 1) addressing the underlying drivers of floodplain encroachment; 2) how these policies and efforts could be improved; and 3) strategies to improve education and awareness.

Underlying Drivers of Floodplain Encroachment

First, it is important to acknowledge some of the key underlying causes of floodplain encroachment. Concern regarding the escalation of more intense uses within floodprone lands is not new. Evidence of this concern includes the establishment of federal wetland protection as stated within section 404 of the Clean Water Act in 1977 and FEMA’s creation of the CRS in 1990. However, floodplain encroachment has continued to increase despite efforts to protect these valuable ecological areas. The main drivers of this include:

- An incremental approach to assessing the effects of development on flood flows;
- A lopsided benefit-cost analysis that is inherently development-centered because it struggles to place value on natural floodplain functions; and
- A widespread belief that floods are destructive forces of nature.

Incrementalism within flood risk assessment fails to acknowledge the cumulative impacts of development and FCI over longer periods of time. Small expansions of levees and channelization structures are evaluated individually. Such interventions are often small enough that they can leverage model uncertainty to assert that the change in flood levels will be negligible (Pinter 2005). Moreover, current floodplain development standards allow flood levels to be increased up to 1 foot. Specifically, policy § 60.3(c)(10) within Title 44, chapter II of the Code of Federal Regulations requires that no new development within the floodplain shall be permitted unless it demonstrates that it will not increase the water surface elevation of the base flood more than one foot (Flood Plain Management Criteria for Flood-Prone Areas, 1976). This implicitly allows floodplain encroachment and disregards future increases in the level of the 100-year flood as well as development immediately adjacent to the 100-year floodplain boundary. The outcome of these incremental increases in control and development results in what

Pinter (2005) referred to as a “death by a thousand blows” as a result of the losses of natural habitat and the increases in runoff from impervious surfaces.

The next driver of floodplain encroachment is a lack of mechanisms to estimate the dollar savings from preserving or restoring floodplain habitat when conducting benefit-cost analyses of specific stream corridor interventions. The claimed economic value of FCI have often failed to factor in the environmental costs of altering the flow regime or stream corridor ecosystems. The major challenges to quantifying ecosystem services include an inadequate knowledge to link changes in ecosystem structure and function to the production of goods and services and that very few ecosystem services have observable marketed outputs (Barbier et al. 2013). As a matter of policy, FEMA requires that the benefits exceed the costs for federal flood control project to be considered justifiable. The inability to determine actual costs of displacing or disrupting the natural floodplain functions skews the benefit-cost ratio calculation. The net result is system that favors clearly defined market values such as the economic gains from increased development (Larson and Plasencia 2001).

The last major driver of floodplain encroachment is the tendency to think that flood damage is caused by destructive forces of nature, when they are caused by the decisions of where development is located. This misconception favors stormwater control instead of controlling how and where human activities are allowed (O'Connell and Justus 2009). This type of thinking is evident within the NFIP which focuses on how buildings within the floodplain are constructed rather than altering land use decisions. That is, the NFIP allows building with 100-year floodplain if particular construction requirements are met (i.e. habitable flood elevation), but does not call for land use changes. Some have argued that floodplain encroachment is encouraged because NFIP guidelines focus the construction guidelines for new development, but remain silent on the infrastructure (e.g. roads and utility lines) required by the development (Larson and Plasencia 2001).

Policy Recommendations

Specific policy recommendations as part of this study will focus on strategies that address the underlying drivers of encroachment as well as those that help meet the four overarching policy and planning objectives. Many of the policies can be achieved, at least partially, by following a simple guideline set forth by Dr. Gerry Galloway who, in a testimony to the House of Representatives' Committee on Transportation and Infrastructure in 2005 stated, "New development in the floodplain – without a specific need to be located in the floodplain – must be discouraged." If there are no feasible alternatives for the development to be located outside the floodplain, then development and its associated flood control infrastructure must have 'no adverse impact' as specified by ASFPM. As describe by Larson and Plasencia (2001) a no adverse impact is one in which: "the action of one property owner of community does not adversely affect the flood risks for other properties or communities as measured by increased flood stages, increased flood velocity, increased flows, or the increased potential for erosion and sedimentation, unless the impact is mitigated as provided for in a community or watershed based plan."

Achieving no adverse impact will require revising current floodplain management policies. Current standards allow flood levels to increase by up to 1 foot as a result of floodplain encroachment. Although the NFIP allows for more stringent, state-level standards that prohibit rises less than one foot of rise to take precedent, it should make it mandatory for any encroachment to have a no-rise impact. At the very least, if the NFIP decides to continue to allow a one foot rise for floodplain encroachments, then it should require the landowners to obtain easements from affected landowners. Such changes will transfer the costs currently considered as externalities (e.g. increased downstream flood risk) onto the developers that will indirectly incentivize floodplain avoidance or require the integration of neighborhood design elements that can absorb and store water (e.g. pervious concrete, bioswales, retention/detention ponds, etc.).

Another benefit of a no adverse impact strategy is that it will require local governments to consider the regional, watershed-level impacts of local developments and flood control projects. That is, no adverse impacts implies that there must be no induced damage throughout the watershed. Often the impacts of a single project may appear to be insignificant, but their cumulative impact over time can become highly significant. To address this, good basin-wide plans need to be in place to adequately address these regional issues. This can help align the often fragmented nature of local government with ecological boundaries of stream corridors and watersheds thereby producing land use management policies within a unified riverine ecosystem management context.

Incentives for exceeding no adverse impact can also be integrated into the CRS. For example, existing activities could be expanded or new ones created focused explicitly on undoing the impacts of previous developments. Such an activity would actively pursue the reestablishment of a natural flood regime through the integration of green infrastructure within existing communities, removing FCI, and floodplain retreat.

CRS activity 420 currently focuses on giving credit for activities that limit the amount of development within the floodplain and on enhancing natural floodplain functionality. However, despite its attention to natural functions and avoidance-based land use approaches, it does little with respect to acknowledging the importance of habitat configuration and landscape-based management planning strategies. Results from this study support the creation of new elements within activity 420 related to increasing habitat connectivity and sustainable landscape planning. For example, communities could receive activity 420 credits for conducting landscape pattern analyses, identifying existing and potential spatial conflicts between anthropogenic disturbances and natural areas, and generating spatially targeted solutions to minimize the impact of development on natural ecosystems. Specific solutions could include protecting and expanding large patches of natural habitat and increasing their contiguity by connecting them with nearby patches. Many of these solutions could be accomplished simply by following Forman (1995) sustainable planning guidelines: 1) maintain large patches of native vegetation; 2) maintain wide riparian corridors; and 3) maintain connectivity between important resource patches.

Funding for these activities could come from FEMA's hazard mitigation grant program (HMGP) as many of these activities could be linked with HMA approved CRMAs. For a flood mitigation project to be eligible for HMGP funds its benefits must exceed its costs. FEMA requires that all proposed hazard mitigation projects to submit a benefit-cost analysis (BCA) in which the future benefits of the project are estimated and compared to its cost. FEMA has developed a software to calculate benefit-cost ratios (BCR) and in 2016 added an ecosystem service benefits calculator as well as floodplain and stream restoration to its BCA Toolkit to help assist communities with their BCR calculations for CRMAs. Results from this study could be used to revise and update these calculations by including actual dollar savings in terms of avoided flood damage by increasing stream corridor landscape connectivity. These updates are promising, but will not make much difference if decision-makers are not aware of their existence. Efforts need to be placed on training, educating, and spreading awareness of these tools if they are to be used.

Finally, in some situations, such as highly urbanized watersheds, restoring stream corridors to their predevelopment state is infeasible and will likely require some level of flood control to prevent catastrophic damages. In such situations attention should be given to multifunctional flood defenses that provide flood risk reduction while meeting ecosystem conservation objectives. Such an approach would encourage floodplain habitat regeneration through natural processes by making habitat production a coequal goal with flood protection. The design of flood control channels would leverage high Manning's *n* roughness coefficients and wide floodplain surfaces to create channel capacity (Greco and Larsen 2014). Levee setbacks, buyouts of repetitive loss properties, transfer of development rights, and conservation easements are examples of some policies that can complement the formation of a multifunctional flood defense strategy by preserving and freeing up land for natural stream corridor habitat. Accomplishing such designs will require engineers, urban planners, and landscape architects to work together in novel ways. The "room for the river" approach and its associated water-based land use activities as used in the Netherlands can be used to help guide efforts along the Gulf of Mexico coast.

Education

Education and outreach regarding the importance of addressing human-stream corridor interactions must be a significant component of flood risk reduction efforts by federal, state, local, and non-governmental organizations. A concerted effort to identify the key constituents that influence floodplain land use and then pair them with agencies that provide technical assistance would be helpful. An example, as identified by Larson and Plasencia (2001), would be to have the Natural Resource Conservation Service act in concert with state conservation agencies in educating Soil and Water Conservation Districts on the importance of a no adverse impact approach. Another example would be to create a new flood resilience institution within FEMA that would partner with state ASFPM chapters to explain the importance of integrating the principles of landscape ecology and resilience theory into their certified floodplain manager (CFM) program. Finally, landscape pattern metrics can be used to convey complex socio-ecological processes that can be used in participatory planning activities. Such an effort could be conducted by universities in partnership with extension programs to illustrate complex concepts in a non-technical manner with the public and local decision-makers so that they are not only aware of the issues but can use the information to make science-based decisions.

Knowledge sharing between planners and hazard mitigation specialists at the local level should also be pursued to help overcome issues associated with the fragmented and poorly integrated nature commonly found within the mitigation planning practice (Burby et al. 1999; Godschalk et al. 1998; Macintosh 2013). A single community will often create and adopt a wide variety of independent plans, with each having various outcomes for flood resilience. A lack of integration and consistency amongst plans can result in conflicts, particularly for land use goals and policies, which can undermine community flood resilience (Berke et al. 2015). As such, the National Research Council (NRC) has recommended the use of a resilience scorecard, which communities can use to identify conflicts, improve coordination across plans, target efforts where they are most needed, and track their progress towards resiliency (NRC 2012). A recent study by Berke et al. (2015) illustrated that such an effort has potential to reduce counterproductive efforts and more efficiently use resources to minimize vulnerability to hazards.

Finally, insight gained from this study can be integrated or help in the creation of new comprehensive flood risk management and urban resilience courses at the collegiate level. There is a strong need for students and decision makers to think about urban issues for a multi-disciplinary perspective particularly as it relates to complex socio-ecological issues. Such coursework would integrate key concepts from environmental planning, landscape ecology, hazard mitigation, coastal resilience, hydrology, spatial analysis, and natural resource management. Examples of courses that could be created would include comprehensive floodplain management, urban flood resilience, and green infrastructure planning. Students would learn how to use Geographic Information Systems and other programs along with the appropriate statistical tests to make spatially targeted decisions in the context of socio-ecological resilience.

7. CONCLUSION

7.1 Research Summary

This study is the first to systematically evaluate the impacts of multiple anthropogenic disturbances on flood loss within what is arguably the most flood vulnerable region in the U.S. These disturbances included developing within the stream corridor, habitat fragmentation and loss, leveeing and stream hardening, and the preservation of open space. The major results from this study are: 1) increasing development within the stream corridor supplants precipitation as the largest contributor to flood damage; 2) single large patches of contiguous stream corridor habitat are the most effective at reducing flood loss; 3) stream hardening increases the risk of flood damage; and 4) efforts to preserve open space within the floodplain can significantly reduce flood risk. The findings can be used to further policy and planning activities that increase the flood resilience of vulnerable coastal communities, and educational and outreach efforts that increase literacy of how specific human-stream corridor interventions influence flooding.

7.2 Broader Impacts of Research

This study integrated concepts from landscape ecology and resilience theory to address the resilience of coastal landscapes to future flood events. For city planners and engineers, this study will empirically corroborate the potential advantages of an ecological flood defense system. Such a system will leverage the flood control services provided by natural habitat while also providing other ecosystem services such as water quality improvement, increased biodiversity, recreation, and erosion control. This approach minimizes costs associated with installing expensive structural interventions while simultaneously minimizing the potential for large scale, high cost flood events. This is of interest to FEMA administrators who are devoting large amounts of resources to identify cost effective ways to reduce the nation's vulnerability to damaging floods as well as improve their mounting debt problem. Moreover, this information will provide the NFIP a new ecological metric (i.e. connectivity) for the Community Rating System

(CRS), a voluntary program created by FEMA that provides community wide insurance premium reductions for specific mitigation activities. For environmental managers, this study will be valuable as it provides an avoided cost valuation in real dollars for a particular ecosystem service: flood mitigation by intact stream corridor habitat.

7.3 Future Research

Although this study is one of the first to comprehensively investigate how human alterations of landscapes influence flood risk, it should be considered an initial step in a more thorough analysis of the topic. Future research will improve on this study in multiple ways. First, the analysis was limited to a 5-year study period. Future research should expand the timeframe to better capture the effect of continued reliance on FCI and stream corridor urbanization on flood damage. Doing so would also capture the effect of a larger variety of storm characteristics. Second, only five landscape metrics were examined for one land cover classification. Additional work should be done that examines the influence of other measures, particularly as they relate to specific land cover types as well as their spatial arrangement to each other. Third, each land cover metric was assessed individually due to high collinearity. More work needs to be done to address this limitation and examine the synergistic impact of multiple landscape patterns. Fourth, more research is needed on the influence of other types of FCI including detention/retention areas, dams, and specific types of stream hardening. Fifth, more work should be done to assess the influence of other socioeconomic factors, specifically those that relate to vulnerability like age, race, and income. Finally, this study only assessed the impact of these interventions within the stream corridor. Future studies should examine other processes and interventions outside the stream corridor that could influence flood damage such as urban stormwater infrastructure characteristics, non-stream corridor relevant ecohydrological landscape metrics, and the spatial distribution of impervious surfaces. Such an analysis could begin to link hydrologically distinct components of the watershed with metrics tailored to specific processes thereby addressing flood resilience at a more comprehensive scale.

REFERENCES

Akanbi, A. A., Lian, Y., and Soong, T. W. (1999). "An analysis on managed flood storage options for selected levees along the lower Illinois River for enhancing flood protection." *Contract Rep. 645,* Illinois State Water Survey, Champaign, IL.

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., and Spirandelli, D. (2007). “The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins.” *Landscape and urban planning*, 80(4), 345–361.

Anderson, B., Rutherfurd, I., and Western, A. (2006). “An analysis of the influence of riparian vegetation on the propagation of flood waves.” *Environmental Modelling & Software*, 21(9), 1290–1296.

Anselin, L. (2002). “Under the hood: issues in the specification and interpretation of spatial regression models.” *Agricultural economics*, 27(3), 247–267.

Arnold Jr, C. L., and Gibbons, C. J. (1996). “Impervious surface coverage: The emergence of a key environmental indicator.” *Journal of the American planning Association*, 62(2), 243–258.

Assessment, M. E., and others. (2005). *Ecosystems and human well-being*. Island Press, Washington, D.C.

Ávila, A., Carvajal, Y., and Justino, F. (2015). “Representative rainfall thresholds for flash floods in the Cali river watershed, Colombia.” *Natural Hazards and Earth System Sciences Discussions,* 3, 4095–4119.

Baker, V. R. (1977). “Stream-channel response to floods, with examples from central Texas.” *Geological Society of America Bulletin,* 88(8), 1057–1071.

Baldassarre, G. D., Viglione, A., Carr, G., Kuil, L., Salinas, J., and Blöschl, G. (2013). “Socio-hydrology: Conceptualising human-flood interactions.” *Hydrology and Earth System Sciences*, 17(8), 3295–3303.

Barbier, E. B., Georgiou, I. Y., Enchelmeyer, B., and Reed, D. J. (2013). “The value of wetlands in protecting southeast Louisiana from hurricane storm surges.” *PloS one*, 8(3), e58715.

Barton, D. R., Taylor, W. D., and Biette, R. (1985). “Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams.” *North American Journal of Fisheries Management*, 5(3A), 364–378.

Bass, B., Juan, A., Gori, A., Fang, Z., and Bedient, P. (2016). "2015 Memorial Day flood impacts for changing watershed conditions in Houston." *Natural Hazards Review*, 18(3), 05016007.

Beatley, T. (2009). *Planning for coastal resilience: Best practices for calamitous times*. Island Press, Washington, D.C.

Beatley, T., and Manning, K. (1997). *The ecology of place: Planning for environment, economy, and community*. Island Press, Washington, D.C.

Beck, N., Gleditsch, K. S., and Beardsley, K. (2006). "Space is more than geography: Using spatial econometrics in the study of political economy." *International Studies Quarterly*, 50(1), 27–44.

Bedient, P. B., Hoblit, B. C., Gladwell, D. C., and Vieux, B. E. (2000). "NEXRAD radar for flood prediction in Houston." *Journal of Hydrologic Engineering*, 5(3), 269–277.

Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P., and Pollock, M. M. (2010). "Process-based principles for restoring river ecosystems." *BioScience*, 60(3), 209–222.

Belsley, D. A. (1991). *Conditioning diagnostics: Collinearity and weak data in regression*. Wiley, New York, NY.

Berke, P., Newman, G., Lee, J., Combs, T., Kolosna, C., and Salvesen, D. (2015). "Evaluation of networks of plans and vulnerability to hazards and climate change: A resilience scorecard." *Journal of the American Planning Association*, 81(4), 287–302.

Berke, P. R. (1996). "Enhancing plan quality: Evaluating the role of state planning mandates for natural hazard mitigation." *Journal of Environmental Planning and Management*, 39(1), 79–96.

Berke, P. R., and French, S. P. (1994). "The influence of state planning mandates on local plan quality." *Journal of Planning Education and Research*, 13(4), 237–250.

Bernard, J. M., and Tuttle, R. W. (1998). "Stream corridor restoration: Principles, processes, and practices." *Engineering Approaches to Ecosystem Restoration*, 320–325.

Bernhardt, E. S., Palmer, M., Allan, J., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., and others. (2005). "Synthesizing U.S. river restoration efforts." *Science*, 308(5722), 636–637.

Berry, W. D. (1993). *Understanding regression assumptions*. Sage Publications, Newbury Park, CA.

Birkland, T. A., Burby, R. J., Conrad, D., Cortner, H., and Michener, W. K. (2003). “River ecology and flood hazard mitigation.” *Natural Hazards Review*, 4(1), 46–54.

Bivand, R. S., Pebesma, E., and Gomez-Rubio, V. (2013). *Applied spatial data analysis with R*. UseR! Series. Springer, NY.

Bras, R. L. (1990). *Hydrology: An introduction to hydrologic science*. Addison-Wesley Publishing Company, Reading, MA.

Brauman, K. A., Daily, G. C., Duarte, T. K., and Mooney, H. A. (2007). “The nature and value of ecosystem services: An overview highlighting hydrologic services.” *Annual Review of Environment and Resources*, 32, 67–98.

Van den Brink, M. A. (2009). *Rijkswaterstaat on the horns of a dilemma*. Eburon, Delft.

Brody, S., Blessing, R., Sebastian, A., and Bedient, P. (2014). “Examining the impact of land use/land cover characteristics on flood losses.” *Journal of Environmental Planning and Management*, 57(8), 1252–1265.

Brody, S. D., Blessing, R., Sebastian, A., and Bedient, P. (2012). “Delineating the reality of flood risk and loss in Southeast, Texas.” *Natural Hazards Review*, 14, 89-97.

Brody, S. D., Carrasco, V., and Highfield, W. E. (2006). “Measuring the adoption of local sprawl reduction planning policies in Florida.” *Journal of Planning Education and Research*, 25(3), 294–310.

Brody, S. D., Davis, S. E., Highfield, W. E., and Bernhardt, S. P. (2008). “A spatial-temporal analysis of section 404 wetland permitting in Texas and Florida: Thirteen years of impact along the coast.” *Wetlands*, 28(1), 107–116.

Brody, S. D., and Highfield, W. E. (2013). “Open space protection and flood mitigation: A national study.” *Land Use Policy*, 32, 89–95.

Brody, S. D., Highfield, W. E., and Blessing, R. (2015). “An analysis of the effects of land use and land cover on flood losses along the Gulf of Mexico coast from 1999 to 2009.” *Journal of the American Water Resources Association*, 51(6), 1556–1567.

Brody, S. D., Highfield, W. E., Blessing, R., Makino, T., and Shepard, C. C. (2017). “Evaluating the effects of open space configurations in reducing flood damage along the Gulf of Mexico coast.” *Landscape and Urban Planning*, 167, 225–231.

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

Brody, S. D., Highfield, W. E., Wilson, M., Lindell, M. K., and Blessing, R. (2016). “Understanding the motivations of coastal residents to voluntarily purchase federal flood insurance.” *Journal of Risk Research*, 1–16.

Brody, S. D., Zahran, S., Highfield, W. E., Grover, H., and Vedlitz, A. (2008). “Identifying the impact of the built environment on flood damage in Texas.” *Disasters*, 32(1), 1–18.

Brody, S. D., Zahran, S., Maghelal, P., Grover, H., and Highfield, W. E. (2007). “The rising costs of floods: Examining the impact of planning and development decisions on property damage in Florida.” *Journal of the American Planning Association*, 73(3), 330–345.

Brody, S., Gunn, J., Peacock, W., and Highfield, W. E. (2011). “Examining the influence of development patterns on flood damages along the Gulf of Mexico.” *Journal of Planning Education and Research*, 31(4), 438–448.

Brody, S., Kim, H., and Gunn, J. (2013). “Examining the impacts of development patterns on flooding on the Gulf of Mexico coast.” *Urban Studies*, 50(4), 789–806.

Bruijnzeel, L. (2000). “Forest hydrology.” In: Evans, J. (Ed.). *The Forestry Handbook 1*. Blackwell, Oxford.

Bullock, A., and Acreman, M. (2003). “The role of wetlands in the hydrological cycle.” *Hydrology and Earth System Sciences Discussions*, 7(3), 358–389.

Burby, R. J. (2006). “Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas.” *The Annals of the American Academy of Political and Social Science*, 604(1), 171–191.

Burby, R. J., Beatley, T., Berke, P. R., Deyle, R. E., French, S. P., Godschalk, D. R., Kaiser, E. J., Kartez, J. D., May, P. J., Olshansky, R., and others. (1999). “Unleashing the power of planning to create disaster-resistant communities.” *Journal of the American Planning Association*, 65(3), 247–258.

Burby, R. J., and French, S. P. (1981). “Coping with floods: The land use management paradox.” *Journal of the American Planning Association*, 47(3), 289–300.

Burby, R. J., and others. (1991). *Sharing environmental risks*. Westview Press, Boulder, CO.

Buyantuyev, A., and Wu, J. (2007). “Effects of thematic resolution on landscape pattern analysis.” *Landscape Ecology*, 22(1), 7–13.

Carter, R. (1961). “Magnitude and frequency of floods in suburban areas.” *Short Papers in Geologic and Hydrologic Sciences*. U.S. Geological Survey Professional Paper, 424-B, p. B9-B11.

Carter, V., Bedinger, M., Novitzki, R. P., and Wilen, W. (1979). “Water resources and wetlands.” *Wetlands functions and values-The state of our understanding. Minneapolis, MN: Water Resources association*, 344–376.

Changnon, S. (2003). “Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming.” *Natural Hazards*, 29(2), 273–290.

Charron, I., Lalonde, O., Roy, A. G., Boyer, C., and Turgeon, S. (2008). “Changes in riparian habitats along five major tributaries of the Saint Lawrence River, Quebec, Canada: 1964-1997.” *River Research and Applications*, 24(5), 617–631.

Chi, G., and Zhu, J. (2008). “Spatial regression models for demographic analysis.” *Population Research and Policy Review*, 27(1), 17–42.

Cohen, M. J., and Brown, M. T. (2007). “A model examining hierarchical wetland networks for watershed stormwater management.” *Ecological Modelling*, 201(2), 179–193.

Conner, W. H., Hill, N. L., Whitehead, E. M., Busbee, W. S., Ratard, M. A., Ozalp, M., Smith, D. L., and Marshall, J. P. (2001). *Forested wetlands of the southern United States: A bibliography*. US Department of Agriculture, Forest Service, Southern Research Station.

Conrad, D. R., McNitt, B., and Stout, M. (1998). *Higher ground: A report on voluntary buyouts in the nation’s floodplains, a common ground solution serving people at risk, taxpayers, and the environment.* National Wildlife Federation, Washington, D.C.

Costanza, R., d’Arge, R., de Groot, R.S., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M. (1997). “The value of the world’s ecosystem services and natural capital.” *Nature*, 387, 253-260.

Cowdrey, A. E. (1996). *This land, this South: An environmental history*. University Press of Kentucky, Lexington, KY.

Criss, R. E., and Shock, E. L. (2001). “Flood enhancement through flood control.” *Geology*, 29(10), 875.

Crosset, K. M. (2005). *Population trends along the coastal United States: 1980-2008*. National Oceanic and Atmospheric Administration, National Ocean Service, Management and Budget Office, Special Projects.

Cushman, S. A., and McGarigal, K. (2008). “Landscape metrics, scales of resolution.” *Designing Green Landscapes*, 33–51.

Daily, G. C., Alexander, S., Ehrlich, P. R., Goulder, L., Matson, P. A., Mooney, H. A., Postel, S., Schneider, S. H., Tilman, D., and Woodwell, G. M. (1997). “Ecosystem services: Benefits supplied to human societies by natural ecosystems.” *Issues in Ecology*, 2, 1-16.

Dramstad, W. E. (1996). *Landscape ecology principles in landscape architecture and land-use planning*. Island Press, Washington, D.C.

Dunne, T., and Leopold, L. B. (1978). *Water in environmental planning*. Macmillan, London, England.

Echeverria, C., Coomes, D., Salas, J., Rey-Benayas, J. M., Lara, A., and Newton, A. (2006). “Rapid deforestation and fragmentation of Chilean temperate forests.” *Biological Conservation*, 130(4), 481–494.

Federal Emergency Management Agency (FEMA). (2012). "NFIP and levees: An overview fact sheet." <https://www.fema.gov/media-library/assets/documents/9635?id=2609> (Accessed May 2017).

Federal Emergency Management Agency (FEMA). (2013). “National flood insurance program, community rating system coordinator’s manual.” <www.fema.gov/library/viewRecord.do?id=243> (Accessed May 2017).

Ferreira, C. S. S., Walsh, R. P. D., Nunes, J. P. C., Steenhuis, T. S., Nunes, M., de Lima, J. L. M. P., Coelho, C. O. A., and Ferreira, A. J. D. (2016). “Impact of urban development on streamflow regime of a Portuguese peri-urban Mediterranean catchment.” *Journal of Soils and Sediments*, 1–14.

Ferreira, H., and Botequilha-Leitão, A. (2006). "Integrating landscape and water-resources planning with focus on sustainability." In: Tress, B., Tress, G., Fry, G., Opdam, P. (Ed.). *From landscape research to landscape planning, Aspects of* *integration, education and application*. Springer, Dordrecht, The Netherlands, 143-159.

Flood Plain Management Criteria for Flood-Prone Areas. 44 CFR § 60.3(c)(10). (1976). Code of Federal Regulations (CFR), Title 44, chapt. II § 60.3(c)(10).

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., and others. (2005). “Global consequences of land use.” *Science*, 309(5734), 570–574.

Forman, R. T. (1995). “Some general principles of landscape and regional ecology.” *Landscape Ecology*, 10(3), 133–142.

Forman, R. T., and Godron, M. (1986). *Landscape ecology*. Wiley, New York, NY.

Foster, H. D. (1997). *The Ozymandias Principles: Thirty-one strategies for surviving change*. UBC Press, Victoria, Canada.

Fredrickson, L. H. (1979). “Floral and faunal changes in lowland hardwood forests in Missouri resulting from channelization, drainage, and impoundment.” *United States. Fish and Wildlife Service. Office of Biological Services. FWS/OBS (USA).*

Fredrickson, L. H., and Kaminski, R. M. (2005). *Ecology and management of bottomland hardwood systems: The state of our understanding: A symposium,* March 11-13, 1999, Peabody Hotel, University of Missouri-Columbia, Memphis, TN.

Gergel, S. E. (2005). “Spatial and non-spatial factors: When do they affect landscape indicators of watershed loading?” *Landscape Ecology*, 20(2), 177–189.

Giambelluca, T. W. (2002). “Hydrology of altered tropical forest.” *Hydrological processes*, 16(8), 1665–1669.

Gillies, C. S., and Clair, C. C. S. (2008). “Riparian corridors enhance movement of a forest specialist bird in fragmented tropical forest.” *Proceedings of the National Academy of Sciences*, 105(50), 19774–19779.

Godschalk, D. R. (2003). “Urban hazard mitigation: Creating resilient cities.” *Natural Hazards Review*, 4(3), 136–143.

Godschalk, D. R., Kaiser, E. J., and Berke, P. R. (1998). “Integrating hazard mitigation and local land use planning.” In: Burby, R. (Ed.). *Cooperating with nature: Confronting natural hazards with land-use planning for sustainable communities,* Joseph Henry Press Washington, DC, 85–118.

Gosselink, J. G., Conner, W., Day Jr, J., and Turner, R. (1981). “Classification of wetland resources: Land, timber and ecology.” In: Jackson, B. D. and J. L. Chambers (Ed.). *Timber harvesting in wetlands.* Division of Continuing Education, Louisiana State University. Baton Rouge, Louisiana.

Graf, W. L. (2001). “Damage control: Restoring the physical integrity of America’s rivers.” *Annals of the Association of American Geographers*, 91(1), 1–27.

Graf, W. L. (2006). “Downstream hydrologic and geomorphic effects of large dams on American rivers.” *Geomorphology*, 79(3), 336–360.

Greco, S. E., and Larsen, E. W. (2014). “Ecological design of multifunctional open channels for flood control and conservation planning.” *Landscape and Urban Planning*, 131, 14–26.

Gregory, K., and Walling, D. (1968). “The variation of drainage density within a catchment.” *Hydrological Sciences Journal*, 13(2), 61–68.

Gruntfest, E., and Wohl, E. (2000). “Nonstructural mitigation of flood hazards.” In: Wohl, E. (Ed.). *Inland Flood Hazards: Human Riparian and Aquatic Communities.* Cambridge University Press, Cambridge, UK.

Heavrin, C. A. (1981). *Boxes, baskets, and boards: A history of Anderson-Tully Company*. Memphis State University Press, Memphis, TN.

Hewitt, K., and Burton, I. (1971). *The hazardousness of a place: A regional ecology of damaging events. Research Publication 6.* University of Toronto, Department of Geography, Toronto, Canada.

Hewlett, J. D., and Doss, R. (1984). “Forests, floods, and erosion: A watershed experiment in the southeastern Piedmont.” *Forest science*, 30(2), 424–434.

Heywood, D. I. (1998). *Introduction to geographical information systems*. Addison Wesley Longman, NY.

Highfield, W. E., and Brody, S. D. (2006). “Price of permits: Measuring the economic impacts of wetland development on flood damages in Florida.” *Natural Hazards Review*, 7(3), 123-130.

Highfield, W. E., and Brody, S. D. (2012). “Evaluating the effectiveness of local mitigation activities in reducing flood losses.” *Natural Hazards Review*, 14(4), 229–236.

Highfield, W. E., Brody, S. D., and Blessing, R. (2014). “Measuring the impact of mitigation activities on flood loss reduction at the parcel level: The case of the clear creek watershed on the upper Texas coast.” *Natural Hazards*, 74(2), 687–704.

Highfield, W. E., Norman, S. A., and Brody, S. D. (2012). “Examining the 100-year floodplain as a metric of risk, loss, and household adjustment.” *Risk Analysis*, 33, 186-191.

Hofer, T. (2005). “What are the impacts of deforestation in the Himalayas on flooding in the lowlads? Rethinking an old paradigm." *Water Resources for the Future,* 137.

Holling, C. S., and Meffe, G. K. (1996). “Command and control and the pathology of natural resource management.” *Conservation Biology*, 10(2), 328–337.

Hubbart, J., Muzika, R., Huang, D., and Robinson, A. (2011). “Improving quantitative understanding of bottomland hardwood forest influence on soil water consumption in an urban floodplain.” *The Watershed Science Bulletin*, 3, 34–43.

Hughes, F. (2003). *The flooded forest: Guidance for policy makers and river managers in Europe on the restoration of floodplain forests*. FLOBAR2 (Floodplain Biodiversity and Restoration), Department of Geography, University of Cambridge, Cambridge, U.K.

Hupp, C. R., and Osterkamp, W. (1996). “Riparian vegetation and fluvial geomorphic processes.” *Geomorphology*, 14(4), 277–295.

Guenni, L. B., Cardoso, M., and Ebi, K. (2005). “Regulation of natural hazards: Floods and fires.” In: *Millennium Ecosystem Assessment. Ecosystems and human well-being: Current state and trends,* Island Press, Washington, D.C.

Javaheri, A., and Babbar-Sebens, M. (2014). “On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding.” *Ecological Engineering*, 73, 132–145.

Jennings, D. B., and Jarnagin, S. T. (2002). “Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: A historical perspective in a mid-Atlantic subwatershed.” *Landscape Ecology*, 17(5), 471–489.

Johnston, C. A., Detenbeck, N. E., and Niemi, G. J. (1990). “The cumulative effect of wetlands on stream water quality and quantity: A landscape approach.” *Biogeochemistry*, 10(2), 105–141.

Johnston, L. (1992). “A status report on the nation’s floodplain management activity: An interim report. Washington, D.C.: Federal Interagency Floodplain Management Task Force.” *Contract no. TV-72105A.*

Johnston, L. and Monday, J. (1992). *Floodplain management in the United States: An assessment report*. The Federal Interagency Flood plain Management Task Force. Boulder: The Natural Hazards Research and Applications Information Center.

Jones, E., Helfman, G. S., Harper, J. O., and Bolstad, P. V. (1999). “Effects of riparian forest removal on fish assemblages in southern Appalachian streams.” *Conservation Biology*, 13(6), 1454–1465.

Kareiva, P., Watts, S., McDonald, R., and Boucher, T. (2007). “Domesticated nature: Shaping landscapes and ecosystems for human welfare.” *Science*, 316(5833), 1866–1869.

Keitt, T. H., Urban, D. L., and Milne, B. T. (1997). “Detecting critical scales in fragmented landscapes.” *Conservation Ecology*, 1(1), 4.

Kelley, R. (1998). *Battling the inland sea: Floods, public policy, and the Sacramento Valley*. University of California Press, Oakland, CA.

Kepner, W. G., Ramsey, M. M., Brown, E. S., Jarchow, M. E., Dickinson, K. J., and Mark, A. F. (2012). “Hydrologic futures: Using scenario analysis to evaluate impacts of forecasted land use change on hydrologic services.” *Ecosphere*, 3(7), 1–25.

King, S. L., Sharitz, R. R., Groninger, J. W., and Battaglia, L. L. (2009). “The ecology, restoration, and management of southeastern floodplain ecosystems: A synthesis.” *Wetlands*, 29(2), 624–634.

Klijn, F., van Buuren, M., and van Rooij, S. A. (2004). “Flood-risk management strategies for an uncertain future: Living with Rhine river floods in the Netherlands?” *AMBIO*, 33(3), 141–147.

Kolber, J. F. (1999). “ESA/AIBS forum on flooding held on Capitol Hill.” *BioScience*, 49(1), 80–81.

Kriesel, W., and Landry, C. (2004). “Participation in the national flood insurance program: An empirical analysis for coastal properties.” *Journal of Risk and Insurance*, 71(3), 405–420.

Larson, L., and Plasencia, D. (2001). “No adverse impact: New direction in floodplain management policy.” *Natural Hazards Review*, 2(4), 167–181.

Laurance, W. F. (2007). “Environmental science: Forests and floods.” *Nature*, 449(7161), 409–410.

Laurance, W. F., Ferreira, L. V., Rankin-de Merona, J. M., and Laurance, S. G. (1998). “Rain forest fragmentation and the dynamics of Amazonian tree communities.” *Ecology*, 79(6), 2032–2040.

Lecce, S. A., and Kotecki, E. S. (2008). “The 1999 flood of the century in Eastern North Carolina: Extraordinary hydro-meteorological event or human-induced catastrophe?” *Physical Geography*, 29(2), 101–120.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., and others. (2011). “High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management.” *Frontiers in Ecology and the Environment*, 9(9), 494–502.

Leitão, A. B., Miller, J., Ahern, J., and McGarigal, K. (2012). *Measuring landscapes: A planner’s handbook*. Island Press, Washington, D.C.

Liao, K.-H. (2012). “A theory on urban resilience to floods-A basis for alternative planning practices.” *Ecology and Society*, 17(4).

Liao, K.-H. (2014). “From flood control to flood adaptation: A case study on the Lower Green River Valley and the City of Kent in King County, Washington.” *Natural Hazards*, 71(1), 723–750.

Llewellyn, D. W., Shaffer, G. P., Craig, N. J., Creasman, L., Pashley, D., Swan, M., and Brown, C. (1996). “A decision-support system for prioritizing restoration sites on the Mississippi River alluvial plain.” *Conservation Biology*, 10(5), 1446–1455.

Loftin, C., and Ward, S. K. (1983). “A spatial autocorrelation model of the effects of population density on fertility.” *American Sociological Review*, 121–128.

Lovell, S. T., and Taylor, J. R. (2013). “Supplying urban ecosystem services through multifunctional green infrastructure in the United States.” *Landscape Ecology*, 28(8), 1447–1463.

Lundholm, J. T., and Richardson, P. J. (2010). “Habitat analogues for reconciliation ecology in urban and industrial environments.” *Journal of Applied Ecology*, 47(5), 966–975.

Lytle, D. A., and Merritt, D. M. (2004). “Hydrologic regimes and riparian forests: A structured population model for cottonwood.” *Ecology*, 85(9), 2493–2503.

Macintosh, A. (2013). “Coastal climate hazards and urban planning: How planning responses can lead to maladaptation.” *Mitigation and Adaptation Strategies for Global Change*, 18(7), 1035–1055.

Mahoney, J. M., and Rood, S. B. (1998). “Streamflow requirements for cottonwood seedling recruitment—An integrative model.” *Wetlands*, 18(4), 634–645.

Malmer, A., and Grip, H. (1990). “Soil disturbance and loss of infiltrability caused by mechanized and manual extraction of tropical rainforest in Sabah, Malaysia.” *Forest Ecology and Management*, 38(1), 1–12.

Marsh, W. M., and Marsh, N. L. (1995). “Hydrogeomorphic considerations in development planning and stormwater management, central Texas hill country, USA.” *Environmental Management*, 19(5), 693–702.

Matthai, H. (1990). “Floods.” In: Wolman, M. G. and Riggs H. C. (Ed.). *Surface Water Hydrology.* Geological Society of America, Boulder, CO.

May, P. J. (1996). *Environmental management and governance: Intergovernmental approaches to hazards and sustainability*. Psychology Press.

May, P. J., and Williams, W. (2012). *Disaster policy implementation: Managing programs under shared governance*. Plenum Press, New York, NY.

McGarigal, K. (2014). “Fragstats help, Version 4.” University of Massachusetts, Amherst, MA. <http://www.umass.edu/landeco/research/fragstats/documents/fragstats.help.4.2.pdf> (Accessed May 2017).

Medlock, S. (2008). “Using freeboard and setbacks to reduce damage.” Two Rivers-Ottauquechee Regional Commission. <http://www.trorc.org/wp/wp-content/uploads/2013/11/floodsheet4_web.pdf> (Accessed May 2017).

Messina, M. G., and Conner, W. H. (1997). *Southern forested wetlands: Ecology and management*. CRC Press, Boca Raton, FL.

Michener, W. K., Blood, E. R., Box, J. B., Couch, C. A., Golladay, S. W., Hippe, D. J., Mitchell, R. J., and Palik, B. J. (1998). “Tropical storm flooding of a coastal plain landscape.” *BioScience*, 48(9), 696–705.

Michener, W. K., and Haeuber, R. A. (1998). “Flooding: Natural and managed disturbances.” *BioScience*, 677–680.

Mogollón, B., Frimpong, E. A., Hoegh, A. B., and Angermeier, P. L. (2016). "An empirical assessment of which inland floods can be managed." *Journal of Environmental Management*, 167, 38–48.

Montz, B. E., and Tobin, G. A. (2008). "Livin' large with levees: Lessons learned and lost." *Natural Hazards Review*, 9(3), 150–157.

Moran, P. (1950). "A test for spatial independence of residuals." *Biometrika*, 37, 178–181.

Morgan II, R. P., Kline, K. M., and Cushman, S. F. (2007). "Relationships among nutrients, chloride and biological indices in urban Maryland streams." *Urban Ecosystems*, 10(2), 153–166.

Mount, J. F. (1995). *California rivers and streams: The conflict between fluvial process and land use*. University of California Press, Oakland, CA.

National Oceanic and Atmospheric Administration (NOAA). (2000). *Flood Losses - Compilation of Flood Loss Statistics*. <http://nws.noaa.gov/oh/hic/flood_stats/Flood_loss_time_series.shtml> (accessed May 2017).

National Oceanic and Atmospheric Administration (NOAA). (2008). "NOAA issues new land cover assessment showing increasing U.S. coastal development." <www.noaa.gov/stories 2008/20080317_landcover.html> (accessed May 2017).

National Research Council (NRC). (2012). "Disaster resilience: A national imperative." The National Academies Press, Washington, D.C.

Ntelekos, A. A., Oppenheimer, M., Smith, J. A., and Miller, A. J. (2010). "Urbanization, climate change and flood policy in the United States." *Climatic Change*, 103(3-4), 597–616.

NRCS. (2012). "Soil Survey Geographic database (SSURGO)." <http://websoilsurvey.nrcs.usda.gov/.> (accessed May 2017).

O'Connell, J.F., and Justus, S. (2009). *Effectively Managing Coastal Floodplain Development*. Woods Hole Sea Grant, Cape Cod Commission, University of Hawaii Sea Grant, Cape Cod Cooperative Extension.

O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., and McMillan, S. (2010). "Urbanization effects on watershed hydrology and in-stream processes in the southern United States." *Water*, 2(3), 605–648.

Ogawa, H., and Male, J. W. (1986). “Simulating the flood mitigation role of wetlands.” *Journal of Water Resources Planning and Management*, 112(1), 114–128.

Olshansky, R. B., and Kartez, J. D. (1998). “Managing land use to build resilience.” *Cooperating with nature: Confronting natural hazards with land-use planning for sustainable communities*, Joseph Henry Press, Washington, DC, 167–202.

Openshaw, S. (1984). *The modifiable areal unit problem.* Concepts and Techniques in Modern Geography No. 38. Geobooks, Norwich, England.

Openshaw, S., and Taylor, P. J. (1979). “A million or so correlation coefficients: Three experiments on the modifiable areal unit problem.” *Statistical Applications in the Spatial Sciences*, 21, 127–144.

Opperman, J. J., Galloway, G. E., Fargione, J., Mount, J. F., Richter, B. D., Secchi, S., and others. (2009). “Sustainable floodplains through large-scale reconnection to rivers.” *Science*, 326(5959), 1487–1488.

Opperman, J. J., Luster, R., McKenney, B. A., Roberts, M., and Meadows, A. W. (2010). “Ecologically functional floodplains: Connectivity, flow regime, and scale.” *Journal of the American Water Association,* 46, 211-226.

Owen, H. J. (1981). *Cooperative flood loss reduction: A technical manual for communities and industries.* U.S. Government Printing Office, Washington, D.C.

Pahl-Wostl, C. (2006). “The importance of social learning in restoring the multifunctionality of rivers and floodplains.” *Ecology and Society*, 11(1), 14.

Pappas, E., Smith, D., Huang, C., Shuster, W., and Bonta, J. (2008). “Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation.” *Catena*, 72(1), 146–152.

Parker, D. J. (1995). “Floodplain development policy in England and Wales.” *Applied Geography*, 15(4), 341–363.

Patterson, L. A., Lutz, B., and Doyle, M. W. (2012). “Streamflow changes in the South Atlantic, United States during the mid-and late 20th century.” *Journal of the American Water Resources Association*, 48(6), 1126–1138.

Peck, S. (1998). *Planning for biodiversity: Issues and examples*. Island Press, Washington, D.C.

Peiser, R. B. (1981). “Land development regulation: A case study of Dallas and Houston, Texas.” *Real Estate Economics*, 9(4), 397–417.

Philippi, N. S. (1996). *Floodplain management: Ecologic and economic perspectives*. R.G. Landes, Georgetown, TX.

Pickett, S. T., and Thompson, J. N. (1978). “Patch dynamics and the design of nature reserves.” *Biological Conservation*, 13(1), 27–37.

Pielke Jr, R. A., and Downton, M. W. (2000). “Precipitation and damaging floods: Trends in the United States, 1932-97.” *Journal of Climate*, 13(20), 3625–3637.

Pielke Jr, R. A., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., and Musulin, R. (2008). “Normalized hurricane damage in the United States: 1900-2005.” *Natural Hazards Review*, 9(1), 29–42.

Pielke, R. A. (1999). “Nine fallacies of floods.” *Climatic Change*, 42(2), 413–438.

Pinchot, G., and Ashe, W. W. (1897). *Timber trees and forests of North Carolina*. N.C. Geological Survey Bull. 6.

Pinter, N. (2005). “One step forward, two steps back on US floodplains.” *Science*, 308(5719), 207–208.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., and Stromberg, J. C. (1997). “The natural flow regime.” *BioScience*, 47(11), 769–784.

Qian, Z. (2010). “Without zoning: Urban development and land use controls in Houston.” *Cities*, 27(1), 31–41.

Qiu, J., and Turner, M. G. (2015). “Importance of landscape heterogeneity in sustaining hydrologic ecosystem services in an agricultural watershed.” *Ecosphere*, 6(11), 1–19.

Quarterman, E. (1957). “Early plant succession on abandoned cropland in the central basin of Tennessee.” *Ecology*, 38(2), 300–309.

Qureshi, Z. (1978). “Surface water resources of Northwest Florida.” *Journal of the American Water Resources Association*, 14(3), 710–718.

Remo, J. W., Pinter, N., and Heine, R. (2009). “The use of retro-and scenario-modeling to assess effects of 100+ years river of engineering and land-cover change on Middle and Lower Mississippi River flood stages.” *Journal of Hydrology*, 376(3), 403–416.

Rijke, J., van Herk, S., Zevenbergen, C., and Ashley, R. (2012). “Room for the River: Delivering integrated river basin management in the Netherlands.” *International Journal of River Basin Management*, 10(4), 369–382.

Rudis, V. A. (1995). “Regional forest fragmentation effects on bottomland hardwood community types and resource values.” *Landscape Ecology*, 10(5), 291–307.

Rutherfurd, I., Hoang, T., Prosser, I., Abernethy, B., Jayasuriya, N., and others. (1996). “The impact of gully networks on the time-to-peak and size of flood hydrographs.” *Hydrology and Water Resources Symposium 1996: Water and the Environment; Preprints of Papers*, 397.

Sauer, V. B., Thomas Jr, W., Stricker, V., and Wilson, K. (1983). *Flood characteristics of urban watersheds in the United States*. U.S. Geological Survey Water Supply Paper 2207.

Saxton, K., and Shiau, S. (1990). “Surface waters of North America: Influence of land and vegetation on streamflow.” Pages 55–80 in M. G. Wolman and H. C. Riggs, editors. Surface water hydrology, the geology of North America, volume O-1. The Geological Society of America, Inc., Boulder, CO.

Schmidt, J. C., Webb, R. H., Valdez, R. A., Marzolf, G. R., and Stevens, L. E. (1998). “Science and values in river restoration in the Grand Canyon.” *BioScience*, 48(9), 735–747.

Schueler, T. R. (1994). “The importance of imperviousness.” *Watershed protection Techniques*, 1(3), 100–111.

Scott, M. L., Auble, G. T., and Friedman, J. M. (1997). “Flood dependency of cottonwood establishment along the Missouri River, Montana, USA.” *Ecological Applications*, 7(2), 677–690.

Scott, M. L., Friedman, J. M., and Auble, G. T. (1996). “Fluvial process and the establishment of bottomland trees.” *Geomorphology*, 14(4), 327–339.

Shadish, W. R., Cook, T. D., and Campbell, D. T. (2002). *Experimental and quasi-experimental designs for generalized causal inference.* Houghton Mifflin, New York, NY.

Shafroth, P. B., Auble, G. T., Stromberg, J. C., and Patten, D. T. (1998). “Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona.” *Wetlands*, 18(4), 577–590.

Sheaffer, J. R., Roland, F. J., Davis, G. W., Feldman, T., and Stockdale, J. (1976). *Flood hazard mitigation through safe land use practices.* Prepared for the Office of Policy Development and Research, U.S. Department of Housing and Urban Development, Kiefer & Associates, Chicago, IL.

Shuai, N., and Sen, Z. (2017). “Assessing the effectiveness of low impact development by bio-retention and cistern system for Tianjin, Northern China.” *International Journal of Environmental Science and Development*, IACSIT Press, 8(2), 135.

Shuster, W., Bonta, J., Thurston, H., Warnemuende, E., and Smith, D. (2005). “Impacts of impervious surface on watershed hydrology: A review.” *Urban Water Journal*, 2(4), 263–275.

Sivapalan, M., Savenije, H. H., and Blöschl, G. (2012). “Socio-hydrology: A new science of people and water.” *Hydrological Processes*, 26(8), 1270–1276.

Smits, A., Nienhuis, P., and Saeijs, H. (2006). “Changing estuaries, changing views.” *Hydrobiologia*, 565(1), 339–355.

Soranno, P., Hubler, S., Carpenter, S., and Lathrop, R. (1996). “Phosphorus loads to surface waters: A simple model to account for spatial pattern of land use.” *Ecological Applications*, 6(3), 865–878.

Stankey, D. L. (1982). “Soil survey of Pasco County, Florida.” United States Department of Agriculture, Soil Conservation Service, US Government Print Office.

Stanturf, J. A., Gardiner, E. S., Hamel, P. B., Devall, M. S., Leininger, T. D., and Warren, M. E. (2000). “Restoring bottomland hardwood ecosystems in the Lower Mississippi Alluvial Valley.” *Journal of Forestry*, 98(8), 10–16.

Stata, A., and others. (2015). *Stata Base Reference Manual Release 14*. Stata-Corp LP., College Station, TX..

Stein, J., Moreno, P., Conrad, D., and Ellis, S. (2000). *Troubled waters: Congress, the Corps of Engineers, and wasteful water projects*. Taxpayers for Common Sense and National Wildlife Federation, Washington, DC.

Sternitzke, H. S. (1976). “Impact of changing land use on Delta hardwood forests.” *Journal of Forestry*, 74(1), 25–27.

Strayer, D. L., Beighley, R. E., Thompson, L. C., Brooks, S., Nilsson, C., Pinay, G., and Naiman, R. J. (2003). “Effects of land cover on stream ecosystems: Roles of empirical models and scaling issues.” *Ecosystems*, 6(5), 407–423.

Stromberg, J. (1998). “Dynamics of Fremont cottonwood (*Populus fremontii*) and saltcedar (*Tamarix chinensis*) populations along the San Pedro River, Arizona.” *Journal of Arid Environments*, 40(2), 133–155.

Stuckey, M. H. (2006). *Low-flow, base-flow, and mean-flow regression equations for Pennsylvania streams*. US Geological Survey Scientific Investigations Report 2006-5130.

Swanson, F. J., Gregory, S., Sedell, J., and Campbell, A. (1982). “Land-water interactions: The riparian zone.” Pages 267-291 In: Edmonds, R. L.. Analysis of coniferous forest ecosystems in the Western United States. US/IBP Synthesis Series 14.

Sweeney, B. W., Bott, T. L., Jackson, J. K., Kaplan, L. A., Newbold, J. D., Standley, L. J., Hession, W. C., and Horwitz, R. J. (2004). “Riparian deforestation, stream narrowing, and loss of stream ecosystem services.” *Proceedings of the National Academy of Sciences*, 101(39), 14132–14137.

Swift, B. L. (1984). “Status of riparian ecosystems in the United States.” *Journal of the American Water Resources Association*, 20(2), 223–228.

Tabacchi, E., Lambs, L., Guilloy, H., Planty-Tabacchi, A.-M., Muller, E., and Decamps, H. (2000). “Impacts of riparian vegetation on hydrological processes.” *Hydrological Processes*, 14(16-17), 2959–2976.

Taylor, J. R., Cardamone, M. A., and Mitsch, W. J. (1990). *Bottomland hardwood forests: Their functions and values.* In: Gosselink, J. G., Lee, L. C., and Muir, T. A. (Ed.). Ecological processes and cumulative impacts illustrated by bottomland hardwood wetland ecosystems. Lewis Publ., Chelsea, MI, 13–86.

Thomas, H., and Nisbet, T. (2007). “An assessment of the impact of floodplain woodland on flood flows.” *Water and Environment Journal*, 21(2), 114–126.

Thorp, J. H., Flotemersch, J. E., Delong, M. D., Casper, A. F., Thoms, M. C., Ballantyne, F., Williams, B. S., O’Neill, B. J., and Haase, C. S. (2010). “Linking ecosystem services, rehabilitation, and river hydrogeomorphology.” *BioScience*, 60(1), 67–74.

Tobin, G. A. (1995). The levee love affair: A stormy relationship? *Water Resource Bulletin*, 31, 359–367.

Tobler, W. R. (1970). “A computer movie simulating urban growth in the Detroit region.” *Economic Geography*, 234–240.

Tockner, K., and Stanford, J. A. (2002). “Riverine flood plains: Present state and future trends.” *Environmental Conservation*, 29(3), 308–330.

Todd, M., and Elmore, W. (1997). “Historical changes in western riparian ecosystems.” In: Proceedings of the Transactions of 62nd North American Wildlife and Natural Resources Conference, 454–468.

Tourbier, J. T., and Westmacott, R. N. (1981). *Water resources protection technology: A handbook of measures to protect water resources in land development*. Urban Land Institute Washington D.C.

Trac, C. J., Harrell, S., Hinckley, T. M., and Henck, A. C. (2007). “Reforestation programs in southwest China: Reported success, observed failure, and the reasons why.” *Journal of Mountain Science*, 4(4), 275–292.

Treiman, D. J. (2014). *Quantitative data analysis: Doing social research to test ideas*. Joessey-Bass, San Francisco, CA.

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., and Thies, C. (2005). “Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management.” *Ecology Letters*, 8(8), 857–874.

Turner, M. G., Gardner, R. H., O’neill, R. V., and others. (2001). *Landscape ecology in theory and practice*. Springer, New York, NY.

Turner, R. E., Forsythe, S. W., and Craig, N. J. (1981). “Bottomland hardwood forest land resources of the southeastern United States.” In: Clark, J. R., and Benforado, J. *Wetlands of bottomland hardwood forests*. Elsevier, Amsterdam, The Netherlands. 11, 13–28.

U.S. Army Corps of Engineers (USACE). (1996). *Water control infrastructure: National inventory of dams.* FEMA 246, Washington, D.C.

U.S. Army Corps of Engineers (USACE). (1999). *Post-flood assessment: Sacramento and San Joaquin river basins*. U.S. Army Corps of Engineers, Sacramento, CA.

U.S. Army Corps of Engineers (USACE). (2002). *Guidance on compensatory mitigation projects for aquatic resource impacts under the Corps regulatory program pursuant to Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899.* U.S. Army Corps of Engineers, Sacramento, CA.

U.S. Army Corps of Engineers (USACE). (2008). *Final environmental assessment, finding of no significant impact, and regulatory analysis for the compensatory* *mitigation regulation*. U.S. Army Corps of Engineers, Sacramento, CA.

U.S. Army Corps of Engineers (USACE). (2009). "Flood risk management: Value to the Nation." <http://www.corpsresults.us/docs/VTNFloodRisk MgmtBro_loresprd.pdf> (Accessed May 2017).

U.S. Army Corps of Engineers (USACE). (2017). “USACE program levees.” <http://www.usace.army.mil/Missions/Civil-Works/Levee-Safety-Program/USACE-Program-Levees/> (May 8, 2017). U.S. Army Corps of Engineers, Sacramento, CA.

U.S. Environmental Protection Agency (USEPA). (2007). *National management measures to control nonpoint source pollution from hydromodification*. Nonpoint Source Control Branch, Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

U.S. Geological Survey (USGS). (2009). *National hydrography dataset feature catalog*. <https://nhd.usgs.gov/userGuide/Robohelpfiles/NHD_User_Guide/Feature_Catalog/NHD_Feature_Catalog.htm> (Accessed May 2017).

Ward, M. D., and Gleditsch, K. S. (2008). *Spatial regression models*. Sage, London, England.

WaterEngineers, Inc. (2004). "Aldine improvement water & wastewater planning study." <http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/2002483472_Aldine.pdf> (Accessed May 2017).

Watt, A. S. (1947). “Pattern and process in the plant community.” *Journal of Ecology*, 35(1/2), 1–22.

Weller, D. E., Baker, M. E., and Jordan, T. E. (2011). “Effects of riparian buffers on nitrate concentrations in watershed discharges: New models and management implications.” *Ecological Applications*, 21(5), 1679–95.

WeatherBill, Inc. 2007. "Precipitation averages, seasonality, volatility and trends in the United States." WeatherBill.

Weller, D. E., Jordan, T. E., and Correll, D. L. (1998). “Heuristic models for material discharge from landscapes with riparian buffers.” *Ecological Applications*, 8(4), 1156–1169.

Wharton, C. H., Kitchens, W. M., Pendleton, E. C., and Sipe, T. W. (1982). *Ecology of bottomland hardwood swamps of the southeast: A community profile*. FWS/OBS-81 - 37 United States Fish and Wildlife Service, Biological Services Pro- gram, Washington, D.C.

Whipple Jr, W. (1998). *Water resources: A new era for coordination*. ASCE, Reston, VA.

White, G. F., and others. (1945). *Human adjustment to floods: A geographical approach to the flood problem in the United States*. University of Chicago, Chicago, IL.

White, M. D., and Greer, K. A. (2006). "The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California." *Landscape and Urban Planning*, 74(2), 125–138.

Wickham, J. D., Stehman, S. V., Gass, L., Dewitz, J., Fry, J. A., and Wade, T. G. (2013). "Accuracy assessment of NLCD 2006 land cover and impervious surface." *Remote Sensing of Environment*, 130, 294–304.

Wickham, J., and Riitters, K. (1995). "Sensitivity of landscape metrics to pixel size." *International Journal of Remote Sensing*, 16(18), 3585–3594.

Wolff, C. G., and Burges, S. J. (1994). "An analysis of the influence of river channel properties on flood frequency." *Journal of Hydrology*, 153(1), 317–337.

Woltemade, C. J., and Potter, K. W. (1994). "A watershed modeling analysis of fluvial geomorphologic influences on flood peak attenuation." *Water Resources Research*, 30(6), 1933–1942.

Wooldridge J. M. (2009). *Introductory econometrics: A modern approach*. South-Western Cengage Learning, Mason, OH.

Zevenbergen, C., Rijke, J., van Herk, S., and Bloemen, P. (2015). "Room for the river: A stepping stone in adaptive delta management." *International Journal of Water Governance*, 3(3), 121–140.

Ziegler, A. D., Giambelluca, T. W., Tran, L. T., Vana, T. T., Nullet, M. A., Fox, J., Vien, T. D., Pinthong, J., Maxwell, J. F., and Evett, S. (2004). "Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: Evidence of accelerated overland flow generation." *Journal of Hydrology*, 287(1-4), 124–146.

Ziegler, A. D., Tran, L. T., Giambelluca, T. W., Sidle, R. C., Sutherland, R. A., Nullet, M. A., and Vien, T. D. (2006). "Effective slope lengths for buffering hillslope surface runoff in fragmented landscapes in northern Vietnam." *Forest Ecology and Management*, 224(1), 104–118.

Zimmermann, B., Elsenbeer, H., and De Moraes, J. M. (2006). “The influence of land-use changes on soil hydraulic properties: Implications for runoff generation.” *Forest Ecology and Management*, 222(1), 29–38.

APPENDIX A

A.1 Multicollinearity Diagnostic

Table 9. Variance inflation factor of OLS regression models

Variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Channelization	1.37	1.32	1.32	1.32	1.30
Leveed	1.15	1.15	1.15	1.16	1.17
Open Space Protection	1.76	1.73	1.71	1.70	1.72
Precipitation	1.12	1.12	1.12	1.12	1.12
Watershed Area	1.18	1.18	1.18	1.18	1.20
KSAT	1.75	1.75	1.77	1.86	1.75
Slope	1.43	1.42	1.40	1.40	1.58
Elevation	1.48	1.48	1.49	1.46	1.46
Drainage Density	1.70	1.55	1.52	1.67	1.55
Structures	1.33	1.32	1.27	1.27	1.36
Proportion	1.41				
Largest Patch Index		1.17			
Patch Area			1.10		
Contiguity Index				1.31	
Correlation Length					1.34
Mean VIF	1.43	1.38	1.37	1.40	1.42

A.2 Heteroskedasticity Diagnostic

Table 10. Breusch-Pagan/Cook-Weisberg test for heteroskedasticity of OLS model residuals

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
chi^2	1.80	2.23	1.65	3.01	2.63
p-value	0.1793	0.1351	0.1992	0.0828	0.1048

Ho : constant variance

A.3 Spatial Autocorrelation Diagnostics and Model Selection

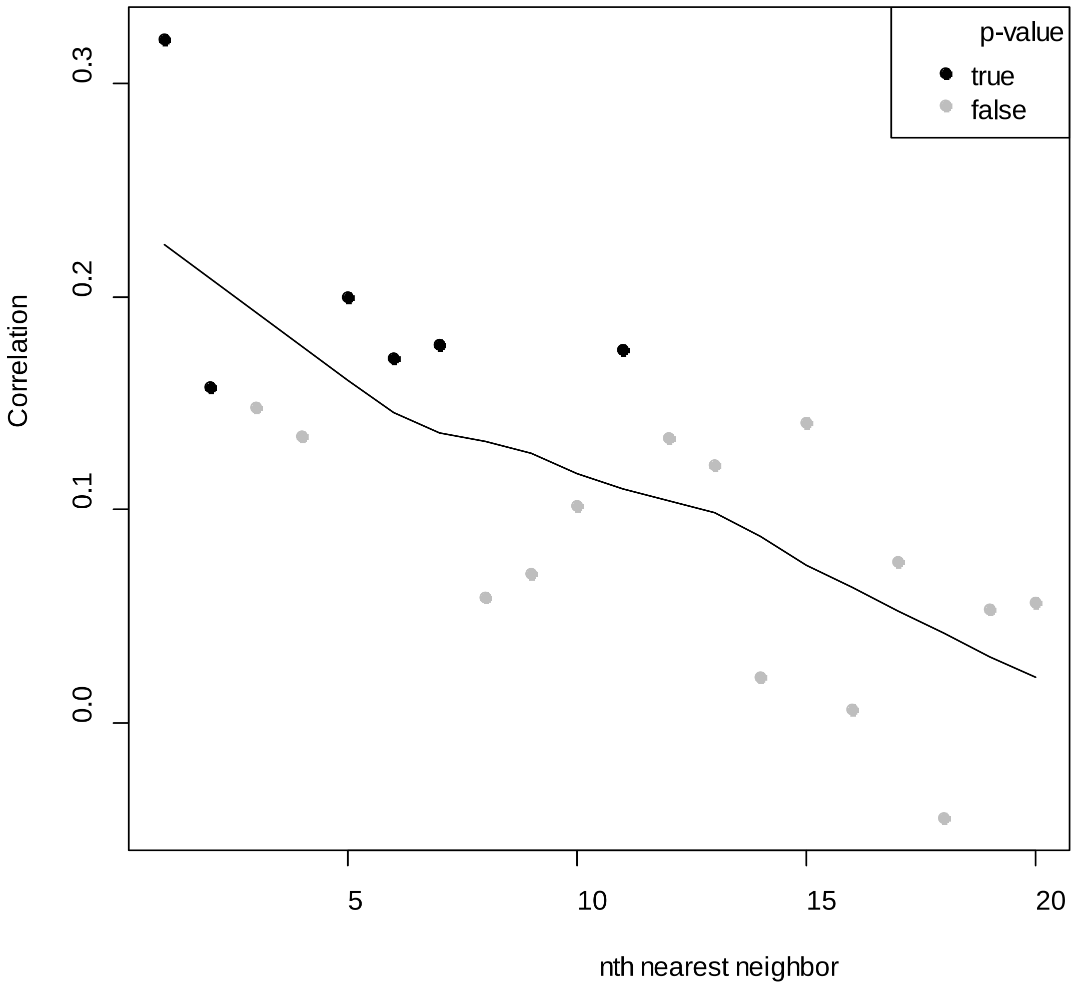

Figure 10. Correlogram of the OLS residuals of each observation with their n^{th} *nearest neighbor*

Table 11. Test for spatial dependencies in the OLS model residuals

	Moran's I	
Weight	**5^{th} Nearest Neighbor**	**7^{th} Nearest Neighbor**
Inverse Distance	0.1718***	0.1757***
Bi-square	0.1338***	0.1483***
Gaussian	0.1797***	0.1792***
Binary	0.1877***	0.1833***

*** p < 0.001

Ho: random distribution

Table 12. Lagrange Multiplier test for spatial dependence

		Lagrange Multiplier Test	
Weight	**Spatial Model**	**5th Nearest Neighbor**	**7th Nearest Neighbor**
Gaussian	**Error Model**	24.912***	34.765***
	Lag Model	38.247***	51.169***
	Robust Error	1.0816	0.35218
	Robust Lag	14.416***	16.755***
Binary	**Error Model**	27.658***	36.933***
	Lag Model	41.070***	54.416***
	Robust Error	0.61043	0.24829
	Robust Lag	14.023***	17.731***

*** p < 0.001

Table 13. AIC and BIC values to compare model fit

		AIC		**BIC**	
		5nn	**7nn**	**5nn**	**7nn**
Gaussian	**Error**	1161	1154	1211	1204
	Lag	1152	1148	1203	1199
Binary	**Error**	1149	1152	1200	1202
	Lag	1158	1146	1208	1196

Note: Lower values indicate a model with a better fit
AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion