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Geospatial Analysis of Flooding in the Cypress Creek Watershed Due to Urban Sprawl

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Abstract

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B.S., Bemidji State University, 2009

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Abstract

Harris County, Texas, experiences flooding almost every year, and the situation is getting worse. Uncontrolled development is leading to an increase in flooding events. This study investigated how rapid urbanization and sprawl led to a higher frequency and intensity of flooding in the Cypress Creek watershed in northern Harris County. According to urban ecology, the basis of the theoretical framework, the human actions on the environment are not just bystanders, but direct contributors as inputs. In this case, the outputs are the intensity of the flooding events caused by Hurricane Ike, the Memorial Day flood of 2016, and Hurricane Harvey. The human activities inputs are the construction of impervious surfaces and the lack of zoning that would typically contribute to the control of development. Harris County Texas does not have the authority to zone by state law. Thus, the issue is how the lack of zoning contributed to the flooding problems in the Cypress Creek watershed. Geographic Information Systems and a spatial-temporal design of the flood events were used to understand the effect of precipitation runoff compared to the land cover changes between Hurricane Ike, the Memorial Day flood, and Hurricane Harvey flood. The area of interest has seen a 27% increase in developed land, which has increased the velocity of runoff, causing over-taxation of the natural drainage networks. The increased flooding during Harvey inundated a hospital and a sheriff’s office, hampering citizens’ rescue efforts. By understanding the effects of increased development on flooding, social capital and equity will increase instead of being hindered by rebuilding or destroying older neighborhoods in the county.

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Dedication

I would like to dedicate this research to my father and my wife. My father always believed in me and reminded me to work smarter not harder has he did. Dad, I wish that you could be here to see what your beliefs and teachings have gotten me. You have been and always will be my hero.

To my wife, who brought me back from the edge of destruction after my military career ended. I walked aimlessly without direction or purpose. Without your love and guidance, I would not be here today, and I am forever in your debt.

"Show me a geographer who does not need them [maps] constantly and want them about him, and I shall have my doubts as to whether he has made the right choice in life"

Carl Sauer (1956)

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Chapter 1: Introduction to the Study

Introduction

From 1906 to 2010, the population of the United States increased by 71% ((U.S. Census Bureau, 2019; Worldometers, 2017). From 1960-2010, the population of the United States has almost tripled. Some of the growth was from a natural growth rate, while the rest was from migrating to the United States in search of better opportunities. With the increase in population migrating into city centers looking for work, regions are looking to meet the needs of the population by finding ways to attract companies and developers for new construction.

Fisher (1989) illustrated that Houston's growth rate has been remarkable since the 1920s when Houston was just a railroad town serving Texas. Its development shifted during the Second World War, when it became the United States' oil and gas capital (Qian, 2010). By the 1970s, the Houston population was increasing by 1,000 people every week (Fisher, 1989). When the oil and gas industry started taking over the primary economic sector (Qian, 2010), many other sectors started to flow into Houston. In 1942, the Texas Medical Center was founded, which later incorporated the University of Texas School of Medicine and then the Michael E. DeBakey Veterans Campus. The medical center development led to the creation of one of the most comprehensive medical campuses in the United States (Texas Medical Center, 2019). Soon after, in 1965, the National Aeronautics and Space Administration (NASA) moved mission control to Houston. With medical, high-tech industries, and the oil and gas activities moving to Houston, the need for development was imperative.

Even in the beginning, Houston did not follow the traditional monocentric city model (Modarres & Dierwechter, 2015). The central business district was not solely in the greater downtown area. The oil industry was to the east, NASA to the south, and the medical center is south of downtown. Modarres and Dierwechter (2015) highlighted how the transportation network helps to shape the modern American city. Houston is a good example. In a mobile city, transportation networks allow for the expansion of the population. The region appeared to spread out instead of building up. While the city is experiencing large amounts of growth, urban development is dominating the landscape. This rapid development creates urban sprawl (Hortas-Rico, 2015).

Urban sprawl increases the city's structural inventories (Hortas-Rico, 2015). Moreover, metropolitan areas tend to expand across the landscape (Hortas-Rico, 2015). When the urban environment expands, the number of impervious surfaces expands as well. Impervious surfaces do not allow precipitation to soak into the ground. Zoning laws usually control urban sprawl. Cities such as Chicago have been using zoning laws to guide and control the city’s development as it increases (Shertzer, Twinam, & Walsh, 2016, 2018). Zoning laws promote health and general welfare through different development practices. Zoning separates residential areas from industrial activities and, in most cases, incorporated into the city's comprehensive plans (Welch, 2016). When zoning policies do not exist, development goes uncontrolled.

Zoning in Texas is not much different from any other state in the United States. The only difference is that Texas grants zoning authority municipalities. Cities and the state are the only political entities that are the only governing authorities with this regulation power (Welch, 2016). In the case of Houston, the city charter allows for zoning only by popular vote from the citizens of the City of Houston. The city has voted three-times to implement zoning regulations, and all three times, the voters denied the measure (Kiger, 2015; Marcano & Shelton, 2017).

To usher in an era of smart development, The Woodlands, Texas, was created. Just 30 miles north of Houston, The Woodlands is a municipal utility district that houses many major companies such as Anadarko Petroleum, Memorial Medical Center North, and supporting companies. The Woodlands is a pedestrian-friendly, mixed-use community. Mixed-use building provides shops and restaurants on the street level and living spaces above the shops. However, The Woodlands is expensive and therefore many employees live south and north of the planned community. The suburbanization of The Woodlands makes Cypress Creek watershed attractive to home buyers. The watershed is void of city and utility taxes and only miles south of the planned community. The Cypress Creek watershed is becoming a rapidly developed part of northern Harris County. Without zoning regulations, the Federal Emergency Management Agency (FEMA) flood zones are being substantially developed.

Current research focuses on Southern Harris County (Bhandari, Maruthi, Sridhar, & Wilson, 2017; Brody, Gunn, Peacock, & Highfield, 2011; Highfield, Norman, & Brody, 2013; Muñoz, Olivera, Giglio, & Berke, 2018). The southeastern part of the county is not only the oil refineries' location but also the location of housing, where the oil industry’s labor force lives. These southern communities have a history dating back to the Second World War.

Harris County is becoming densely populated, and without zoning regulations, there are no controls on development. This poses a problem for the Cypress Creek watershed. This study investigated human development and its effects on the Cypress Creek drainage system's flooding; the study also reassessed the FEMA flood zones to better understand urban development in the watershed. With the use of Geographic Information Systems (GIS), the development patterns for selected years will show a change in the urban environment and compare the precipitation of selected flooding events in those years.

Problem Statement

For Harris County, Texas, flooding has become an all too frequent event in recent years (Harris County Flood Control District, 2018). The problem is that uncontrolled development in the county is leading to an increase in flooding events. The free-market economy influences Harris County's urbanized areas and how the development takes place (Derossett, 2015). The free-market system helps shape the desire to have single-family homes outside of city centers, creating a large amount of surface area to be developed from its natural state. As surfaces become impervious, impacting the absorption of water, the surface flow rates increase (Lei & Zhu, 2018; Peacock, Grover, Vedlitz, Brody, & Zahran, 2008; Reja, Brody, Highfield, & Newman, 2017). Resnik (2010) referred to this form of development as urban sprawl, that is, the expansion of the urban environment driven by population, changes in housing desires, and increased mobility with respect to the city center (Hortas-Rico, 2015). Currently, research into northern Harris County and Cypress Creek watershed using GIS is limited. In contrast, most of the research is being conducted downstream or with in Houston's city limits (Brody, Blessing, Sebastian, & Bedient, 2014; Brody, Kim, & Gunn, 2013; Highfield et al., 2013; Muñoz et al., 2018). It appears that population density drives research for the city center. However, water moves toward the natural drainage direction, which in this case is from Cypress Creek watershed toward the San Jacinto River in northeast Houston.

Cypress Creek and the Cypress Creek watershed flow from the west to east and drain into the San Jacinto River. The creek has flowed directly south over the impervious landscape straight into Addick's Reservoir, causing major flooding for west Houston (Gori, Blessing, Juan, Brody, & Bedient, 2019). Since 1900, there have been 41 major floods in Harris County, 13 involving Cypress Creek (Harris County Flood Control District, 2018). Since 2008, there have been five significant floods with the most recent from Tropical Storm Imelda. The problem with uncontrolled free-market development policy is that Harris County and the Houston region are becoming more prone to flooding.

Nature of Study

This study used a GIS framework conceptual design. The conceptual design is based on the principles that data has a spatial location in development and precipitation. The design determined the development of the human environment in the Cypress Creek watershed. The increase in development caused a need for the reassessment of the no zoning policies in Harris County and in the FEMA flood zones. Spatial analysis determined the amount of urban growth and the dispersion of floodwater in comparison to flood zones.

Research Questions

This study sought to explore the primary research question: What is the impact of urban sprawl on flooding in the Cypress Creek Watershed? To answer this question, the research explored the following subquestion:

R.Q.: How has the lack of zoning contributed to the flooding problems of Cypress Creek watershed?

H_1: The number of impervious surfaces has increased in the watershed, causing more significant floods.

H_0: The number of impervious surfaces has not increased in the watershed and there is no cause for more exceptional floods in the Cypress Creek watershed.

Purpose of the Study

The purpose of this quantitative, deductive study was to investigate how, since 2008, urban sprawl has led to the high frequency of flooding in the Cypress Creek watershed. The impervious surfaces caused by urban development hinder the land's ability to disperse the rainwater (Brody et al., 2014). The excess water runoff from the impervious environment overwhelms the creeks and bayous.

This study reviewed how the urban landscape has changed along Cypress Creek as well as compared flooding since 2015 to current flood zones created by FEMA. The data used for this study were a compilation of GIS data which are open to the public for review and use. Data samples included highwater marks, land use/land cover (LULC), and digital elevation models. The datasets were provided by the Harris County Flood

Control District, the State of Texas, FEMA and the National Oceanic and Atmospheric Administration (NOAA).

Theoretical Framework

This study's framework was urban ecology, as set forth by Loughran, Elliott, and Kennedy (2019). Ecology is the study of an organism and is interaction with the ecosystem in which it lives. Human ecology is the study of humans in the ecosystem they build. The past study patterns did not consider human activities as inputs. Urban ecology is deeply rooted in the earlier forms of ecology. Urban ecology is based on the premise of inputs and outputs of social entities, their built environment, and the natural world. In this case, the built-up environment on the natural landscape (the input), and hazardous landscape, flooding (the output) were studied. Wu (2014) defined urban ecology "as the study of spatiotemporal patterns, environmental impacts, and the sustainability of urbanization with emphasis on biodiversity, ecosystem process, and ecosystem services" (p. 213). Urban ecology is a multi-faceted theory that takes on the viewpoint of the researcher. In this study, urban ecology was used to review the symbolic relationships between the natural landscape and the policies (or lack of policies) that have created a hazardous environment in frequent flooding (Loughran et al., 2019). Furthermore, this research design defined the inputs as either internal, for example, urban sprawl, or external precipitation.

Outside Loughran et al. (2019), GIS is not the primary instrument for studying urban sprawl and flooding. For ecology studies that deal with the human environment the qualitative process is used (Mugerauer, 2010). Rarely are human/urban ecology studies conducted quantitatively. New research needs to find ways to study the human and urban environment when dealing with spatiotemporal patterns. With the improvements in remote sensing, GIS, and spatial analysis methods, urban ecology can study the progress of urban development and its effects of the natural ecosystems (Wu, 2014).

The social sciences have had relationships with urban ecology since the early years of the Chicago School of thought in the 1940s (Loughran et al., 2019; McDonnell, 2011). With new scientific methods and technologies, urban ecology can now start to fill in gaps in the urban landscape. McDonnell (2011) pointed out that new research could be conducted into the built-up environment and watershed flooding and the health of drainage systems (p. 12). Using these methods, human activities have been shown to play an essential role in how the ecosystems have changed and generated possible solutions for future activities.

While urban ecology is not a framework that highlights social sciences, it is crucial to understand that natural and human activities interact and are not just a snapshot in time. The activities are always changing, they are and continuous over the landscape. Each study conducted in the region varies greatly, and no one study can answers all the questions. Each research area is a template on how to conduct research using different techniques and processes. Thus, GIS was the grounding instrumentation for studying the effects of land development in interactions with the natural processes of the atmosphere and hydrosphere.

Operational Definitions

The following are terms used within this dissertation and their definitions:

Geographic Information Systems (GIS): A geographic information system (GIS) is a framework for gathering, managing, and analyzing data. (ESRI, 2019)

Impervious surfaces: Surfaces that are covered with materials that impede the grounds of natural ability to absorb rainfall. (Lei & Zhu, 2018)

Inertial Measurement Units (IMUs): Units uses to accurately navigate aircraft and missiles. (National Ocean Service, 2017)

LiDAR: Light Detecting and Ranging (LiDAR) is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth (McDougall & Temple-Watts, 2012)

Spatial analysis: Spatial Analysis is a geographical analysis that studies humans and the environment through mathematical terms and shapes. (Mayhew, 2004)

Zoning: Zoning is the regulation by a municipality of the use of land located within the municipality's corporate limits as well as the regulation of the buildings and structures located thereon. (Welch, 2016)

Assumptions

This study used the collected data from satellite imagery, LiDAR, and precipitation. The assumption was that urban sprawl is the primary contributor to the frequency and intensity of the flooding hazards. Using land cover data, the change in the landscape determined if the number of impervious surfaces was increasing and at what rate. By comparing that information to the atmospheric events of the same periods, the rainfall and urban development would show cause and effect.

Limitations

The main restriction with LULC data was to collect datasets for the years inside the study's time frame. The challenge for the study was whether the stream gauges would provide enough coverage in the watershed. If the gauges (high watermarks) along the basin did not contain data for the years specified, then the validation process would not have been as complete as it should have been. There were no foreseen barriers in data collection because the data were government-based and open-source.

Scope and Delimitations

The study sought to understand the effects of urbanization and uncontrolled development on flooding in the Cypress Creek watershed. The LULC, precipitation for the different periods, and LiDAR data were used to create digital terrain models. The three different periods studied were Hurricane Ike in 2008, the Memorial Day flood in 2015, and Hurricane Harvey in 2017. The data from government websites adhered to Open Geospatial Data Standards. The internal data sources were land use and elevation; precipitation was the external data source.

Much of Harris County has been developed to the south, west, and east. It was not until 2000 that development occurred in the northern part of the county. More companies are moving to The Woodlands, Texas, causing employees to look for shorter commuting times. The Cypress Creek watershed is the next logical step for development in housing, commerce, and social attractions. Data from 2008 (Hurricane Ike) to 2017 (Hurricane Harvey) provided a nearly 10-year period where development went unchecked in Houston's sub-regions.

Significance

Flooding in Harris County is happening almost every year. Understanding the land-use changes in a policy-free environment can help explain why the flooding is occurring and intensifying. The use of GIS can identify the effects of flooding and influence a policy change on the flood zones and on zoning regulation. GIS is a useful tool for investigating the effects of flooding and can be harnessed to increase resilience, thereby saving lives. Displacement from homes during flood episodes can cause multiple health impacts. The spread of disease and illness from floodwater can affect the physical health of those who did not evacuate. Displacement can also affect mental health (Hammond, Chen, Djordjević, Bulter, & Mark, 2015). Hammond et al. (2015) investigated the cause of post-traumatic stress disorder on the people of flooded communities.

Not all the districts flood simultaneously; it appears to be happening in different places based on where the rain falls. During Hurricane Harvey, however, the flooding was not a localized issue. A good portion of the county flooded, and many people evacuated to shelters.

Most of the relevant research has been in southern Harris County. The studies investigated flooding from aspects of environmental injustices (Chakraborty, Collins, & Grineski, 2019), and urban sprawl (Brody et al., 2014; Muñoz et al., 2018). In the realm of urban sprawl, quantitative methods used linear regression models for scatterplot diagrams of the probability. While building on the ideas of earlier research, GIS is not the first option used for public policy on the issue of flooding.

Local government's use of GIS has been limited to parcel data storage, project designs, and infrastructure mapping. The use of GIS in large-scale analytical process does not consider the effects of flooding and the impacts on citizens and flood zones. Flood zones are corrected only on limited bases. Push backs from local governments cause low action due to cost (Highfield & Brody, 2017).

Summary

Coastal regions around the world have challenges when it comes to population, urbanization, and water resources. The Gulf of Mexico and its northern coastline experience a significant number of tropical cyclones. The most recent to make landfall in the Houston region was Tropical Storm Imelda in 2019. Just 2 years prior, the region experienced one of the most rain intense hurricanes in the Gulf of Mexico with Hurricane Harvey in 2017. In both events, heavy rain and street flooding took place. Imelda was confined to the City of Houston with flooding in some neighborhoods and along highways. Harvey's reach was much more extensive, affecting all of southern Texas.

With the threats of tropical cyclones and heavy rainfall, the investigation of the impervious surfaces can provide answers to the intensity of flooding events. While zoning laws do not apply to county-level agencies in Texas, new construction design measures are implemented during the permitting process.

In Chapter 2, a literature review on urban sprawl and flooding from not only Houston but also from select locations around the United States were investigated to create a hypothesis and process to conduct the research. Chapter 3 includes the inputs (i.e., internal and external), the instruments, the descriptions of data, and data collection along with processes. Chapter 4 presents the result of the analysis and the interactions of the different data attributes. Chapter 5 contains a discussion into the social change's implications for the permitting process and the effects on the social makeup of different neighborhoods.

Chapter 2: Literature Review

Introduction

This research investigated how urban sprawl is leading to the high frequency of flooding in the Cypress Creek watershed. The rapid urbanization of the Cypress Creek watershed has led to the intensity and frequency flooding events. This study was conducted by investigating (a) the differences in land use pattern, and (b) comparing the patterns to major flooding events of Hurricane Ike (2008), the Memorial Day flood (2015), and Hurricane Harvey (2017).

To address the gap for northern Harris County. For the review, the goal was to:

1. Define what zoning means in the State of Texas, Houston, and Harris County;
2. Determine how urban sprawl leads to impervious surfaces;
3. Determine the role FEMA flood zones play in the planning process in Harris County;
4. See how other studies are conducted research in Harris County (which informed the development of the methodological approach outlined in Chapter 3).

The review used the following databases (2015-2020) ProQuest, Taylor & Francis, and Thoreau. Key terms searched were urban ecology, flooding, zoning policies, Houston flooding, impervious surfaces, LiDAR, GIS, and spatial analysis. The following related research topics were used to gain an historical context: transportation, directional heterogeneity of urban settlements, urbanization, urban sprawl, and the understanding of urban ecology.

Population Density

Three of the four largest cities in the United States are located next to a significant coastline. New York is along the Upper and Lower Bays, which lead to the Atlantic Ocean. New York City is susceptible to nor'easters and coastal damage. While Los Angeles is positioned along the Pacific Ocean and mainly considered a desert environment, crustal earthquakes can inundate the city with water from the Pacific Ocean. Houston is situated in southern Texas, just off the Gulf of Mexico. It has 23 different bayous and creeks that drain into Galveston Bay along with the San Jacinto River flowing south into the bay just to the northwest of Houston.

All three cities host large employment centers for labor force migration. From 1980 to 1990, the population of Houston from increased only by 2.22 %. While this was a manageable number for the city to absorb, the increase from 1980 to 2018 was 45.8 % (Housotn, Texas Poluation, 2019). The population increase swelled past the city limits and spread out to Harris and surrounding counties. The demand for a labor force to meet the needs of what is to become a high-tech city has put pressure on the urban carrying capacity.

As the population increased in Houston, Los Angeles, and New York, the low-elevation regions along the coastal waters are hindered in their ability to drain water (Small, Gornitz, & Cohen, 2000). One of the primary critical outcomes of population increase is built-up urban conditions. The urban region needs housing, transportation networks, and other socio-activities to meet its population's needs. In turn, the city creates an unhealthy relationship with respect to impervious surfaces and increases in population increases (Nguyen, Nghiem, & Henebry, 2018). Cons (2017) suggested urbanized areas have entered an era of flooding around the world with the development of larger cities.

Flooding

Bangladesh is one of the countries in the world that hosts a multi-river confluence of the Brahmaputra, Padma, and Meghna rivers creating an extensive delta system. The country also has a large urbanized population inside of the delta system (Cons, 2017) . The flooding that takes place in Bangladesh is from river flooding from upstream rain from the Tibetan Plateau. Closer to the study are the Tax Day and Memorial Day floods, which were from a combination of significant rainfall and upstream congestion making its way through the Cypress Creek watershed. Harris County is also susceptible to tropical cyclones (hurricanes). The Gulf of Mexico is very active with tropical cyclones during the summer and fall months of the northern hemisphere. In 2017, the region was very active. In August-September of 2017, Hurricane Irma made landfall in Puerto Rico (Cangialosi, Latto, & Berg, 2018), to only have Maria make landfall just a month later (Pasch, Penny, & Berg, 2019). Moving from the Caribbean to the Gulf of Mexico, Harvey made landfall in southern Texas and stalled out over the west side of Harris County in September of the same year (Blake & Zelinsky, 2018). Tropical Storm Imelda hit Houston only two years later, causing flooding in the city (Latto & Berg, 2019).

In the case of Harvey and Imelda, many factors that contributed to the flooding. Intense rainfall in the Houston region and the urban built-up areas caused massive amounts of water to exceed the drainage system and create flash flooding of streets and highways. There are many factors to why flooding takes place in the urban environment. Land-use practices, rain runoff from surfaces and upstream inputs, and the total amount of rainfall are a few of the contributors to urban flooding (Marafuz, Rodrigues, & Gomes, 2015) In recent years the Houston region has become flood-prone.

Qiang (2019) suggested that urban and population development should avoid flood-prone areas. The issue is that because of political, social, and economic pressure, the avoidance of flood zones has been ignored, primarily because of a lack of awareness of the hazards and governmental controls. The pressures of development in flood zones influence the way urbanization takes place. Historically, Houston is known for its lack of control on land-use policies and regulations. Houston and Harris County started as a land speculation, which now creates a free-market type of development. When land is available, it is developed in a manner to maximize profits. The development practice leaves the flood zone vulnerable to speculation and development with no regard for its natural process.

Urbanization

Urbanization is a reaction to a post-industrial society and is not a new concept. In pre-industrialized cities, the elite lived in the city center while the lower-income population lived in the outskirts (Levy, 2013). Living in the rural surroundings of the city usually meant much of the population was engaged in the agricultural sector of the economic scale. In more recent history, the roles of living have changed. Post-industrial cities now host the lower-income families while the elite members flees to the suburbs (McFarland, 2019). In the advent of industrialization, farms no longer need large labor forces, and the factories soaked up much of that labor force. The factories were located near or in city boundaries. While the concept of urbanization has not changed, the way we urbanize has changed the more technology has changed.

Urban development patterns have gone from high density living to low density, single-family homes were everyone has a front and back yard. Many of the residents in the low-density areas rely on automobiles for modes of transportation to and from work (Brody et al., 2013). Suburbanization also creates pockets where residents become automobile-dependent for all their needs, such as grocery shopping, church, and social activities. Segregation of the people from their activities and jobs is more costly than public transportation networks (Brody et al., 2013). In many cases, construction and maintenance of road networks become costly.

Transportation was and still is one of the significant components of the way urbanization has changed. In older cities like New York and Chicago, population centers congregate along with major public transportation networks (Orsi, 2018). Subways and elevated rail systems changed how people get to work. By having a mature public transportation network, older cities can control how the city spreads out or builds up. Newer cities have changed mobility within and around the city. Places such as Houston, Dallas, and San Jose are automobile-dependent cities. They have lower density suburbs and rely on the automobile to commute to work (Orsi, 2018).

Highways have influenced urban land use patterns. The use of highways causes a decentralization of the population from the city center (Modarres & Dierwechter, 2015). While the population is moving out of the city center into the suburbs, highways and transportation networks are starting to create pockets of the employment center. The urban population no longer needs a central business district for employment. Oller, Martori, and Madariaga (2017) referred to this type of development as directional heterogeneity. The theory is that the distances to the city center are different; they are also in different directions. Houston is a directional heterogeneity city, NASA is to the south and The Woodlands to the north along U.S. Interstate 45, oil refineries to the east, and the Energy Corridor to the west using U.S. Interstate 10. This development pattern leads to urban sprawl.

Resnik (2010) defined “urban sprawl as a pattern of uncontrolled development around the periphery of a city” (p.1853). Urban sprawl and living have benefits that include clean drinking water, security, transportation, and employment opportunities. While there are benefits to an urban lifestyle, there are also health-related issues due to modern construction practices. With urban sprawl, there is an increase in impervious surfaces. Surfaces that do not allow for the natural absorption of rainwater are considered impervious. When the water cannot be absorbed, it is to pool and create runoff. It is from this runoff that, chemicals and oils from the concrete environment contaminate the rivers and streams that flow through the city. In this reduction of water quality from an increasing amount of surface runoff, health issues such as disease and cancers increase (Resnik, 2010). The best control for the health issues related to the built-up environment is the implementation of zoning policies. In most cases, zoning can help control urban sprawl or at least lot size and design.

Zoning

The purpose of zoning is to regulate the use of land and structures within a municipality and to promote public health, safety, and general welfare of the people (Welch, 2016). Welch (2016) also indicated that zoning endeavors to preserve historical and culturally significant sites. Zoning has two parts to land-use controls. Building characteristics and where to build residential or commercial structures outline the first part of zoning. This principle segregates residential neighborhoods from industrial and commercial activities. The next focus for environmental concerns is the site layout requirements in the zoning ordinance. These sets of practices regulate how small the lot size can be for the type of structure and the design usage for that structure. It also regulates setbacks from roads and percentages of land cover types. For example, the minimum lot size is a quarter of an acre and must have at least 30% open landscaped area (Levy, 2013).

In most major cities, zoning is a primary function of the local government. For example, Chicago has one of the most comprehensive and historic zoning practices in the United States (Shertzer, Twinam, & Walsh, 2018). While it started as a people ordinance, which regulated land-use practices but also separated different types of districts, it was the beginning of zoning. Industrial districts and residential districts are kept separate from each other. The practices also included building volumes and lot coverage percentages (Shertzer, Twinam, & Walsh, 2018). While Chicago serves as an example for researchers and practitioners on zoning and planning, that is not the case concerning to Houston and Harris County.

The state regulates the right to zone in the State of Texas. Welch (2016) used a court case to highlight that Texas Chapter 211 of the Texas Local Government Code set forth; that only the state has the authority to zone property in Texas. In the matter of zoning, municipalities have the right to zone if they apply for authority from the state. Most cities and towns have already done so; then, there is Houston. Houston started as a land speculation town based around profits. The charter for the City of Houston, Code of Ordinances: Section 13, zoning can only take place after a six-month review of the proposed planning and then pass through a general election (City of Houston Planning and Development, 2013). The idea of zoning has been brought before the people three times in history, and the citizens voted down the measure each time. Houston remains unzoned (Qian, 2010). While Houston does not practice zoning in the city, this is not to say that the city does not apply some regulation to land use.

When it comes to the county, there are no avenues for zoning authority. What the county does have are permits for construction in flood plains. These permits outline how to construct the building with regards to elevation and design. Other measures to ensure that someone does not open a tire shop inside of a residential community are through homeowners association (HOA) and deed restrictions (Qian, 2010). One caveat to deed restrictions and HOAs is that these policies do not take effect until the completion of the subdivision, and families start purchasing homes.

FEMA Flood Zones

In the studies presented, the idea of the FEMA flood zones is presented. Whether to calculate flood loss damages or compare flood zones to current flooding issues, flood zones, are a highly political abstract. To modernize the current floods maps the changes in geography, precipitation, and urbanization need to be understood. While this appears to be a favorable process, local officials do not always agree with the process. The idea is to move more people out of the flood zones to show they will not need to purchase flood insurance. The mapping process seems to be moving more people into the flood zones. Officials believe this will place an undue burden on the residents in the flood zones and diminish property values. The loss of property values brings a loss in revenue for the local governments (Pralle, 2019).

Flood plains mitigate risk to property and people in proximity to the water networks. Flood insurance is, in most cases, still a mandatory part of federally back mortgages. There are still properties that only require voluntary flood insurance (i.e., homes with no mortgage loans or properties deemed lower risk in outdated flood zones; Highfield et al., 2013). To redraw the zones is an expensive task for any region. It is almost impossible to redraw the zones every year. This would be the case for Harris County and the rapid urbanization that takes place.

While Harris County does not have zoning authority, it controls or restricts the standards and regulations (Lyles, Berke, & Smith, 2014) by permitting building designs and first floor elevations inside the FEMA flood zones (Blount, 2018). The purpose of the flood zone designator is to identify geographic regions and the flood risk levels associated with those areas (Flood zones, 2019).

While flood zones have different codes to determine the flood possibility and mitigating practices to reduce flooding, the two main principles are the 100 and 500-year flood zones. One-hundred-year flood zones are areas that have at least a 1 % chance of flooding every year (usually identified by an A code or combination of A and another code). Highfield, Norman, and Brody (2013) processed data concerning flood impacts and damages paid for a period from 1978 to 2008 and, found that 47% of all the claims were located outside the 100-year flood plain (p.189).

The 500-year zones are areas that, based on elevation, should only have a 0.2% chance of flooding annually (FEMA, 2019). As the name identifies, areas in the 500-year flood plain should only expect to flood once every 500 years. In the case of outdated maps, the urban environment has not been considered for modern development. During the Tax Day and Memorial Day floods (2016), Cypress Creek experienced two 500-year flood only months apart to only experience another 500-year flood in 18 months, during Hurricane Harvey.

Flood zone mapping still is a contentious process. Many of the current flood maps are out of date and date back to the late 1980s (Highfield et al., 2013). Furthermore, flood mapping and updating remain under political influence. Pralle (2019) discussed the updating process for the city of New Orleans. Local politicians agreed that the map does not represent the near future with the completion of new projects. These project designs are to mitigate future flooding issues in the city. However, their argument does not cover when new building construction overwhelms the projects. In either case, the flood map does not represent the current situation for New Orleans (Pralle, 2019). Politics can influence how the flood mapping is to take shape. Much of the concern is over the economic implications of flood mapping. When parts of a city fall in disrepair, officials look to private investors to rejuvenate these areas in the city. The private capital improves infrastructure and building quality (Poole, 2018).

One of the ways to mitigate flooding in the urban city, flood zones were developed to identify where the flooding is most prevalent in 100- and 500-year time frame. While this process is time-consuming and costly to local governments, flood zones become outdated in a short time. The rapid development of suburban and inner cities places stressors on the flood zones and maps. Couple the stressors with political and economic pressers, and many flood zones go unchanged.

Land Use and Flooding

While population increases, Houston and Harris County need to meet the residents demands, and these needs come at a cost to the people and the environment. There are many reasons to study the bayous and creeks in Harris County; some look at the flooding from a qualitative perspective and resiliency (Chakraborty, Collins, et al., 2019; Chakraborty, Grineski, et al., 2019; Lynn, 2017). While other studies have investigated the quantitative aspect of flooding and land-use practices, in all relevant literature, the one standard independent variable is the use of LULC and impervious surfaces data to identify the changes in urbanization. The research outcome varies from researcher to researcher and in the different processes to reach a result.

Huron River

In Lower Michigan, the Huron River basin flows in a southeasterly direction, which eventually drains into Lake Erie. The focus is on how the urban environment has begun to encroach into the rural setting of the watershed and the Huron River. It is not just the investigation of the development but also the type of development that is taking place. It is important to note that the study's instrument was the FRAGSTATS software developed by the University of Massachusetts, an add-on extension for ArcGIS (Lei & Zhu, 2018).

In 1992, the watershed was almost 50% agriculture and grassland, followed by 28% forest land. Then again, in 2011, agriculture and forest lands decrease by 10% and 6% respectively. The most significant increase was in low-density development (urban sprawl) in the watershed (Lei & Zhu, 2018). The most exciting section of the study was how the stream discharge over the same period increased by 37% (Lei & Zhu, 2018). The higher discharge from the streams into the river causes a decrease in the river's ability to handle the extra water, then leads to flooding. The last variable used was precipitation. Precipitation in the region comes in many forms. In the summer months, rain is prevalent, while snow and snowpack influence the stream discharges in the winter. The precipitation in the watershed did not present a significant change; the discharge from urban areas was significant (Lei & Zhu, 2018).

This study provided the basis of comparing how land-use changes along waterways influence the frequency of the flooding hazards. The combination of loss of natural land cover, and the introduction of fabricated structures in the watershed is the primary focus on flooding. The study represents a guideline for interior waterways, development, and flood potential. While Cypress Creek is an interior waterway, it is also located in the coastal region of southeastern Texas. Harris County's only direct access to the Gulf of Mexico is through Galveston Bay. While the watershed is in the coastal region of Texas, its primary influence is to the San Jacinto River, which flows into the bay.

Pawtuxet Watershed

Campbell, et al. (2018) conducted a study on the Pawtuxet Watershed in Rhode Island. The venture was to investigate the impact of urbanization in the watershed to the risk of flooding severity. The Pawtuxet watershed is very similar to the Harris County region, meaning that while the study area is not on the coastline of the Atlantic Ocean, it drains into the Narragansett Bay, then into the ocean. Using the soil and water assessment tool (SWAT), the study employed digital elevation models, soil surveys (SSURGO), and the global weather database to ascertain the effects of water runoff from precipitation and impervious surfaces.

The SWAT analysis considers the amount of water that can be absorbed by soils to the point of saturation before surface water runoff enters the drain network. The LULC model was used for each year of the five years (2008-2013), except for 2010, which used the 2025 projected land-use model. Kendall's rank correlation has an increase in runoff from the land-use changes compared to precipitation increasing in the watershed. The prediction of the SWAT for 2025 did not accurately reflect the high and lows in peaks of the river basin. The prediction was based on current precipitation, not 2025 future climate rates (Campbell et al., 2018) .

South Texas and Harris County

Many different approaches have performed analysis of flooding and impervious surfaces. Brody et al., (2013) studied the impacts of urban development patterns along the

Gulf of Mexico, ranging from the Florida Keys to the southernmost tip of Texas along with the mouth of the Rio Grande River. They used Landsat 7 satellite data to identify the patterns along the coast. By using the data, they could reclassify the imagery to locate low, medium, and dense development patterns. Their findings showed that high development patterns and impervious surfaces did not produce a risk of flood loss damages. In these flood plain areas, they found high losses to flood damages (Brody et al., 2013).

Galveston County separates Harris County from the Gulf of Mexico. Along the eastern edge of the county is Galveston Bay, which empties into the gulf. The significance of this is that tropical cyclones in the gulf can move into the bay and continue extreme rain patterns that affect the county. Muñoz, Olivera, Giglio, and Berke (2018) focused on the Sim Bayou and the impact of urban sprawl on the streamflow in the 100-year flood plain. The process was to georeference parcel polygons and used a footprint area formula to calculate the number of impervious surfaces along the bayou. Through regression analysis, the increase of impervious surface was correlated to the rise in streamflow capacity. The principle investigation was the effect on the hydrology of the bayou caused by urbanization.

There have been two studies on hydrology for the Brays Bayou. Bray Bayou is in southwestern Harris County, and it drains into the main shipping channel for Houston in the east. The first study examined the effects of precipitation from tropical cyclones and the LULC data to calculate the amount of discharge of the bayou. This study also included the three other bayous, and no significant difference was found, mainly due to their proximity to each other. However, the study shows that the loss of natural landscape increased the propensity for the waterways to flood (Zhu, Quiring, Guneralp, & Peacock, 2015).

While the second study did not investigate the frequency of flooding, it did explore what the discharge was carrying. In this example, the researchers investigated the elements carried into the drainage network. The results concluded with the presence of heavy metals found in large quantities compared to other places. Their hypothesis confirmed with the loss of natural vegetation, heavy metals are more likely to present from runoff in the bayous (Bhandari et al., 2017).

Continuing in Harris County, there was a study on impervious surfaces in the Clear Creek watershed. Brody et al. (2014) used a spatially weighted linear regression model to identify the influence of the LCLU on properties that have flood claim losses. The research team was quick to highlight the LULC and impervious surface and the effect on the discharge compared to the volume capacity of the creek. While evaluating was the best defense from flooding in the watershed, the study did explain that with the increase of impervious surfaces over the 11 years, precipitation became the more powerful predictor of flooding. The higher amounts of rainfall produce more significant floods even to higher elevation structures (Brody et al., 2014).

In August of 2017, Hurricane Harvey made landfall in southern Texas, moved up the coast and temporarily stalled out just west of Houston. Harvey dropped over 51 inches of rain on the Houston region. Zhang, Villarini, Vecchi, and Smith (2018) found that urbanization did not affect rainfall; it did, however, influence the discharge into the drainage network. The study showed that impervious surfaces impacted the amount of runoff caused by Hurricane Harvey precipitation. Zhang et al. (2018) investigated the urbanization compared to the Harvey rainfall. Miller and Shirzaei (2019) found that compaction of the natural ground also plays a significant role in the discharge. When looking into the Jasper Aquifer, the ability to replenish the aquifer was hindered by the compaction of the clay layers, therefore creating more runoff and volume capacity for the main of the drainage networks around the Houston region during Harvey.

In many cases, these studies were in the southern areas of Harris County or conducted at a macro scale. Few studies investigated the Cypress Creek watershed. Gori, Blessing, Juan, Brody, and Bedient (2019) investigated the outcomes of urban hydrology to understand why Cypress Creek not only swelled its banks but also identified why the creek overflowed across the landscape to move directly south to the Addicks Reservoir. The drainage network had never moved directly south. The creek drains into the west fork of the San Jacinto River, which flows directly into the North Galveston Bay by way of the Lake Houston reservoir. The land use projection model provided insight into the development pattern north from the city center and its rapid expansion due to unregulated growth practices through zoning (Gori et al., 2019).

In 2016, Kim, Li, Kim, and Jaber (2016) performed a SWAT analysis on the Cypress Creek watershed. The intent was to calculate the suburban surface runoff in the watershed. The SWAT analysis used past and current LULC and precipitation data to identify the change in surface runoff. Sound judgments for future development can be made from this analysis, but predictors from the study can guide future development.

However, in a vacuum of uncontrolled development, many of the predictions can be miss guided due to unknown advancements in development practices in a free market system.

The previous studies provide a blueprint from which pieces can be brought together. While the SWAT analysis hinges on the soil absorption to predict flowing, other studies focus on older techniques in developing impervious footprints. In the older techniques, the studies only use a cross-section of the main drainage way. In most cases, they omit the rest of the watershed, leaving other factors in the watershed unused. The idea is to use the complete watershed as the principle environment and the human activity as actors that disrupt the natural order of water drainage and disbursement.

Summary

Flooding is a growing issue with communities and regions close to coastal waters. The water has been a significant attraction for population migration throughout history. In the past, water provided transportation and food for daily living. Today, the coastal waters are more than economic and subsistence; the coastal regions are a prime attraction for recreation and aesthetics. As the population increases, the need for social, political, and structural environments increases. In the case of Harris County, Houston has attracted people from all around the world. Today the city is one of the most diverse hubs in the nation.

Much of that population has now spread out into the county, and zoning policies do not exist for urban development. The free-market system of development is driven by economics and not environmental concerns. A look into different bayous and creeks in southern Harris County provided for a blueprint of other research designs that helped guide this study.

In Chapter 3, the research design is spatial temporal. The result showed how no zoning policies have created an environment for current flood hazards to exist in northern Harris County. There is also a description of the data used and the methods in which the data were collected. The chapter also provide a section on any ethical concerns and how to avoid them while maintaining internal and external validity for the study.

Chapter 3: Research Method

Rapid urbanization and flooding are becoming more frequent in the Houston region. This study added to the growing collection of literature on Harris County flooding by investigating urban sprawl in a system with few to no controls on development; it introduced a different spatial method to identify urban changes and flood potentials in an unzoned region. The chapter covers the following topics: research design, study area, data collection, spatial-temporal process, materials and data collection methods, and ethical considerations.

Current literature research focused on flooding zones, flooding, and urban sprawl in the southern part of Harris County, very few use GIS as a base for model production. When the research is focused on human resiliency, these studies are in highly populated low social, economic neighborhoods in and around Houston. Outside of the study were Cypress Creek flowed south over the landscape, very little research has been conducted in northern Harris County or the Cypress Creek watershed.

Study Area

The Cypress Creek watershed is 23 miles north of downtown Houston and 68 miles from the Galveston Island coast. The watershed measures 203,570 acres and includes roughly 450,000 people. The area of interest (AOI) was the center section of the watershed (Figure 1). The eastern section was designed as a runway safety area and belongs to the George Bush Intercontinental Airport. To the west, the watershed has been historically rural and remains rural today. The AOI lies between the Hardy Toll Road in the east and State Highway 249 (Tomball Parkway) in the west. This area is developed and has attractions for social activities and significant corridors to Houston and The Woodlands.

The watershed drains to the east at the San Jacinto River, then to Galveston Bay via Lake Houston. When the watershed becomes inundated by storm waters, the water flows south toward the high urbanization areas of north Houston. The land use classifications include agricultural, natural, and different primary levels of urban development and sprawl. The AOI can provide a record of urban sprawl.

The watershed is vital to transportation networks. These networks are used for evacuation routes and rescue services. Once an event is over, the transportation systems are needed for local, state, and federal aid to assist the help residents with necessities for survival. In conjunction with the aid, the roads allow for the transport of materials during the reconstruction process.

Spatial-Temporal Process

Four different processes were employed in conducting the research (see Figure 2).

1) urban watershed delineation
2) rainfall to runoff conversion
3) runoff to flow conversion
4) inundation estimation & mapping

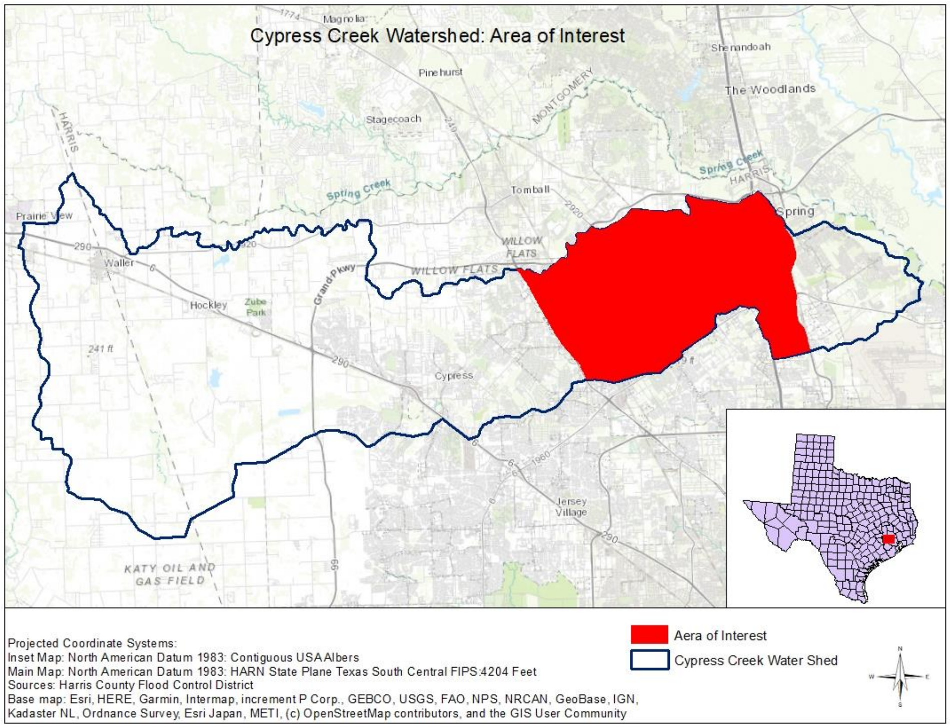

Figure 1. Cypress Creek watershed Area of Interest

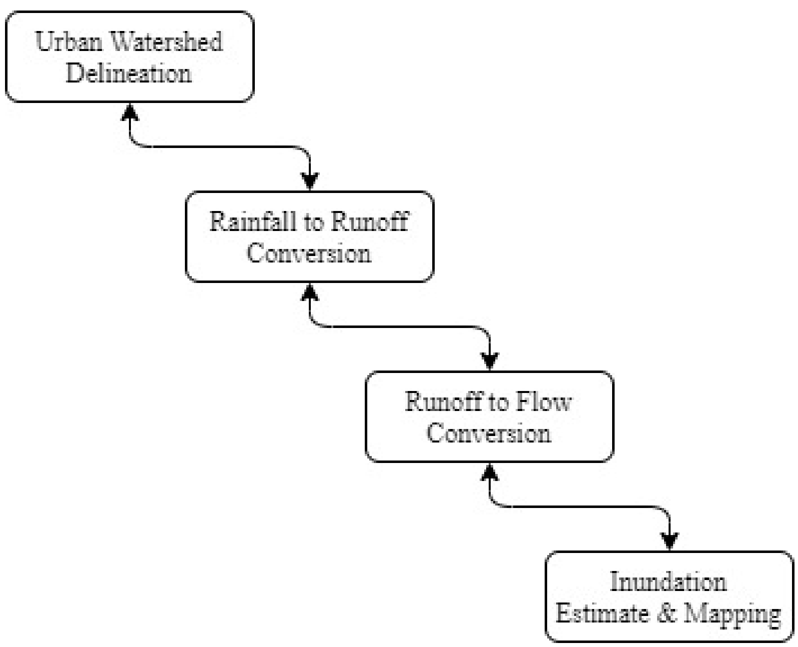

Figure 2. GIS framework "GIS Framework for spatiotemporal mapping of urban flooding" by S. Abedin and H. Stephen, 2019, *Geosciences*, 9(2) p. 79

The framework used in this study was created by Abedin and Stephen (2019), to identify accumulation over a temporal period. While the study framework is for flooding for one single event, this research study used the processes for total rainfall over multiple events to identify urban flooding inside the watershed. Each event had a total amount of rainfall—that input was used against the LULC for that event year. The events used for the study were Hurricane Ike in 2008, the Memorial Day flood in 2015, and Hurricane Harvey in 2017.

Hurricane Harvey rainfall data and the LULC model for all three periods were compared to understand the effects of heavy precipitation on urbanizing areas. The effect of Harvey on the watershed in 2017 was the first allocation of the data. The 2018 LULC and Harvey data completes the framework for that specific period. The idea was to use the result to create sound information for future planning processes on development inside of the flood zones set forth by FEMA.

Urban Watershed Delineation

The delineation process incorporated the elevation of the watershed and the stream network. LiDAR data were used to create the digital terrain model (DTM). The point cloud data model isolated the pulse returns for the natural surface. By using the first return, the terrain was accurate and allowed for the correct implementation of the flow network using the stream in the watershed (Abedin & Stephen, 2019).

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The Harris County Flood Control District has already produced watershed models for the county. Since the process required a multi-facet approach, the watershed was divided into sub-basins (catchments). The same process was used for the watershed delineation. The watershed model created by the county examined the county, which was a macro scale model. The catchments looked to a micro-scale; in this case the AOI.

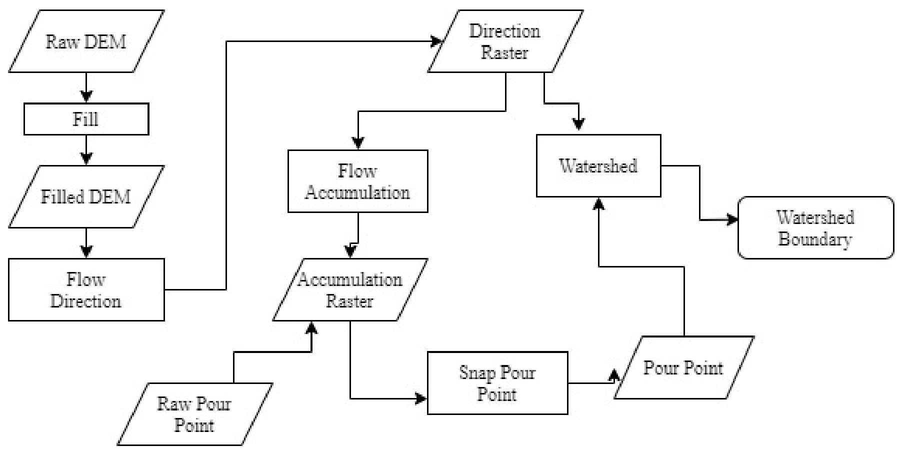

Figure 3 Urban watershed delineation

Rainfall to Runoff Conversion

Rainfall to runoff conversion was a vital step in the process. When the natural ground is no longer able to absorb the rainfall, runoff becomes an input into the drainage network. The network is only able to handle so much of the surface water. When the banks of the stream no longer hold the water, the landscape tends to flood.

The Soil Conversation Service (SCS)-curve number (CN) method was used in the calculation of the runoff water in the watershed. The SCS-CN was the number assigned to different soils and surfaces based on their absorption characteristics. The equation is:

$$q(x,y) = \frac{|R(x,y) - I(x,y)|^2}{R(x,y) - I(x,y) + S(x,y)}$$

the proceeding equation is *q(x,y)*, which constituted the runoff for each given cell in the output raster, the *(x,y)* are the coordinates of the centroid for each of the cells (pixel). The *R(x,y)* was the total rainfall for the event, *I(x,y)* was the initial rainfall contained in the watershed soil before the runoff, and *S(x,y)* was the maximum amount of water the soil retains. All amount are in inches.

R(x,y) was a natural input into the equation, where *I(x,y)* and *S(x,y)* were products of other processes. The *S(x,y)* was the product of the C.N. at the *(x,y)* divided by 1000.

$$S(x,y) = \frac{1000}{CN(x,y)}$$

I(x,y) was where the initial abstraction ratio (*γ(x,y)*) was multiplied by the *S(x,y)*. The SCS deemed the standard value of 0.2 for γ.

$$I(x,y) = \gamma(x,y)S(x,y)$$

For each catchment basin, the process to determine the composite curve numbers (CCN) was produced for each catchment. The CCN was designed for the rainfall runoff in a micro process. In each catchment, the Hydrologic Soil Group (HSG) was figured based on the soil types in the catchment. Soil groups have an HSG group (A, B, C, or D) assigned based on the characteristics of the soil and presented by the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conversation Service (Urban Hydrology for small watersheds, 1986).

The HSG was divided into four different classifications. The HSG A had the smallest runoff, while group D had the highest runoff. Each soil group was assigned an

A, B, C, or D based on the soil capability of absorbing water. The soil groups' square footage was calculated to find the predominant HSG classification for each catchment. For example, a catchment may have different soil types. When adding all the soil types based on the HSG identifier, the sum consisted of the totals for A, B, C, or D . If D has the largest total of square feet in the catchment, then the catchment used D in the next process (Major, 2010).

Table 1

CCN Example

Composite Curve Numbers						
CatchID	16	Curve Number for HSG				CN*Area
Land cover type	Area(ft^2)	A	B	C	D	Total Area
Open water		100	100	100	**100**	
Developed open space	4,325,176.87	39	61	74	**80**	346,014,149.48
Developed low intensity	34,765,247.40	54	70	80	**85**	2,955,046,029.39
Developed medium intensity	22,084,615.22	77	85	90	**92**	2,031,784,600.44
Developed high intensity	917,461.76	89	92	94	**95**	87,158,867.20
Barren land		77	86	91	**94**	
Forest/Shrubs	7,601,826.01	33	50	64	**70**	532,127,820.78
Pasture/Grasslands	1,965,989.49	40	64	75	**81**	59,245,148.34
Cultivated crops	262,131.93	67	78	85	**89**	23,329,741.90
Wetlands	720,862.81	100	100	100	**100**	72,086,281.14
Total area	72,643,311.49					6,206,792,638.66
Composite Curve Number (CCN) =						85.44203879

To finally come to the CCN, the curve number ranged from 40 to 100. The higher the amount of runoff, the larger the number, except for water. Water was always labeled 100 since there was no way to calculate runoff of rain in the water. To finally arrive at the CCN, the land-use type and the amount of area for each was multiped by the CN. In the case of Table 1, for the catchment, D was the dominant HSG. Curve numbers assigned to each land-use classification under each group was inputted, but not computed. Once the total area was calculated, the sum was divided by the original area (Major, 2010). The CCN was inserted in the formula to calculate for *S(x,y).*

Runoff to Flow Conversion

To calculate the flow rate, the deterministic method was used. This method was statistically not a complicated as other models used in hydrological modeling. The modeling calculated the time water traveled from the centroid of one cell to the next. While time can be subjective, the time it took water to travel from the center of each cell could be estimated by the velocity and length of the flow to the watershed discharge outlet. The equation for this process was as follows:

$$V(x,y) = 0.3048 * K(x,y) * \sqrt{M(x,y)}$$

V(x,y) (m/s) was the speed at the centroid and depended on the coefficient K(x,y) and the slope of the landscape *M(x,y).* the K value depended on the flow type classified by Sorrell and Hamilton (2003). For a small inlet stream, the K value was 2.1, compared to a larger waterway at 1.2 and a sheet flow at 0.48. Since the time flow was for the total rainfall was in effect, there was only one band of water inundation. The process included a single factor of one for fully clogged. The process was to show how widespread the flooding was dispersed compared to the LULC for that time (Abedin & Stephen, 2019).

Inundation Estimation and Mapping

Urban flooding consists of large amounts of rainfall, impervious surfaces, and the drainage network's discharge rate. Ponding is the beginning of widespread flooding. Ponding takes place in low elevation areas, and as those areas begin to fill, the water starts to flow across the landscape. Incorporate the ponding with discharge clogging, and the water begins to fill the landscape.

The clogging factor is the relative flow discharge in the outlet. Since the original study only accounted for street drains and not watershed drainage, the outlet at the San Jacinto River was considered clogged. The reason behind this was that the river is a significant outlet for many different watersheds. Water is flowing into the river north of the watershed and south of the watershed. When the river reaches capacity from other inputs, the creek begins to slow and flow across the region. As the water begins to back up at the confluence, the backup flows back upstream and into the watershed.

In the study's scope, time estimation was relaxed since the overall rainfall was the targeted precipitation period. The spatial-temporal process was compared against different flooding occurrences and not one single episode. Water volume, discharge, and runoff flow only had one singular precipitation input and not a series of inputs.

Materials and Data Collection Methods

The data collected data were from government open-source data warehouses found on the internet. Two main raster-based products were collected from the Texas Natural Resources Information System. The LiDAR data consisted of a point cloud data package used to create a DTM. LiDAR data are a quick, accurate, and inexpensive way to create elevation models compared to satellite data (Priestnall, Jaafar, & Duncan, 2000).

In contrast to satellite data, LiDAR also has the capability of capturing more than just ground elevation. The data can be queried to isolate the ground's elevation from the elevation of structures and natural vegetation heights. The second raster product consisted of the LULC data. The LULC provided historical and current land-use models. The LULC identified urban development and sprawl from natural and agricultural land uses. The SCS-CN is housed inside the LULC.

The vector data collected were the streams and watershed boundaries. The streams were clipped to the watershed boundaries and the FMEA's flood zones. Outside of spatial data, aspatial data were also collected for the study. The SSURGO table was used for the soil percolation factor for surface runoff. The next set of aspatial data were collected from the Harris County Flood Control District. The table of flooding events was converted into GIS vector data. The table contains the highwater marks for each of the monitor stations along with the water networks inside the Cypress Creek watershed. The final tables collected were the total precipitation tables for each of the events studied. These data were transformed from vector to raster data. Raster data format was the desired format for the process.

Data Management

The collection, processing, and creation of data adhered to the Federal Geographic Data Committee standards. The metadata successfully fulfilled these requirements. Metadata consist of a catalog record of who created the data, how the data are to be used, which includes the limitations of the data, when the data were created, and information about the data. The last part of the metadata that was important was the location of the data. The location of the data had two parts: Cypress Creeks watershed on the Earths surface and relative position within Harris County. The second part of the location was the spatial location with the extent of the north/south and east/west limitations of the data.

When examining the limitations of the data, the spatial reference was cataloged in the metadata. The spatial reference for the research was the North American Datum 1983 State Plane Texas South Central (FIPS 4204 ft U.S.). The state plane projection was used to control for distortion to the edges of the study area. Distortion created measurement issues in the east and west sections of the study area. Projection helped control for the distortion. More importantly, by using the right projection, measurements in the study were accurate and concise.

Flood Plain Delineation

Floodplain elevation used LiDAR points to assign the extent of the floodplain delineation (Figure 4). The FEMA flood zones, and the delineation identified the essential parcels within the floodway, 100-year, and 500-year flood zones. The delineation process validated the runoff model. While the validation process was essential, it also was a start to recommendations later in the study.

The DTM from LiDAR points is used to compare the water surface triangular irregular surfaces to calculate the surface difference. The results were then compared to the FEMA flood zones and the digital surface model (DSM). If any of the essential buildings were inside the 500-year flood plain, new flood zones were created. New flood zones identify the urban sprawl and correct the current policies for developing in the flood zones.

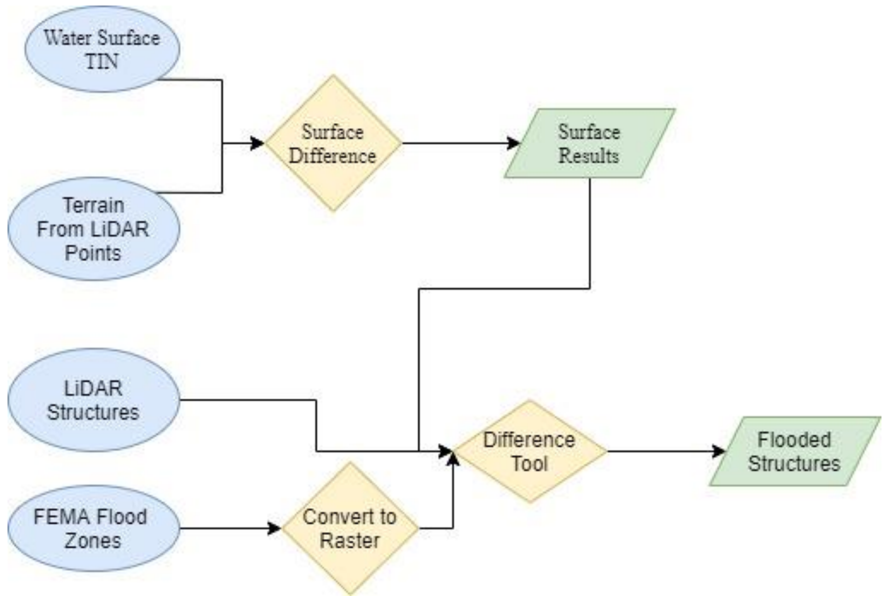

Figure 4 Floodplain delineation from LiDAR

Ethical Considerations

This study was void of human subjects. The principle was to examine human activity and its effects on the landscape, not the people themselves. At no time were human participants needed. Any parcels collected had the owner names and addresses stripped from the dataset at the county level. By striping the information at the county level before using the AOI data, parcels owners remained anonymous. All LULC data were void of personal information since they were collected and processed from Landsat 7 and 8 satellite radar telemetry from an Earth orbit.

Summary

While this process accounted for flooding stages across impervious surfaces during a singular occurrence, this research temporal stages were over three incidents from 2008 to 2017. The urban development for each period identified how each flood is affected by the consistent urban sprawl in the watershed. For this study, it was more important to understand how the land changes over the 9 years created higher flooding frequencies. With the results, a direct correlation between urban sprawl and flooding events was evident. This research led to understanding how human activities in the urban environment were leading to the flooding issues in Harris County, Texas.

Chapter 4 will present the results for each of the processes of the gathered data. The investigation of the links between the land use cover and the soil characteristics. The process of compiling the curve numbers to understand the amount of runoff based on the soil and land cover. The examination will provide insight into the amount of runoff water going into the drainage network. The velocity test will show the influence of terrain and speed in which the runoff hits the drainage networks. Finally, a comparison of Hurricane Ike and the Memorial Day floods to the flood zones will be presented.

Chapter 4: Results

Introduction

Increased urbanization in Harris County has been perpetuating the frequency of flooding events in the county. The AOI in the Cypress Creek watershed saw a 3.6% growth rate from 2000-2010. Approximately 280,000 people living in the area deal with flooding almost every year (TIGER/Line shapefiles, 2010). The region is certain to increase in population and, in turn, increase in urbanization and cause a change in the LULC. The AOI has seen an increase in developed land in LULC. Between 2008 and 2018, the region had a 27.13% increase in developed land, there was a 147.66% increase from 1992 to 2018 (Table 2). The increase in the developed property only exacerbate the flooding issues in the district.

Table 2

LULC Change

		Percentage of change				
Year	Acres	1992-2008	2008-2015	2015-2018	2008-2018	1992-2018
1992	16034.40	94.81%				147.66%
2008	31237.10		8.98%		27.13%	
2015	34041.60			16.66%		
2018	39711.41					

The first part of the chapter covers the spatial-temporal process of flooding based on the land use and soil conditions of the AOI. The second part of the chapter discusses the effects of the research on the hypothesis. A summary of the chapter findings and hypotheses follows.

Spatial Temporal Process

The spatial temporal process uses GIS to understand the urban landscape. The problem is that uncontrolled development in the county is leading to an increase in flooding events. Using GIS, critical issues within the building policies can be realized in the Harris County development policies. These critical issues are identified when comparing flood undulation to FEMA flood zones.

Urban Watershed Delineation

The State of Texas has a watershed created for Cypress Creek. To understand the AOI, catchments were created from the LiDAR-derived DTM. During this process, the AOI was divided into 18 separate zones based on drainage properties in the landscape elevation (Figure 5).

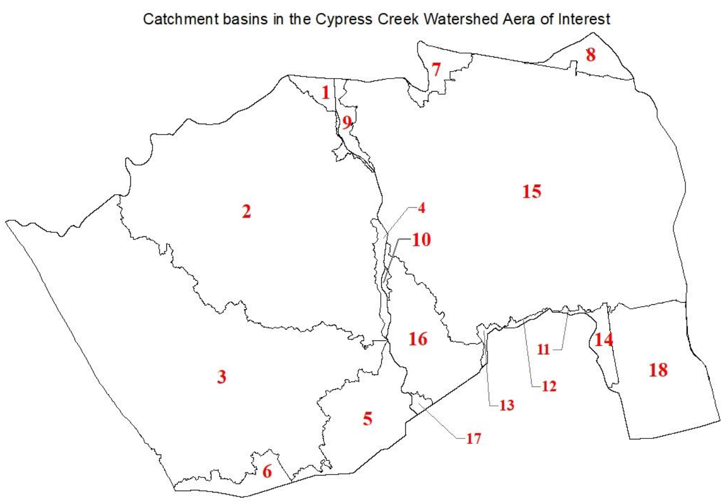

Figure 5. Sub-basins for the AOI

Rainfall to Runoff Conversion

Hourly precipitation was not available for each occurrence. The absence of data was a product of time and new storms; smaller datasets were deleted from the database. To calculate the runoff, the total rainfall for the event was used. For the first step, a CCN needed to be calculated for each period using land cover and soil data. CNs ranged from 0 to 100. Water bodies had 100 for a CN. Open and natural landscapes surfaces have varying curve numbers. CNs determine the amount of runoff and percolation during a precipitation event.

While the soil characteristics do not change with get frequency, the land cover is in a constant state of change. Within changes, curve numbers need to be calculated for each year. The curve numbers for the area have not changed too dramatically over the 10-year period. It is worth noting that the curve number decreased from 2008 to 2018. The average curve number in 2008 was 92, while in 2018 it was 85. This drop can be attributed to the increased development of open spaces along the creek bed.

When the curve numbers were complete, the runoff total was calculated for each of the subbasin. The runoff calculation was for the years 2008, 2015, and 2018 compared to the flooding events of Hurricane Ike, Memorial Flood, and Hurricane Harvey (Table 3). The runoff for Hurricane Ike decreased from 93% in 2008 to 86% in 2018 of the water flowing into Cypress Creek. Each of the other events also showed a decrease in the amount of water flowing into the creek versus percolation. Even so, in 2018, 94% of the water flowed into the creek.

Table 3

CN for Subbasin by Year

Basin	Composite Curve Numbers 2008	2015	2018
1	90	89	90
2	84	77	74
3	82	65	63
4	93	85	86
5	94	88	87
6	95	87	88
7	91	88	85
8	94	89	87
9	89	87	86
10	96	87	88
11	99	92	93
12	97	88	87
13	97	90	90
14	93	90	88
15	86	78	74
16	92	89	85
17	97	91	90
18	94	88	88

Runoff-Flow Conversion

Runoff-flow conversion is based on the flow rate of the water across different types of slopes and land cover. Much of the sheet flow of the water travels up to 1.22 meters per second. Thus, the main channel for the water to flow can see speeds up to 4.79 meters per second (Figure 6). The runoff water moves slowly until it reaches the flow channels, in this case, Cypress Creek.

There are large areas that have a 0 to 0.28 m/s velocity for the runoff. By having such a low speed for sheet flow, many areas create pooling secondary to the significant flooding along the creek. At some point, the pooling and flooding converge and exacerbate the flooding in the region. Within the pooling areas, if a section has a significant amount of water, it could cause erosion, which makes the sections ground unstable for structure support.

Table 4

Rainfall Runoff

	2008			2015			2018		
Basin	Ike	Memorial	Harvey	Ike	Memorial	Harvey	Ike	Memorial	Harvey
1	12.96	12.25	33.86	12.83	12.12	33.72	12.96	12.25	33.86
2	12.15	11.46	32.97	11.16	10.48	31.81	10.72	10.04	31.27
3	11.88	11.18	32.66	9.31	8.67	29.43	8.99	8.35	28.98
4	13.35	12.64	34.27	12.29	11.60	33.13	12.43	11.73	33.28
5	13.47	12.76	34.41	12.70	12.00	33.57	12.56	11.86	33.43
6	13.60	12.89	34.54	12.56	11.86	33.43	12.70	12.00	33.57
7	13.09	12.38	34.00	12.70	12.00	33.57	12.30	12.00	33.13
8	13.47	12.76	34.41	12.83	12.12	33.72	12.56	11.86	33.43
9	12.83	12.12	33.72	12.56	11.86	33.43	12.43	11.73	33.28
10	13.72	13.01	34.66	12.56	11.86	33.43	12.70	12.00	33.57
11	14.04	13.38	35.04	13.22	12.51	34.14	13.35	12.64	34.27
12	13.85	13.13	34.79	12.70	12.00	33.57	12.56	11.86	33.43
13	13.85	13.13	34.79	13.00	12.25	33.86	13.00	12.25	33.86
14	13.35	12.64	34.27	13.00	12.25	33.86	12.70	12.00	33.57
15	12.43	11.73	33.28	11.31	10.62	32.00	10.72	10.04	31.27
16	13.22	12.51	34.14	12.83	12.12	33.72	12.29	12.00	33.12
17	13.85	13.14	34.79	13.90	12.38	34.00	12.96	12.25	33.86
18	13.47	12.76	34.41	12.70	12.00	33.57	12.70	12.00	33.57

Note: Total rainfall for each event: Ike-14.21, Memorial-13.5, and Harvey-35.16

Overall the AOI contains a low-velocity rate, and the fastest moving water is where it is to be expected. The major waterway, Cypress Creek, contains the fastest water, and the smaller tributaries provide the next speed increment.

Inundation Estimation and Mapping

Inundation mapping provides a clear picture of the current state of affairs in the flooding extent. The flooding for Hurricane Harvey was used in this section of the research. By providing the highwater marks and the velocity of the runoff, and extent of the flood could be mapped and compared to Cypress Creek and the flood zones issued by FEMA.

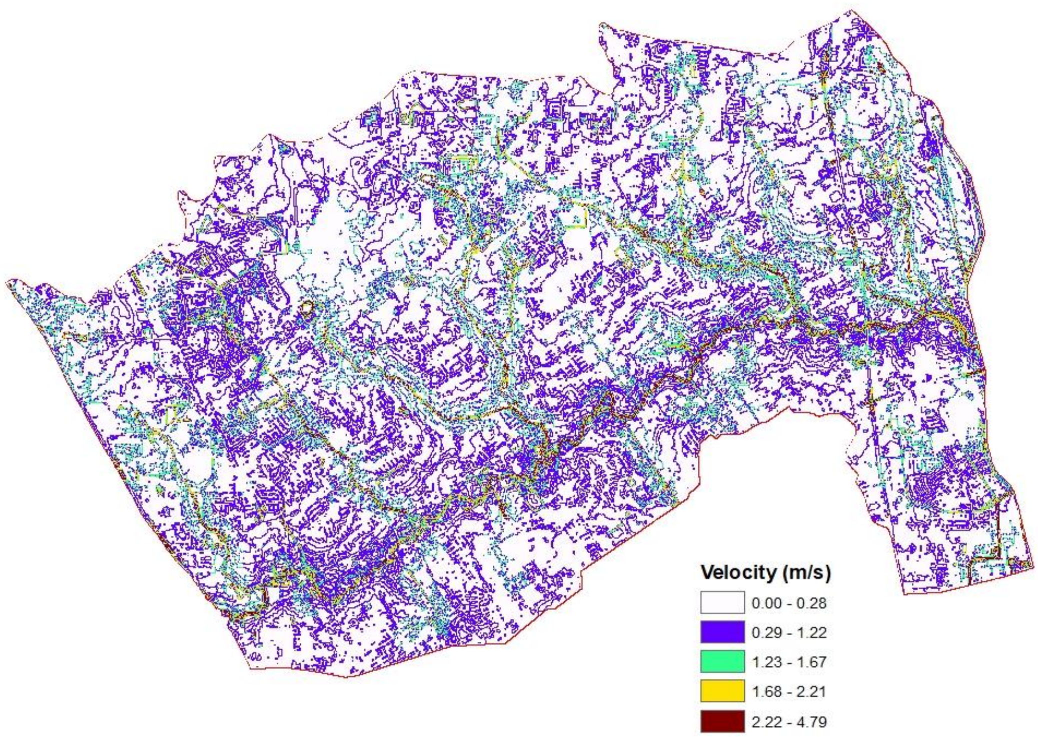

Figure 6. Velocity of water across the landscape

The Harvey flood extent exceeded the 500-year flood plain in many sections of the creek. The flooding was centralized to the main flow channel. Of the 75,640 parcels in the AOI, 8,979 were in the flood zones, including two different independent school districts, two hospitals, and a sheriff's office, which are discussed in Chapter 5. Harvey produced the most significant amount of precipitation in the region to date. To better understand the comparison of flooding over time, the inundation of Hurricane Ike and the

Memorial floods were a better comparison since the rainfall difference was only seven-tenths of an inch.

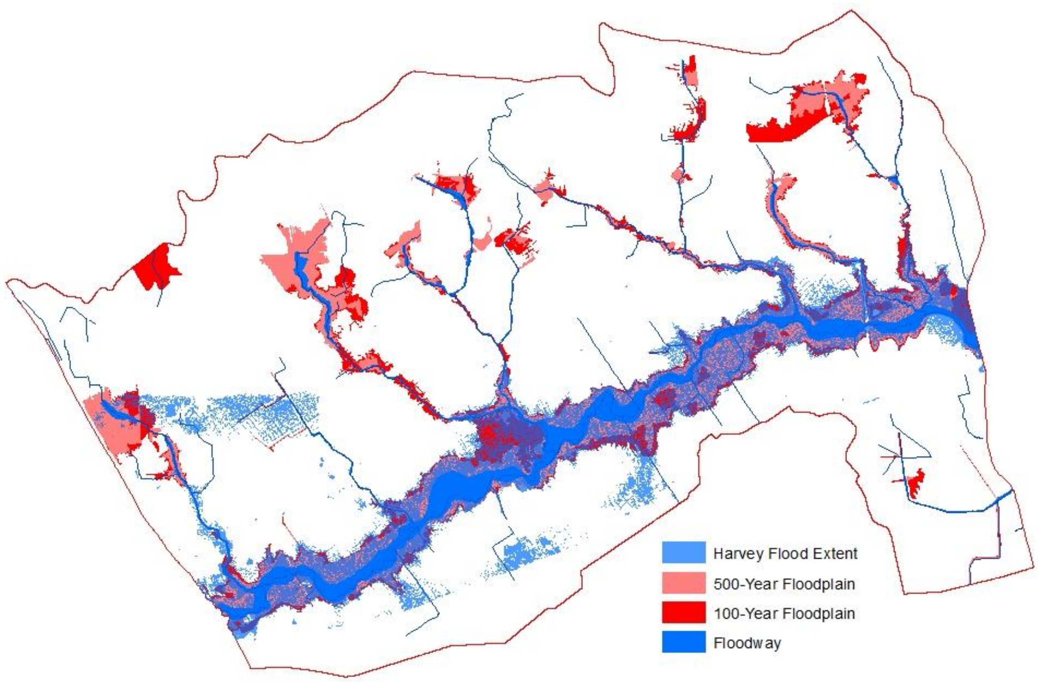

Figure 7. Harvey flood extent

While both occurrences were similar in rainfall totals and composite curve numbers, there was little difference in the inundation. Hurricane Ike produced more rain than Memorial Day; there was a noticeable difference in the flood extent toward the eastern side of the AOI (Figure 8). In either case, the flooding from Ike and Memorial Day reached areas in the 500-year flood zone. Subsequently, these areas saw a 500-year flood in 2008, 2015, and again in 2017.

A lot of the flooding intensity depended on precipitation duration. With hurricane or tropical storm precipitation, the duration was usually short term. Regular rainfall-induced flooding can take place over a couple of days, and in many cases, for Harris County can be affected by flooding from upstream rainfall.

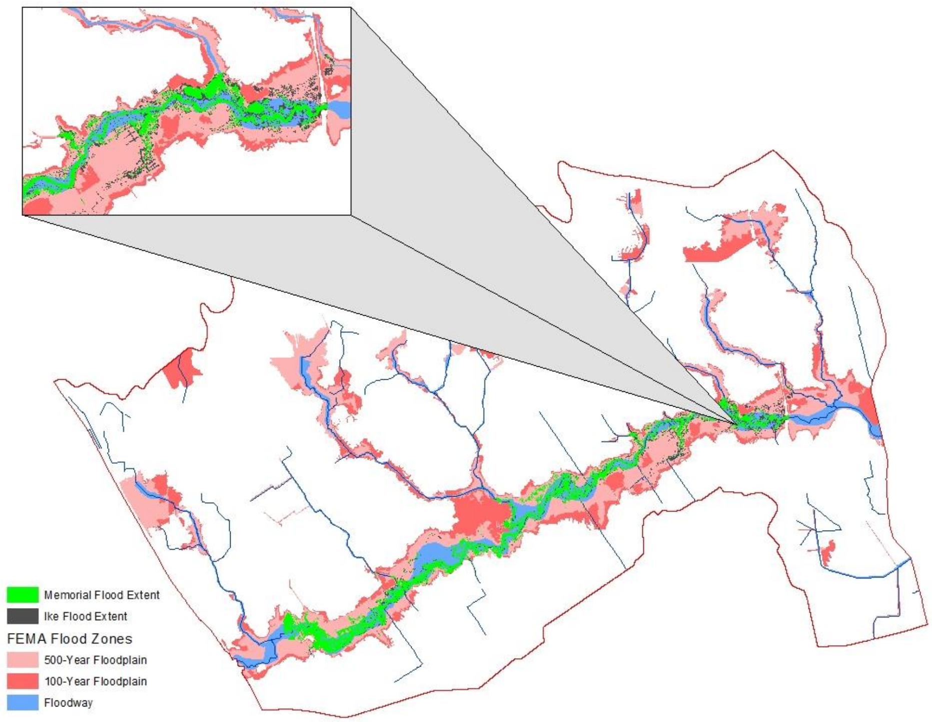

Figure 8. Memorial and Hurricane Ike floods

Summary

The research question was: "With the lack of zoning, had the amount of impervious surface increased and led to higher flooding frequency?" The amount of developed land increased by over 23% in the 10 years. While the increase in developed land has taken place, the research suggested that composite curve numbers have decreased on average. One explanation for this is that the land cover data were compiled from satellite imagery. When the satellites receive a software updated or a complete replacement, the ability to assess land cover data becomes more precise, and much of the guesswork is decreased. This could affect the composite curve numbers.

The data show that flooding in the 500-year flood plain, during all three events, appeared to be a continual issue for the residents of northern Harris County. One issue with the flooding analysis process was that the velocity model did not consider the ground cover type. Much of the AOI, was sheet runoff. Would the speed of runoff change if the region was wholly urbanized? It is difficult to say at this point. Many different factors go into the equation that each parcel of land needs to be ground truth before a blanket analysis is to be completed. Not all property is built entirely impervious. Driveways could use pavers that provide some percolation, and new flood control measures are created every fiscal year.

Overall the flooding between Ike and Memorial Day showed that each storm had different areas where the flooding wandered into the 500-year flood zone. When the rainfall amounts doubled, such as for Harvey, the 500-year flood zone becomes entirely covered by floodwaters.

Chapter 5 discusses the effects of what Harris County has developed to reduce residential flooding in flood plain development. Also, what are the implications for the future of the residents who do not opt for the voluntary buy-out program set forth by the Harris County Flood Control District?

Chapter 5: Discussion, Conclusions, and Recommendations

This study sought to determine if the rapid urbanization of the Cypress Creek watershed was contributing to the frequency and intensity of flooding events. Urban ecology generally does not examine environmental issues with the population as a contributing factor to the problem. But for the inputs to this study, human activity in direct action to the landscape was investigated. Urbanization constitutes a direct action to the environment, and to better understand these actions, GIS was used.

Spatial data were vital in understanding how the developed landscape increased over the 10 years. The land-use data provided critical information to the difference between the Memorial Day and Hurricane Ike floods. While Ike provided more rainfall than Memorial Day, the Memorial Day floods covered the same amount of land. This study did not cover the implication of climate shifts; there is a consensus that the rainfall amounts have increased with the tropical cyclones coming out of the Gulf of Mexico.

Since 2001, Houston has seen four major events, two tropical storms, and two hurricanes. Tropical Storm Allison dropped 37 inches of rain in 2001, and Tropical Storm Imelda released 44 inches of rain. Of the two hurricanes, Harvey was by far the larger producer of precipitation.

Floodplain Development Policy

Flood development is a policy regulation action and not a zoning action. The engineering office must set the regulation for floodplain development before the Harris County Commissioners Court can adopt the measure. These regulations are only for the areas that are not incorporated into the city boundaries of 34 municipalities. Most of the towns are in the southern or eastern portions of the county. Of the cities in Harris County, 10 are stretched across multiple counties. This leaves the Cypress Creek watershed void of official city limits. The areas are only place names for communities or zip codes.

The regulation set forth by the county only requires county engineering to focus on the 1% or 100-year floodplain provided by the flood insurance rate maps created by FEMA. The flood plains were created for Harris County in 2007 (Lindner & Fitzgerald, 2018) and were not updated until 2019 (FEMA, 2019). The need for updates on a more regular basis is required to keep up with the changes in the developed land. From 2008 to 2018, there was an increase of 27.13% in the urban environment. Under normal circumstances, this rate of development would be appropriate. But when dealing with a coastal county and high urbanization, the 500-year flood should have been included.

The current development plan is to avoid increasing flood levels or flood hazards (Blount & Smith, 2019). The focus is on the 100-year flood plain and structure heights, not necessarily on the region's dense construction practices. The regulation states that when building in the 100-year flood plain, the bottom of the structure should be elevated to the beginning of the 500-year floodplain. This elevation could range from 110 to 116 feet above sea level. In some cases, the structure would be elevated by 10 feet; many elevations in the 100-year flood plain are at 106 feet above sea level.

The AOI has seen an increase of 27.13% in developed land. Even with the focus on structure heights, the policy does not consider the amount of pervious land lost to impervious surfaces. Lot sizes play a role in the amount of runoff. A different regulation controls the development of property outside the flood zones. The Approval and

Acceptance of Infrastructure oversees the permitting process for land-use regulations. Even with the focus on structure heights, the policy does not consider the amount of previous land lost to impervious surfaces. Lot sizes play a role in the amount of runoff. Quarter acre lots only require setback distances and no regulation on coverage type and percentages of each lot (Blount, 2018). Outside of setbacks, there should be proper acreage for sewage services.

The regulations do not consider that all the property in the county is not connected to the natural drainage network. Previously, the velocity of the AOI was presented. There was minimal land without a speed for water to the drainage system. It can be considered that land in the watershed and how it is developed influences the developed land in or near the 100-year flood zone.

The county's purpose for flood plain management is to adhere to the National Flood Insurance Act of 1968: to protect human life and health; to avoid increasing flood levels or flood hazards or creating new flood hazard areas; to minimize public and private losses due to flooding; to reduce the need for expenditures of public money for flood control projects; to reduce the need for rescue and relief efforts associated with flooding; to prevent or minimize damage to public facilities and utilities and to aid the public in determining if a property is in a potential flood area (Blount & Smith, 2019). The flood zones updates occur every 20 years or so. How does the regulation stay up to date to the current landscape?

Interpretation of Findings

Hurricane Ike and Memorial Day floods dropped 14.21 inches and 13.5 inches, respectively. Memorial Day precipitation was almost an inch less of rain. There was also an 8.98% increase in developed land in the AOI. There was a clear correlation between the increase in developed land and the rainfall that became runoff. This extra runoff came from the lack of percolation due to impervious surfaces.

The findings between the storms provided clear evidence that the hypotheses could be validated. With the increase in developed land and almost one inch less precipitation, the flooding extents were practically similar in coverage on the landscape. Even with the increase in developed land, the CCN, on average, was less in 2008 than in 2015. The soils had not changed; the change comes from the advancement in technology. The developed increase allowed for the same flood extent, even with a difference of less than an inch of rain.

When precipitation occurs in a region, the water wants to be level. In this case, the slope of the landscape is toward the main creek and tributaries in the AOI. The higher the slope, the greater the water velocity. The closer the water is to one of the channels, the faster the speed is. Most of the AOI had the potential for a velocity of 0.29 m/s; some parts indicated that the velocity was less than 0.28 m/s. Localized flooding from pooling water can contribute to the continued build-up of the urban environment that has less than 0.28 m/s; this would decrease the soil's absorption factor.

The impervious surfaces captured the water until it swelled over the barrier. With large amounts of water, the pooling evacuation speeds were far higher than the calculation of the current velocity when fast water escaped, the barriers, whether natural or human-made, and the erosion process took place. Zoning regulations do not control the human-made structures. The control is in the flood plain construction design of the flood plain development policy.

The policy focuses on the development of land in the flood plain, mainly the 100-year zone. Localized flooding that takes place is outside the flood plain. One of the primary objectives of the policy is to protect personal and public property from losses. A flooding continues to be an issue away from the flood zones, the policy is left short of its goal.

Hurricane Harvey provided the most significant flood for the AOI in the last decade. The flooding covered the 500-year floodplain along the main channel of the drainage system. Harvey caused Cypress Creek to swell its banks and created a tremendous obstacle for any movement in and out of the watershed.

When comparing the extent of all three floods, Harvey's flood was in the 500-year flood plain the main channel of the drainage network and the 500-year flood plain in many of the tributaries. Much of the flooding covered roadways and bridges in most directions. For example, the bridge over Cypress Creek at Interstate 45 was in passable. This is a main road to the north for evacuation.

Inside the flood, there was a sheriff’s office and a hospital. Both entities are constructed inside the 500-year flood plain. These services are vital to the rescue of residents stranded in the floodwaters. The self-proclaimed “Cajun Navy” drove in from Louisiana to rescue people all over the county, but mainly in the north.

Limitations of the Study

The foundation of any study is the data. When comparing historical GIS data to a more current dataset can constitute changes in the data processing. Most lessons are learned after the fact. In the case of flooding, these lessons include collection methods and more collecting equipment. This is the case for Harris County, Texas.

During the flooding events of Hurricane Ike and Memorial Day, measurement stations were confined to the area around U.S. Interstate 45. Both floods showed a need for more stations along Cypress Creek. The monitor stations went from 13 during Hurricane Ike to 36 stations for Hurricane Harvey. The increase in stations shows that the county realizes the need to understand the landscape and land-use changes during rainfall. The increase in stations provides better coverage of the region, but this leaves gaps in the data compared to historical floods and contemporary floods.

The area of coverage for the study has also been hindered by older LULC data. The satellite data used to create the land-use dataset for 2008 was an older technology and out of date for current processing. This could be why there are higher increases in the curve numbers in the developed land from 2008 to 2018. The processing power of computer software is continually being updated and changed to provide a better product. The cost of going back and reprocessing the raw data is not feasible with current budgets.

The only interaction with the data was to process the information for the need for the study. Parcel data were used in the study. All information except for spatial reference was removed from the data before it was introduced into the study. The rest of the data were open-source data provided by government websites.

A considerable amount of time was used to explore the data. The conceptual framework contained processes based on hourly rainfall amounts. The datasets only contained total rainfall for each of the occurrences. This caused a minor shift in the process. Instead of basing the study on an hourly period, the process adjusted for the three events.

Overall, the limitations of the study were small. The older datasets and technologies provided a clear understanding of the changes in technology and how they might have hindered the original understanding of the landscape. Time was the biggest issue with this study. Time frames from when and what data were collected compared to the data collected that were only a few years old posed the most significant limitation.

Recommendations

Harris County has many different types of research-based studies. One of the limitations of this research was the primary focus was on flooding in urbanized areas. Coastal cities are generally large population centers and provide attractions for many tourists. Houston could be a study as a single unit or in a comparison study to other large metropolitan cities.

The Houston region is a mature urbanizing center. Rapidly growing coastal cities, such as Wilmington, North Carolina or Mount Pleasant South Carolina could use Houston and Harris County’s development practices and compare them to how they could handle development in floodplains. The results could help keep the citizens safe and control new practices to avoid flooding.

Evacuation Routes and Rescue Shelters

A local hospital and law enforcement offices in the region were underwater. What would the evacuation routes and rescue possibilities look like? Most major road networks flood in the county and, more notably, closer to the City of Houston. Five significant roads flooded, and the most important was Interstate 45. The highway was completely inundated. During Harvey, the Cajun Navy came into the region from Louisiana to rescue citizens from their homes. Many of these homes had never flooded before.

A study that contained the evacuation routes and spatial distribution of emergency shelters would provide valuable insight into new rescue and evacuation efforts. Many of the local public and private buildings were opened to flood survivors. The George R. Brown and Lakewood Church opened for relief efforts and places for people to house temporarily. Both locations are securely located in downtown or the Greenway district of Houston. The current system seems to lack the capability to shelter victims in the northern part of the county. Rescue and relief efforts in Harris County should be studied to the effect of a storm event that could be more intense than Harvey. While the storm amounts are hypothetical, the best way to plan for future events is to proceed with more extremes than the last occurrence.

Creation of New Hazard Zones

One focus for the future is to see how the development patterns continue with the current policies. The National Flood Insurance Act of 1968 highlights the creation of new hazard zones. When looking to the future, does the current policy abide by this mandate?

With rapid urban development, new hazards will be created. The focus would be on how to create development without increasing the hazards.

The current reduction in hazards is a reaction to the problem and not a reliable solution. To understand the problem and find ways to construct for the future and not a respondent to the land grab system currently in place, how would the State of Texas help relieve these issues to development without zoning? Much of the flooding in the county is due to restrictions placed on unincorporated areas of the state.

Buy-out

This research did not mention the voluntary buy-out of flooded parcels. The flood control district has identified a series of properties that have experienced multiple flooding events. As for many people, the property is tied to the belief of personal liberty and selling their home for flood control takes away that freedom. Repurposing the development of personal property for flood control could create a checkerboard effect on the landscape using the buy-out system.

A future study in this pattern could shed more light on the development practices and to a sense of place. The buy-out program, at its vital foundation, could dismantle historical neighborhoods. The local identity for older families could be lost. Inclusion would be the process of eminent domain. There would be a need for a qualitative study to look at the financial loss of the community, but also the loss of emotional stability.

Implications for Positive Social Change

Social change in metropolitan cities encompasses inequity and inequality. Many parts of this study looked to the urban environment for answers in flooding. At the core, inequalities and inequities were present. The idea of families being displaced from their homes and spending personal capital in rebuilding creates inequalities. If the personal, family, and community capital was not spent on rebuilding, in some cases multiple times, would there be a gap in some societal communities? Urban development is intended to increase capital and provide homes and services to citizens. When the citizens are continually rebuilding and now under pressure to sell the property to the county, the county risks the chance of losing the confidence of the citizenry in their ability to lead and keep them safe.

The county is dealing with a conundrum. Harris County waits to own property in the flood plains to correct the flooding issue. Still, it allows for land to be developed upstream. While saving human lives is essential, it is also important not to repeat the same mistakes in development. When communities can be constructed with current building constraints, what will happen 20 to 30 years from the time of construction? The communities will be established, and when the new buy-out comes along, it will dismantle social connections.

Outside of the financial burden placed on the displaced population, there are emotional hardships. There is no clear answer on how to fix the sense of place, but policies can be developed to eliminate such hardships. Social equity is vital to community development. When that equity has vanished, communities no longer flourish. Development can no longer be about here, and now, it needs to be for the future. By saving residents money in rebuilding and keeping communities secure from natural disasters, social equity will advance, and many health issues with flooding can be removed.

Summary

Harris County has attracted many different people for jobs, coastal living, and its diversity. This has led to land speculation, and the more it did, the better the economic base has become. As more people move to the region, Harris County will be running out of land to develop new residential communities. At the same time, the public transit system is not robust.

By having a directional heterogeneity transit society (Oller et al., 2017), Harris County residents rely on interstates and highways to circumvent the city for work and entertainment. When the region builds out from the city center, urban sprawl takes over the natural landscape. In the case of Harris County, urban sprawl occurs in the flood plains of the 23 bayous and creeks.

Since 2008 the amount of land cover for developed land has increased by 27.13%. The development has taken away the ability for the natural landscape to percolate water and ease pressures on the drainage networks. When a rainfall event occurs, we have seen that with an inch less water, a regular rainfall can produce that same flood capacity as a tropical cyclone. When the land does not absorb water, more runoff enters the streams and creeks. With the West San Jacinto Cypress/Spring confluence to the east, the water is captured in Lake Houston. The freshwater supply for Houston comes from this lake, which is nothing more than a reservoir. While the dam at the south end of the lake is rarely open, water will back up into the flood plains.

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