ABSTRACT

Title of Document: **Risk Analysis and Damage Assessment For Flood Prone Areas in Washington DC**

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This thesis presents a loss estimation method regarding areas of District of Columbia susceptible to flooding, specifically the Southwest quadrant, the National Mall, and Federal Triangle. This thesis develops data for input to a flood model that considers parameters such as detailed digital elevation data, global warming potential, and storm surge for a category IV hurricane. The main goal of this study is to employ a standard method for estimating flooding damages in Washington by supplying combination of the mentioned parameters to the HAZUS-MH 2.0 program. The results of this research is useful for planning purposes, such as reducing natural hazard losses and preparing emergency response and recovery. It is predicted that in the projected storm surge flood more than 1500 buildings would be damaged and about ten thousand people would seek temporary refuge in public shelters. The estimate of total loss for flooding is approximately $1,300 million dollars.

Key Words: Risk Analysis, Loss estimation, Potential Flood Risk in Washington DC

RISK ANALYSIS AND DAMAGE ASSESSMENT FOR FLOOD PRONE AREAS IN WASHINGTON DC

By

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Dedication

To my parents and my brother for their unconditional help and support

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Table of Contents

List of Figures

List of Tables

1. Introduction

This thesis uses standardized methodologies for estimating potential flood losses in flood prone areas of Washington DC. In this research the program HAZUS-MH 2.0 has been used to perform loss estimation for potential storm surge associated with a category 4 hurricane traveling directly up the Chesapeake Bay estuary toward Washington (FEMA, HAZUS-MH 2.0, 2011). The results of this study are intended for use by local, state, regional government to improve mitigation planning, emergency response, and recovery preparedness. The results are compared to the 100-year riverine flood risk on the Potomac River, which has been identified by FEMA under the National Flood Insurance Program. An integrated systems approach is used to identify and quantify flood risks based on HAZUS analysis.

1.1. Research Objective

The purpose of this study is to support analytical decision-making regarding the management of floodplain areas and the development of emergency plans. This is done by developing flood models for estimating flood losses. The estimation method consists of two processes. The first process considers hydrologic and hydraulic parameters. These parameters generate velocity and flood depth in spatial models. The second process considers damages to structures and all other inventories in the flooded region. These are implemented through a Geographic Information System (GIS).

1.2. Washington DC Hydrologic Concerns

Washington DC is located in the Chesapeake Bay drainage basin, between Atlantic Ocean and the Appalachian mountains, that has a moist climate. Precipitation is evenly distributed throughout the year, but can be elevated in summer due to short-duration storms with high-intensity winds. Topographic studies show that a large proportion of the city drains either toward Rock Creek in the northwest or toward the Anacostia River in the south (NOAA, 2006).

In the 1800's two major waterways drained into the low-lying regions of Washington: Tiber Creek and James Creek (see Figure 1). Tiber Creek was the largest stream in Washington at the time, draining 2,500 acres, or about 43 percent of the District. Tiber Creek ran south, beginning near the Armed Forces Retirement Home, through the site of the modern Union Station. Near the East Building of the National Gallery, it turned west and ran along Constitution Avenue for the length of the National Mall. At the base of the White House lawn, where it met the Potomac River, the Tiber was between 700 and 800

Figure 1 Critical reaches of downtown Washington, DC (NCPC, 2008)

feet wide. James Creek, in Southwest Washington, formed near where the Tiber turned west, and flowed southeast along modern South Capitol Street, broadening into a marshy area abutting the Anacostia River near Fort McNair (Heine, 1953).

By the 1870s, all the above waterways were essentially open sewers and were impounded. The DC Board of Public Works embarked on a massive sewer construction program by enclosing the creeks. The canals were buried and the resulting sewer system worked well until the late 1970s. In the early 1990s, the Water Resources Research Center of DC found that the ruined old canal beds still act as a conduit for water (Evelyn, February 8, 1894). This groundwater routinely infiltrates sewer pipes and building foundations along the former waterways. Renovation of these channels has been deferred for many years, due to the complexity of the restoration project and its cost, estimated at some $2 billion. This poor drainage system inhibits water from draining out of the region during heavy rainfall and has contributed to pluvial flooding in Federal Triangle (NCPC, 2008).

There are two unique situations that make flood control and stormwater management difficult. The first is the priceless monuments, museums, and national buildings located in the flood zone. The second is that a flood in in the nation’s capital could have significant impact on government operations.

1.3. Flooding Types for DC

There are three major types of flooding in Washington: overbank flooding, urban drainage flooding, and storm surge flooding. The first two are caused by rainfall or snow melt, and the last is related to hurricane surge.

Overbank flooding occurs when a large discharge of water flows down the Potomac or Anacostia River and the capacity of the channel is inadequate to carry it. Such flooding may also occur if the river is blocked. Urban drainage flooding occurs when a sewer system cannot handle the demand placed upon it. In the Washington pumps are needed to remove drainage water. Storm surge flooding in Washington occurs when the low pressure and wind of a hurricane pushes water up the Chesapeake Bay and into the Potomac estuary. This type of flooding has a large impact on the city and region and can cause severe damage (NCPC, 2008).

1.4. Global Warming

Current climate models project that the Earth could warm by two to six degrees Fahrenheit by the year 2100 (Showell, 1997).

Recent trends appear consistent with these predictions: the recent years have been the most intense storm periods on record based on the National Oceanic and Atmospheric Administration's hurricane season index (PEW, 2007). Scientists point out that global warming is making stronger storms (Ridder, 2004). The assumption is that a warming ocean allows tropical storms to pick up more energy and become more powerful (National Resources Defense Council, 2005). Another theory is that moisture levels in the atmosphere have risen 4 percent in the last 20 years thus increasing the potential for severe storms (Masters, 2011).

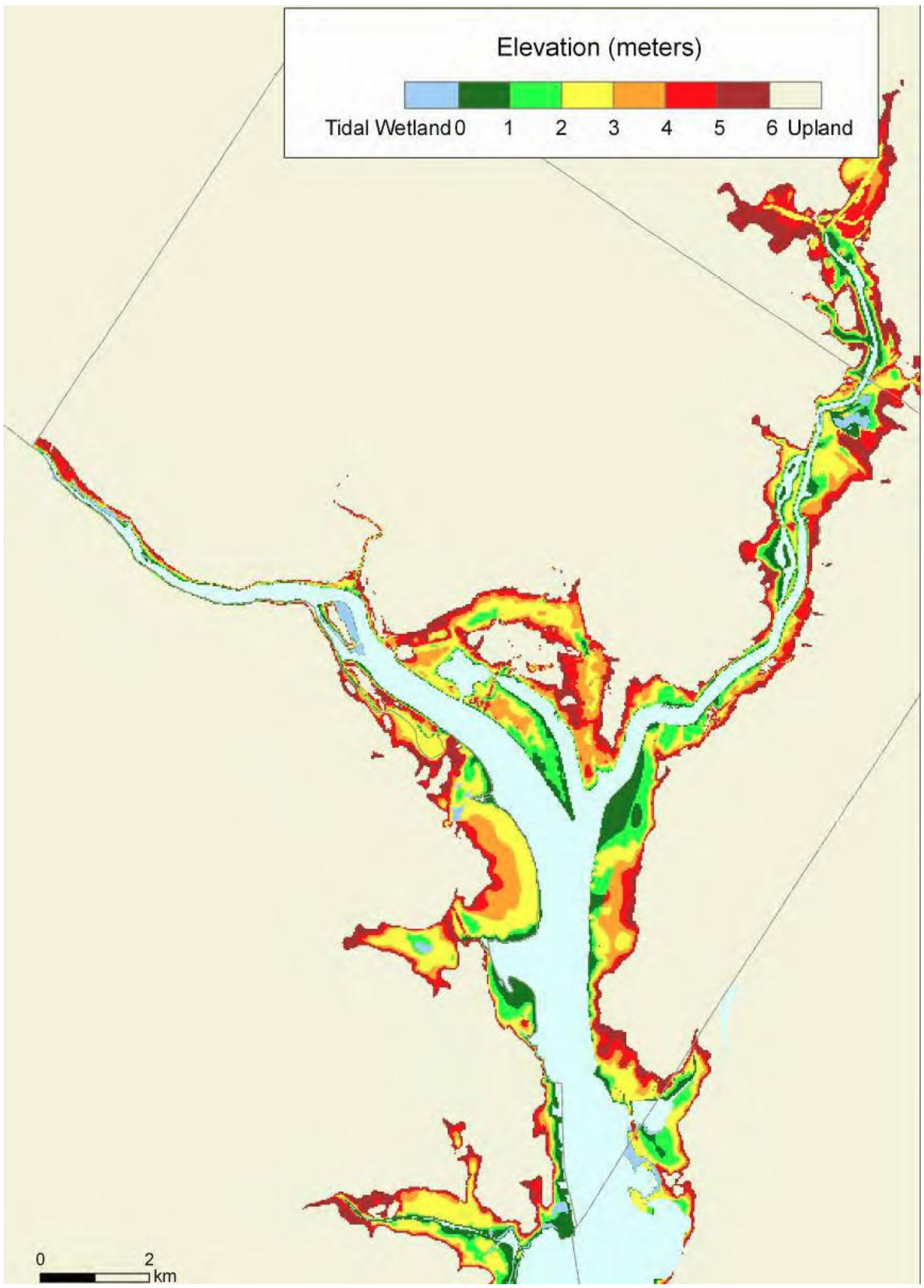
Global warming also raises sea levels by the expansion of warming ocean water and by the melting of polar ice sheets. Recent research suggests that the coastlines of North America and the nations of the southern Indian Ocean face the greatest threats from rising sea levels (Mitrovica, 2009). A median estimate according to the Global Warming Forecast by the Institute of Marine Sciences, is that water will rise by about three feet by 2025.

Data have shown that global warming causes sea level rise over the entire earth. According to the U.S. Geological Survey, the water level rise in the Chesapeake Bay and Potomac River in the DC area is at least one foot within next 25 years. Southern Washington, DC and Potomac River are included in this threat. This fact can increase the risk of flooding and tidal effects in the study region (USGS NWRC, 2011). Intergovernmental Panel on Climate Change (IPCC) estimated that global sea level is likely to rise about 25–75 cm over the next century. Along the mid-Atlantic coast, sea level rise is generally expected to be 10–20 cm more than the global average rise. IPCC also estimates that by the 21st century, global sea level could be rising 4–14 mm/year, which would imply a rise of 5–16 mm/year along the mid-Atlantic coast. (IPCC, 2007)

If sea level rises a foot or more, a major storm surge would push the Potomac River over its banks. The Arizona's interactive model of sea level rise represents estimation of two meters sea level rising in Chesapeake Bay and Washington DC by 2100 (Jensen, 2011). These are all fact to the point that sea level rise exacerbated flood risk of the Washington area. Therefore, the future flooding would be more intensive while they have shorter return period than the historical floods.

Figure 2 shows the Environmental Protection Agency (EPA) sea levels of the Washington DC. These elevations show projections of water rise in the area in meter scale. The water surface elevation for different levels are determined based on spring high water rather than fixed reference plane, so that the data set measures the magnitude of sea level rise required to tidally flood lands that are currently above the tides.

Figure 2 Elevations relative to spring high water: Washington, D.C., and vicinity (Titus & Wang, 2008)



2. Literature Review

This chapter introduces two approaches to define the floodplain in Washington DC. The first one approach considers storm surge hazard leads to flooding in the area. USACE has prepared a flood map that each hurricane category can produce in the region. Flood Insurance Study (FIS) is the second study which has been conducted by FEMA to introduce the official flood maps for 100-year and 500-year flooding of Washington, DC.

2.1. Strom surge hazard

The National Hurricane Program (NHP) has conducted Hurricane Evacuation Studies (HESs) for most US coastal communities impacted by tropical storms for the past 27 years. In 2003, Hurricane Isabel demonstrated that areas around the Nation's Capital are vulnerable to hurricanes and the various impacts are associated with tropical storm systems. Consequently, the NHP began the initial phase of a HES studies on this region. (USACE Batlimore District, 2009)

This 2009 study determines the intensities of hurricane that could strike the Washington region. This study contains hurricane categories one, two, three, and four based on the Saffir-Simpson scale (see section 2.1.4) of hurricane intensity. In this study the National Oceanic and Atmospheric Administration's (NOAA) Sea, Lake and Overland Surges from Hurricanes (SLOSH) model was used to produce storm surge map of the region.

2.1.1. Storm Surge

Storm surge is the abnormal rise of water level caused by a large scale meteorological disturbance. Sever hurricanes have the potential to affect a shoreline over distances of more than 100 miles and produce surges that can cause an extreme flood in a region.

Storm surge is produced by water being pushed toward the shore by the force of winds and by low atmospheric pressures within a hurricane (NHC, www.nhc.noaa.gov, 2011). Storm surge is a complex phenomenon because of its sensitivity to different factors such as intensity of hurricane, path of the storm, forward speed, and radius of winds. The heights of the surges also depend on basin bathymetry, roughness of the continental shelf, configuration of the coastline, and natural or man-made barriers.

Factors related to the surge flood elevation, or storm tide, are the initial water level within the basin at the time the hurricane strikes, and wave effects. The timing of the arrival of storm surge relative to the astronomical tide cycle can affect flood elevations. This difference in total flood elevation can be as much as 3 to 4 feet in the District of Columbia and Potomac River.

Another contributing factor to storm tide is the height of the waves themselves. The NOAA Sea, Lake and Overland Surges from Hurricanes (SLOSH) model does not provide heights of waves generated on top of the still-water storm surge. However, since a large portion of the Washington floodplain is away from shorelines, wave heights are negligible for this study region.

2.1.2. SLOSH Model

Sea, Lake and Overland Surges from Hurricanes (SLOSH) is a computerized model developed by the National Hurricane Center (NHC) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes (NHC, 2011).

SLOSH data for the Chesapeake Bay Basin, most recently updated in 2008, was supplied by NOAA. The SLOSH numerical storm surge model was developed by the National Weather Service to calculate potential surge heights from hurricanes. The SLOSH model was first conceived for real-time forecasting of surges from approaching hurricanes.

The Chesapeake Bay SLOSH model was used for the District of Columbia Storm Surge Mapping. After initialization with observed geophysical values (depths of water and heights of terrain and barriers), the SLOSH model output provides heights of storm surge for various combinations of hurricane strength, forward speed, and approach direction. Storm strength is modeled using the minimum central pressure and radius of maximum winds for four of the five categories of storm intensity. Because of their extremely low chance of occurrence, Category 5 hurricanes were not modeled for the Chesapeake Bay SLOSH basin. The SLOSH model simulates inland flooding from storm surge and permits flow through levee openings and current levee overtopping. The height of the water surface well before the storm directly affects the area of interest and is an input to this model.

The SLOSH model is a mathematical model and produces results only with some uncertainty. There are statistical analysis adjustments by the National Weather Service for this model. SLOSH results have been compared with those measured from the available meteorological data of historical storms to make any necessary adjustments. These adjustments represent the basin characteristics or historical storm parameters accurately. The model is accepted with a range of 20% accuracy compare with the real storm surge event. (U.S. Army Corp of Engineers, 2009)

2.1.3. Maximum Envelopes of Water (MEOWS)

The highest surges reached at all locations within the affected area of the coastline during the passage of a hurricane are called the maximum surges for those locations; the highest maximum surge in the affected area is called the peak surge. The location of the peak surge depends on where the eye of a hurricane crosses the coastline, hurricane intensity, basin bathymetry, configuration of the coastline, approach direction, and radius of maximum winds. The peak surge from a hurricane in the northern hemisphere usually occurs to the right of the storm path and within a few miles of the radius of maximum winds.

Due to the National Hurricane Center's (NHC) inability to precisely forecast the landfall locations of hurricanes, the NHC Storm Surge Group developed Maximum Envelopes of Water (MEOWs). MEOWs determine the potential peak surge at every location within the SLOSH basin.

Accordingly, MEOWs were produced by running the SLOSH model to create a group of storms, all having the same characteristics, but with parallel tracks 10 miles apart. At each grid square, the maximum surge value that was calculated was saved. The result was a "maximum envelope of water." Thus the MEOW is the "worst case" surge that could be produced at any location by a storm with a particular combination of approach direction, forward speed, and intensity, regardless of where landfall may have occurred. Since the MEOW is the "worst case" at all locations, no one storm will duplicate the flooding depicted by a MEOW. (U.S. Army Corp of Engineers, 2009)

USACE analyzed the results of the 248 MEOWs to determine which changes in storm parameters (i.e., intensity, approach speed, and approach direction) resulted in the greatest differences in the values of the peak surges for all locations, and those that could reasonably be combined to facilitate evacuation decision-making Changes in storm category accounted for the greatest change in peak surge heights. Careful consideration was given to the impacts of various combinations of storm parameters on hurricane evacuation planning and decision-making. To simplify these processes, the NHC was asked to compile additional MEOWs.

The NHC subsequently combined MEOWs to create MOMs (Maximums of the MEOWs), eliminating consideration of hurricane approach speed and direction, but maintaining the separation of categories 1, 2, 3, and 4. It was from those MOMs that the storm surge maps were developed for the District of Columbia and Northern Virginia area using high tide conditions. The storm surge heights that result from the SLOSH model for the Chesapeake Bay basin are referenced to the NGVD29 vertical datum. (U.S. Army Corp of Engineers, 2009) In the research method these elevation are converted to the NAVD88 to calculate the depth of flooding.

2.1.4. The Saffir-Simpson Hurricane Wind Scale

The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 categorization based on the hurricane's intensity at the indicated time. The scale – originally developed by wind engineer Herb Saffir and meteorologist Bob Simpson – has been an excellent tool for alerting the public about the possible impacts of various intensity hurricanes (Saffir, Saffir-Simpson Hurricane Scale, 1974). The scale provides examples of the type of damage and impacts in the United States associated with winds of the indicated intensity. In general, damage rises by about a factor of four for every category increase (R. A. Pielke, Jr. and colleagues, 2008). The maximum sustained surface wind speed (peak 1-minute wind at the standard meteorological observation height of 10 m [33 ft] over unobstructed exposure) associated with the cyclone is the determining factor in the scale. (Note that sustained winds can be stronger in hilly or mountainous terrain – such as the over the Appalachians or over much of Puerto Rico - compared with that experienced over flat terrain (C. A. Miller, and A. G. Davenport, 1998).) The historical examples provided in each of the categories correspond with the observed or estimated maximum wind speeds from the hurricane experienced at the location indicated. These do not necessarily correspond with the peak intensity reached by the system during its lifetime. It is also important to note that peak 1-minute winds in hurricane are believed to diminish by one category within a short distance, perhaps half a mile of the coastline (P. J. Vickery a. c., 2009) The scale does not address the potential for other hurricane-related impacts, such as storm surge, rainfall-induced floods, and tornadoes. It should also be noted that these wind-caused damage general descriptions are to some degree dependent upon the local building codes in effect and how well and how long they have been enforced. For example, building codes enacted during the 2000s in Florida, North Carolina and South Carolina are likely to reduce the damage to newer structures from that described below. However, for a long time to come, the majority of the building stock in existence on the coast will not have been built to higher code. Hurricane wind damage is also very dependent upon other factors, such as duration of high winds, change of wind direction, and age of structures. . For example, Hurricane Wilma made landfall in 2005 in southwest Florida as a Category 3 hurricane. Even though this hurricane only took four hours to traverse the peninsula, the winds experienced by most Miami-Dade, Broward, and Palm Beach County communities were Category 1 to Category 2 conditions. However, exceptions to this generalization are certainly possible.

Earlier versions of this scale – known as the Saffir-Simpson Hurricane Scale – incorporated central pressure and storm surge as components of the categories. The central pressure was used during the 1970s and 1980s as a proxy for the winds as accurate wind speed intensity measurements from aircraft reconnaissance were not routinely available for hurricanes until 1990 (Sheets 5. R., 1990). Storm surge was also quantified by category in the earliest published versions of the scale dating back to 1972 (National Hurricane Operations Plan, 1972) However, hurricane size (extent of hurricane-force winds), local bathymetry (depth of near-shore waters), topography, the hurricane's forward speed and angle to the coast also affect the surge that is produced (J. L. Irish, D. T. Resio, and J. J. Ratcliff, 2008). For example, the very large Hurricane Ike (with hurricane force winds extending as much as 125 mi from the center) in 2008 made landfall in Texas as a Category 2 hurricane and had peak storm surge values of about 20 ft. In contrast, tiny Hurricane Charley (with hurricane force winds extending at most 25 mi from the center) struck Florida in 2004 as a Category 4 hurricane and produced a peak storm surge of only about 7 ft. These storm surge values were substantially outside of the ranges suggested in the original scale. Thus to help reduce public confusion about the impacts associated with the various hurricane categories as well as to provide a more scientifically defensible scale, the storm surge ranges, flooding impact and central pressure statements are being removed from the scale and only peak winds are employed in this revised version – the Saffir-Simpson Hurricane Wind Scale. (The impact statements below were derived from recommendations graciously provided by experts in hurricane boundary layer winds and hurricane wind engineering fields (Marshall, 2009).)

2.1.5. Probability and Return periods of Storm Surge in Washington DC

Hurricane return periods are defined by NOAA as the frequency at which a certain intensity or category of hurricane can be expected within 75 nm (86 statute miles) of the location (NOAA NHC, 2011). For example, in the Chesapeake Bay on average during 210 years a category 4 hurricane passes within 75 nm (86 miles) of the location once. Table 1 shows the return periods and probability of occurrence of each hurricane category at least once in next 10 years for the Washington area. All probabilities are calculated based on binomial distribution (see section 2.3.1).

Table 1 Probability and return periods for all four hurricane categories in Washington DC

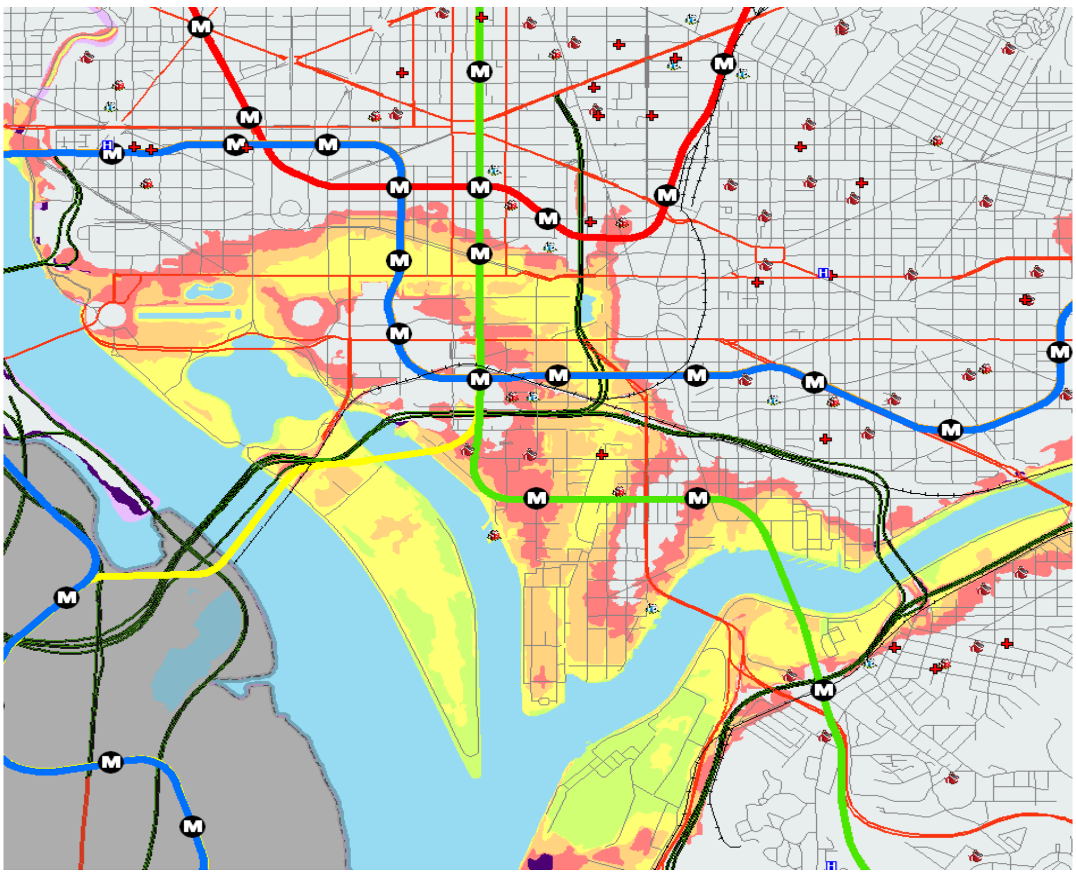
(NOAA NHC, 2011)

Hurricane Category	Storm Surge Map Color	Return Period (years)	Probability of occurrence al least once in next 10 years
Category 1	Green	15	49.8 %
Category 2	Yellow	43	21.0 %
Category 3	Orange	84	11.3 %
Category 4	Red	210	4.7 %

2.1.6. GIS Storm Surge Mapping

USACE has developed a hurricane storm surge GIS mapping process within the Model Builder environment of ArcGIS. This mapping process calculates the difference between Storm Surge Heights and elevation grids from the digital elevation map. The final product is a single polygon GIS file that represents the extents of inundation for all categories of hurricanes for the four standard intensities. Figure 17 shows the Storm Surge Map for Southern Washington DC. Green, yellow, orange, and red, respectively, represent Saffir-Simpson hurricane categories one through four.

Figure 3 Storm Surge Map due to four types of hurricane categories for Washington DC (U.S. Army Corp of Engineers, 2009)



2.2. FEMA Flood Maps

There are several approaches to flood studies, focusing on land use, emergency management, floodplain rules and regulations, and flood insurance. In downtown Washington the majority of studies have been made for insurance purposes. This section introduces The Flood Insurance Study (FIS) conducted under funding by the Federal Emergency Management Agency (FEMA). FIS is established based on actuarial flood risk in Washington in support of the National Flood Insurance Program (NFIP). The result of this study is a set of Flood Insurance Rate Maps (FIRMs) for the Washington region showing boundaries of areas expected to be flooded with probability p=0.01 and p=0.002 per year. (FEMA FIS, 2010)

2.2.1. Flood Insurance Study

A Flood Insurance Study (FIS) is a report that contains information regarding flooding in a community and is developed in conjunction with the Flood Insurance Rate Map (FIRM). The FIS, also known as a flood elevation study, frequently contains a narrative of the flood history of a community and discusses the engineering methods used to develop the FIRMs (refer to section 2.3). The study also contains flood profiles for studied flooding sources and can be used to determine Base Flood Elevations for some areas (FEMA Website, 2011).

FIS revises and supersedes the FIS reports and Flood Insurance Rate Maps (FIRMs) in the geographic area of the District of Columbia, Washington D.C. and aids in the administration of the National Flood Insurance Act of 1968 and the Flood Disaster Protection Act of 1973. (FEMA FIS, 2010)

FIS has developed flood risk data for various areas of the community that will be used to establish actuarial flood insurance rates. This information will also be used by D.C. to update existing floodplain regulations as part of the Regular Phase of the National Flood Insurance Program (NFIP), and by local and regional planners to further promote sound land use and floodplain development. (FEMA FIS, 2010)

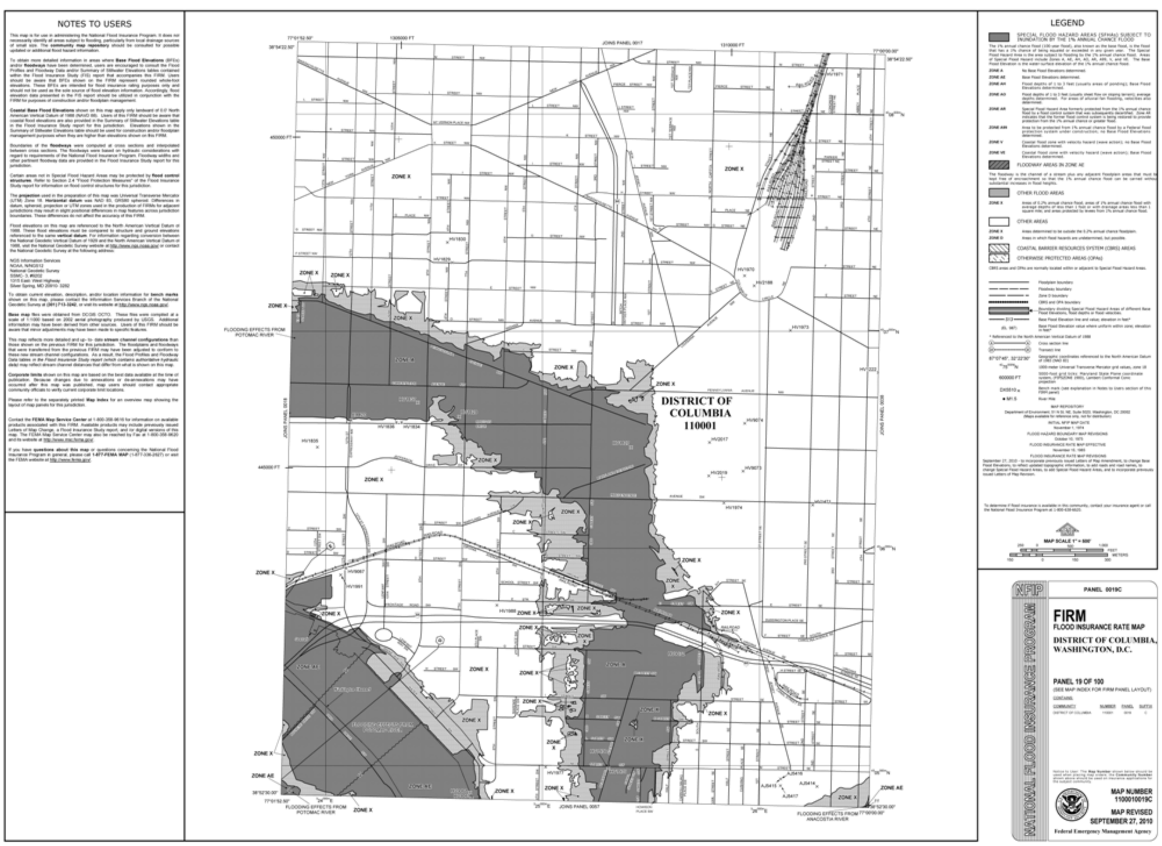
The base mapping for this study was obtained from the D.C.'s Office of the Chief Technology Officer (OCTO), which is responsible for implementing and managing the enterprise-wide geographic information system (GIS) for Washington D.C. The sources of authority for this Flood Insurance Study are the National Flood Insurance Act of 1968 and the Flood Disaster Protection Act of 1973. The hydrologic and hydraulic analyses for this study were performed by the U.S. Army Corps of Engineers (USACE) for the Federal Emergency Management Agency (FEMA). Coordination with City officials and Federal, State, and regional agencies, such as U.S. Geological Survey (USGS), D.C. Emergency Management Agency (EMA) and D.C. Department of Environmental Services (DES), has produced information pertaining to floodplain regulations, community maps, flood history, and other hydrologic data. (FEMA FIS, 2010)

Photogrammetry for this mapping has implemented based on aerial photography in spring 1999, and published in June 2002, and then updated in December 2004. The first meeting for the evaluation flood insurance studies was held in May 1979 by the Consultation Coordination Officer (CCO). The Department of Environmental Studies (DES) also served as D.C.’s coordinating agency for these studies. The results of the study project were coordinated with the U.S. Geological Survey (USGS) and the DES (FEMA FIS, 2010)

2.2.2. Flood Insurance Rate Map (FIRM)

FIRM is the official map of a community on which FEMA has delineated both the special hazard areas and the risk premium zones applicable to the community (FEMA, www.fema.gov, 2011). This map also indicated 100-year and 500-year floodplain area for insurance purposes. FEMA develops the maps in conjunction with the DDOW.

Figure 4 Revised FIRM, 100-year and 500-year Flood Map (FEMA, Dec 2010)



In March 2010, the last revised flood maps for Washington DC designed to help local officials and residents identify known flood risks and assist in making insurance and development decisions. In revising flood maps, FEMA believes that it works closely with local communities to ensure that any verifiable data and additional input that will strengthen the flood maps is included and incorporated along with detailed ground elevation data, decades of rainfall and storm gauge information, and engineering models. The dark grey area indicated in the figure above represents the 100-year flooding in the DC. The light grey is the associated floodplain of 500-year flooding in the area. The floodwater elevation of the 100-year flooding is predicted about 15ft above sea level.

2.2.3. Return Period

This study has considered five standard return periods for flood frequencies: 10-year, 50-year, 100-year, 200-year, and 500-year floods. These years determine the probability of a flood occurring in the given return period. The theoretical return period is the inverse of the probability that the event will be exceeded in any one year.

Probability function of flood frequencies is determined by the binomial distribution. If the probability of an event occurring is p, then the probability of the event not occurring is q = (1 − p). The binomial distribution can be used to find the probability of occurrence of an event r times in a period of n years. In this equation, r is the number of days that flood can occur, and n is the interval period that that number of floods may occur.

$$P = \binom{n}{r} \times p^{r} \times (1-p)^{n-r}$$

In order to find the probability of occurrence at least once in next n years the following formula may be used. This percentage is the reverse of probability that such flood not occurring within next ten years. (r = 0).

$P = 1 - (1 - p)^n$

For example, given that the return period of an event is 100 years, the probability of occurrence in each year would be:

$P = \frac{1}{100} = 0.01$ or 1%

Therefore, the probability that such an event occurs at least once within a 10 year is;

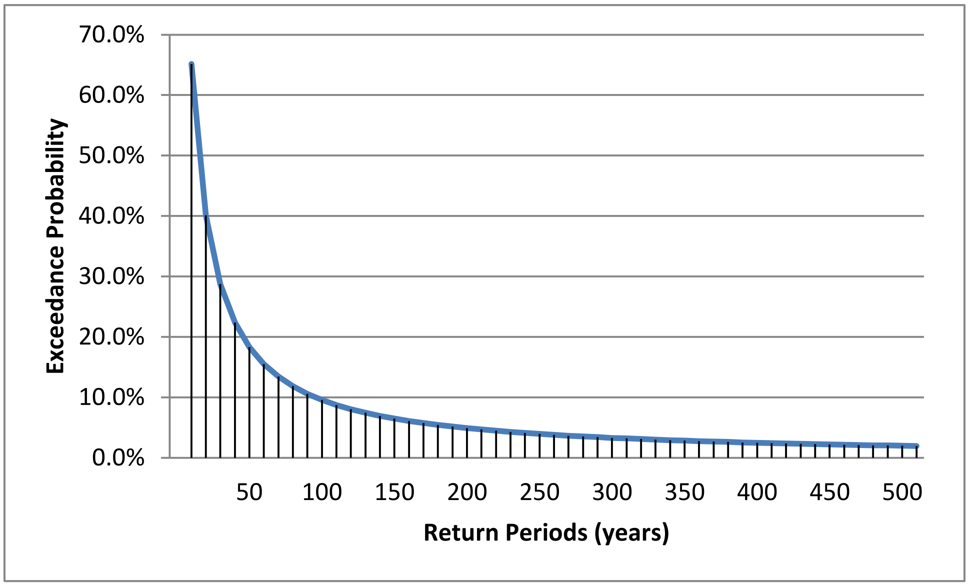
$P = 1 - (1 - 0.01)^{10} = 9.6\%$

Table 2 Return period and associated probability of occurrence

Return Period	Probability of occurrence	Probability of Non- occurrence	Probability of occurrence at least once in next 10 years (%)
10	0.1	0.900	65.1
50	0.02	0.980	18.3
100	0.01	0.990	9.6
200	0.005	0.995	4.9
500	0.002	0.998	2.0

Figure 5 also shows the diagram of probability that floods with certain return periods occur at least once within the next ten years for different return periods.

Figure 5 Probability of exceedance at least once in next ten years for each flood frequencies



3. History of Flooding in Washington DC

This Chapter contains an introduction of Washington DC in geographical and population point of view, and then describes history of flooding in the region since late 18's. Flooding in Washington can be caused by at least three phenomena: tidal and storm surge flooding, riverine flooding, and pluvial or drainage flooding. Amongst all storm surge or hurricanes has created the worst damages and fatalities in recent decades. These storms mostly occur in the month of September and during summers. A combination of tidal effects at the edge of Southwest DC, a low-lying area called Hains Point, where the Potomac and Anacostia Rivers join together, makes a potential for storm surge along the rivers from the Chesapeake Bay and fluvial flows. These surges can push the water upward through the city and make severe floodings.

3.2. District of Columbia

The District's location at the confluence of the Potomac and Anacostia Rivers, combined with three buried waterways, broad floodplains, and relatively flat elevations, renders it highly susceptible to periodic flooding. A large part of the National Mall and adjacent areas were originally underwater and were filled as L'Enfant's plan was realized. Urban development has increased impervious surfaces, reduced vegetation coverage, and further exacerbated flooding and stormwater runoff through the entire watershed. This problem is especially acute in the National Mall area given its downstream location. (NCPC, 2008)

Washington, D.C. is bordered by Maryland to the north and east and Virginia to the south and west. The city has a population of 601,723 and 272,636 houses. Approximately 40% of these houses are older than 1939 (United States Census Burea, 2010).

During the day, the population of the city swells to over a million, including government employees and tourists. The US government owns 23% of the land in the District (Bureau of Land Management, 1999). The presence of the U.S. federal government makes the city an important political center. Moreover, many of the nation's monuments and museums and 176 foreign embassies are located there.

The District has a total area of 68.3 square miles (177 km^2), of which 61.4 square miles (159 km^2) is land and 6.9 square miles (18 km^2) is water. A large portion of the city is urbanized and about 20% remains forested. The elevation of the city ranges from slightly below sea level at the National Mall to 414 feet at Tenleytown (Dvorak, 2009).

3.3. Hurricane of 1878

On October 23, 1878, a category 2 hurricane hit the Washington region. This is the strongest storm to ever his this region since record keeping began in 1851. (NOAA NWS, 2008)

3.4. Flood of 1889

The earliest large flood of record in D.C. was the flood of June 1-2, 1889 (U.S. Geological Survey Water, 1991). The Potomac River crested 12.5 feet above flood stage, flooding many areas of Washington (weatherbook, 2011). Flood in June 1889 reached a stage of 30 feet, from flood marks, discharge, 56,000 ft^3/s (USGS National Water

Information System, 2011). This flood is very well described by an observer quoted by U.S. Signal Corps (FEMA FIS, 2010):

"The waters of the Potomac rose higher (June 2nd) than ever before known. At about noon the water had risen until the tide gauges were hidden, and was fully three feet above the 1877 flood mark, and that was fully eleven feet above the spring-tide high water. The streets and reservations on the lower levels in the center of the city and all the wharves and streets along the river front were under water. Toward evening the water had begun to recede ... The flood caused great damage along the river front and on Rock Creek; the harbor improvements were injured and two spans 8 of the Long Bridge were washed away. Serious, if not irreparable, damage was caused along the length of the Chesapeake and Ohio canal, which was rendered entirely unnavigable throughout its entire length .... Considerable damage was caused to the machinery plants and material in the Navy Yard."

Figure 6 Pennsylvania Avenue during the Flood of June 2, 1889 (weatherbook, 2011)

3.5. Hurricane of 1893

On October 12-13, 1893, category 1 hurricane moved through the region (NOAA NHC, 2011). Heavy winds produced a 4 to 5 feet tidal surge up the Potomac River (Columbia, 2011).

3.6. Hurricane of 1896

On September 30, 1896, a Category 2 hurricane started near Georgia, but by the time its eye passed slightly to the west of Washington, the winds had dropped considerably and turned to category 1 hurricane. The storm buffeted the area with hurricane-force winds, causing extensive damage throughout the city and producing twelve fatalities. (NOAA NWS, 2008)

This hurricane began during the daylight hours of September 29, when the tropical storm moved through the Carolinas. By evening, the storm reached southern Virginia, then curved to the left and raced to the north at over 50 mph. In Washington, the southeast wind suddenly jumped from 30 mph to hurricane-force late in the evening of September 29 (NOAA NWS, 2008). According to the Schwartz's report, for the next two hours, the wind was "unparalleled in this part of the country, spreading destruction in every direction." Telegraph wires and city buildings began to succumb to the strong winds. Thousands of trees fell – many were snapped off 10-15 feet above the ground. Very few properties escaped having windows blown in or shutters torn off. Many major streets in the downtown area were blocked by fallen debris (Schwartz, 2007). Destructive winds were the main reason of damages in this hurricane because this hurricane didn't make any major flood or storm surge.

3.7. Floods of 1924

On March 28-30, 1924, intense rainfall and snowmelt runoff at the Potomac River caused five casualties and about four million damages for the Washington DC (R.W. James, 2011). Less than two month later, on May 12-15, another flood occurred in the Potomac Basin after several periods of rainfall in the banks of the Chesapeake (Columbia, 2011).

3.8. Chesapeake-Potomac Hurricane; 1933

On August 23, 1933, the hurricane tracked northwest through the Atlantic, passing south of Bermuda on August 21. It made landfall at Nags Head at 4:00 a.m. on August 23, with a central pressure of 28.50 inches. The storm then tracked between Norfolk and Richmond to just west of Washington at 7:00 p.m. on August 23. In Washington, the storm produced 50-mph winds, dropped 6.18 inches of rain, and caused the pressure to fall to 28.94 inches. (Schwartz, 2007)

The hurricane produced extensive tidal flooding of the Potomac River. A train crossing the Anacostia River was swept off its tracks by the floodwaters, killing ten people. In addition, four people drowned in their cars on the Washington-Baltimore Road when the Little Patuxent River went over its banks. An amusement park in Colonial Beach, located on the Potomac River, was completely swept away. The Washington-Richmond Highway was submerged under ten feet of water near Alexandria, Virginia. A total of eighteen fatalities were recorded in the Washington area as a result of the storm. The eye of the storm traveled up the west side of the Bay and just to the west of Washington DC. This allowed the storm's strongest winds to funnel water into the mouth of the bay and then northward right up the Potomac. (NOAA NWS, 2008)

This storm caused record high tides up the entire west side of the Chesapeake Bay and in Washington DC with damages the highest ever recorded from a storm surge. (Cobb, 1991) In Washington DC, the surge reached 11 feet. This storm caused a total of 14 deaths and $12.3 million (1933 USD, equivalent to $215M 2011) in damages to Washington area (R.W. James, 2011). This hurricane is best known for its huge tidal surge up the Chesapeake Bay and the Potomac River.

3.9. Flood of 1936

the greatest flood experienced since the flood of 1889 was at March 27-29, 1936. Earlier freezing and thawing resulted in the formation of thick ice throughout the eastern United States. Ice jams on the Potomac River were reported in January and February of 1936 (USACE 2005). Rainy weather in late February and early March caused floodwaters to rise again, but it was the extremely heavy rain on March 15 (over five inches in less than 12 hours) in the headwaters of the Potomac River falling on saturated and semi-frozen ground. This flood is known as the most severe ice-related flood which created the peak stage of 17.2 feet at Wisconsin Avenue. (FEMA FIS, 2010)

3.10. Flood of 1937

On April 25-28, 1937, northeaster1 accompanied by heavy rain caused widespread flooding in the entire region (Columbia, 2011). Northeaster (or nor'easter) is a type of macro-scale storm along the East Coast of the United States and Atlantic Canada, so named because the storm travels to the northeast from the south and the winds come from the northeast. This flood was the Third Largest flood after 1936 and 1889 Comparable to

May 1924 (FEMA FIS, 2010). Heavy rains were the main cause of this widespread flooding. Flooding on the Potomac was not as bad as the previous year, yet the river reached 14.3 feet at Wisconsin Avenue and portions of Alexandria and Arlington again flooded (NOAA NWS, 2008).

3.11. Flood of 1942

On October 13-17, 1942, extended rainfall at Washington caused overbank flooding at the Potomac River. Washington's rainfall was 6.27 inches, but 10 to 15 inches of rain fell to the west of D.C (weatherbook, 2011). The water stage at Wisconsin Ave has been 0.3 feet higher than flood of 1936 (FEMA FIS, 2010). The Potomac at Washington reached 17.6 feet, were flood stage was 7 feet. Tropical storm moved in across eastern North Carolina into central Virginia. Torrential rains fell from through the 16th in Northern Virginia and Maryland. Highways and bridges were washed away across the region. Hundreds of homes were flooded in Georgetown, and one person died. Transportation was interrupted for three days. Severe damage occurred to agricultural products. Flood losses on the Potomac River were $4.5 million dollars 1942 USD (equivalent to $60M 2011 USD). (Wilson, 2011)

Figure 7 Floodwaters reach to the steps of the Jefferson Memorial, October 17, 1942. (weatherbook, 2011)

3.12. Hurricane Able; 1952

Hurricane Able reached the southwest section of the District of Columbia in the early morning hours of September 1st. It was attended by heavy rains and winds of 30 to 40 mph with occasional gusts up to 50 mph. The peak gust reported at Washington National Airport was 60 mph. A tornado struck with destructive force at the Potomac River and caused flooding along Rock Greek (Columbia, 2011). Rainfall was ranging from 2 to over 3 inches. Property damage in the area was estimated to be in excess of $500,000 caused primarily by flooding for the DC metro area. Falling trees and branches disrupted power and telephone facilities. (NOAA NWS, 2008)

3.13. Hurricane Hazel; 1954

Hazel made landfall near Wilmington, NC by mid morning on October 15th and by that afternoon the eye of the storm was passing west of DC. This put the strongest winds across the city. Reagan National Airport recorded sustained winds at 78 mph with gusts to 98 mph. Gusts near 100 mph were common throughout the Chesapeake Bay region (Columbia, 2011). These records still stand today. Some of the installations were damaged. Huge damages caused by hurricane per se. There were 3 deaths in the District, 13 in Virginia and 6 in Maryland and many injuries. Over a half of a million of 1954 dollars (equal to $4.2M 2011 USD) in damage occurred in the District. Historical database shows that this storm was already extratropical when it moved through the area as it had already merged with a front, so it cannot be considered as hurricane, but a rather strong extratropical storm. This hurricane is also known as last storm to bring hurricane force winds to Washington DC (NOAA NWS, 2008).

Hurricane Hazel accompanied by Heavy rain flooded the Potomac River and its tributaries. In Washington, the rainfall was not particularly heavy. Only 1.73 inches of rain fell during the storm. A drought had been in progress and the rain was considered welcome. During the height of the storm, the rain was quite light with only a warm mist occurring during peak winds. However, the raging southeast winds caused water to back up on the Potomac and spill out of its banks in several locations. Many riverfront buildings were flooded in Alexandria, and Route 1 and Mt. Vernon Highway were inundated. In addition, floodwaters up to five feet in depth covered Hains Point. Dozens of small craft harbored at Potomac marinas were sunk or swamped by the wind and wave action. At least a half-dozen buildings were partially or totally unroofed by the winds, while others sustained damaged or crumbled walls. Countless trees were ripped apart or felled, blocking streets, crushing houses, smashing cars, and cutting power lines. In the city, nearly every streetcar line was blocked, due to fallen trees and limbs, forcing sanitation employees to work double shifts after the storm to clear the debris. On the Capitol grounds, twenty trees fell, and at the White House, two trees were blown down. In the immediate Washington area, 39 injuries were reported, with most injuries occurring from falling trees and shattering glass. (Ambrose K. , 2011)

3.14. Hurricane CONNIE; 1955

On August 13, 1955, the eye of Connie moved up the Chesapeake Bay. Two events within a 2-week period resulted in region wide flood damage from Rock Creek, Potomac and Anacostia River basins (Columbia, 2011). The storm's rainfall produced flooding on the Rock Creek, and on the Anacostia River. Connie dropped as much as 9.5 inches in Prince Georges County, MD, which is just outside Washington. The rains produced by Connie saturated the soil and set the stage for the devastating floods which followed the passage of Hurricane. 16 people were killed when a small boat capsized in the Chesapeake Bay. This hurricane caused damages total of $5 million in Maryland and Virginia. (NOAA NWS, 2008)

3.15. Hurricane Agnes; 1972

On June 22, 1972, devastating floods occurred from North Carolina to New York (NOAA NWS, 2008). In the Washington area, occasional heavy rains began around mid-afternoon of June 21, accompanied by a light northeast wind. During the evening hours, a constant deluge occurred punctuated by nearly continuous lightning and thunder. In a five-hour period nearly five inches of rain fell at National Airport. During the downpour, winds backed to northwest and strengthened to tropical storm force, reaching sustained speeds of 43 mph at National Airport, with gusts as high as 49 mph. Trees and branches fell throughout the area and wires snapped in the gale, cutting power and phones for tens of thousands of homes. (Ambrose K. , 2011)

10 to 14 inches of rain fell over a broad area of Virginia, Maryland and Washington. Major River flooding occurred on Potomac River Basins. At Wisconsin Avenue in NW DC, the river rose 15.5 feet making it third worst flood in 100 years of history (Columbia, 2011). Sixteen people in the Washington area were swept to their deaths in the swirling floodwaters. Most of drowning involved motorists that were

trapped in automobiles. At National Airport, Agnes' 24-hour rainfall total of 7.19 inches nearly broke the all-time record of 7.31 inches set in 1928 (Ambrose K. , 2011). A crest of 22 feet was reached at Little Falls, 10 feet above flood stage but about 3 feet below the record flood of March 1936. At Wisconsin Avenue, the river rose to 15.4 feet on June 24, 8 feet above flood stage, but 2.3 feet below the record flood of 1942. While the flood in the Washington area was not disastrous, it caused fairly heavy damage to both private and public property (NOAA NWS, 2008). In Washington, Rock Creek Parkway was closed as abandoned cars were strewn along its length. Likewise, Canal Road and the Whitehurst Freeway were closed, as were parts of Maine Avenue and Independence Avenue (Ambrose K. , 2011). This hurricane has been one of the costliest natural disasters in the national history with $2.1 billion in damages (NOAA NWS, 2008).

3.16. Hurricane David; 1979

On September 6, 1979, hurricane David spawned eight tornadoes across the greater Washington metro area (Schwartz, 2007). This hurricane caused 1.5 times the discharge having a 100-year recurrence interval (Columbia, 2011). Hurricane David resulted in five to six inches of rain north and northeast of D.C., which caused flooding along Rock Creek Parkway (USGS National Water Information System, 2011), as well as funnel clouds and tornadoes throughout the city. According to DC HSEMA, $374,000 in damage was caused. USGS (1991) reported that the Rock Creek discharge at Sherrill Drive gage was about 1.5 times the 1-percent annual chance discharge during that event. (Ambrose K. D., 2002)

3.17. Hurricane Juan; November 4-7, 1985

Hurricane Juan combined with stationary front. Isolated tornadoes were reported across Maryland and Virginia associated with this storm. This event is referenced as the “Election Day Flood”. Flood kills three people and hundreds of homes and businesses were destroyed (Columbia, 2011). $9 million damage along C&O canal and $113 million along Potomac is reported. (FEMA FIS, 2010)

3.18. Flood of 1988

According to DC HSEMA, up to five inches of rain fell in D.C. on May 5, 1989. Three people were killed, and hundreds of homes and businesses were destroyed (FEMA FIS, 2010).

3.19. Flood of 1996

On January 19-21, Flood along the Potomac River Basin raised water level up to 13.9 feet (Columbia, 2011). This flood is categorized as a snowmelt flood and it is the fifth highest flood on official record (FEMA FIS, 2010). Washington DC declared $10M in property damages (Columbia, 2011).

3.20. Hurricane Fran; 1996

On September 6, 1996, hurricane Fran made landfall near Cape Fear, North Carolina and weakened to a depression while moving through Virginia. Fran dropped up to 16 inches of rain in Big Meadows causing Record River flooding on the Potomac River and the Shenandoah River (Mayfield, 1996). Tidal flooding was also a problem on both the

Potomac River and Chesapeake Bay. A surge of 5.1 feet created moderate flooding along the Washington Harbor. Some areas in lower Georgetown and along the marina reported flooding. (Mayfield, 1996)

In this hurricane event, Nearly all major streams and rivers in the Potomac River basin experienced serious flooding during September 6-9, according to the U.S. Geological Survey. According to USGS scientists, the Potomac River at Washington, D.C., had a peak stage of 17.81 feet and a flow of 313,000 cubic feet per second (202 billion gallons a day) about mid night. By comparison, the peak of the January 1996 flood produced a flow of 347,000 cfs. During Hurricane Agnes, the peak flow was 359,000 cfs, and the highest peak flow of record was 484,000 cfs in 1936. (USGS, 1996)

3.21. Hurricane Floyd; 1999

Hurricane Floyd made landfall near Cape Fear, North Carolina on September 16th as a Category 2 hurricane. Floyd weakened as it moved swiftly along the Delmarva Peninsula. Heavy rainfall preceded Floyd over the Mid-Atlantic States due to a pre-existing frontal zone and the associated overrunning. Wind gusts of 50 to 70 MPH caused trees and power lines to come down. A 2 to 3 feet surge occurred along the Chesapeake Bay due to strong southerly winds blowing ahead of the storm. Minor flooding of low lying areas occurred in St. Mary's, Calvert and Anne Arundel counties. In Virginia, there were 280,000 people without power at some point. Total damages in Virginia reached $255 million with 64 jurisdictions affected. Three people lost their lives directly related to the storm. In Maryland, there was one death and over 250,000 customers without power at some point. (Schwartz, 2007)

3.22. Flood of 2001

On August 10-12, 2001, flood induced by heavy rainfall, 6 inches of precipitation in less than 3 hours happened in the region. This flood exacerbated by an undersized combined sewer system which resulted in the worst flash flood since 1944 (Columbia, 2011). According to the USGS report Rock Creek discharge at Sherrill Drive gage reached about 1.5 times the 100-yr discharge (USGS National Water Information System, 2011).

3.23. Hurricane Isabel; 2003

One of the most significant tropical cyclones to affect the Chesapeake Bay region since Hurricane Hazel in 1954 and the Chesapeake - Potomac Hurricane of 1933. Isabel made landfall near Drum Point on the NC Outer Banks on the September 18th as a strong category 2 hurricane with maximum sustained winds of 105 mph. Isabel will be remembered for the very large field of tropical storm force winds which caused a great deal of tree damage, the extensive flash flooding and the unusually high storm surge in the Chesapeake Bay and the Potomac River Basin. Fallen trees and limbs were the overwhelming reason for widespread power failures and damage and destruction to nearly 8,000 homes, which will likely made Isabel as one of the most expensive storms. At the peak of the storm, well over 2 million people were without power. Isabel is a reminder that if the impacts of a Category 2 hurricane can be so extensive, the impact of Category 3 or higher could be devastating. (Schwartz, 2007)

Rainfall totals were generally in the 1 to 3 inches across Washington metro areas. Isabel also caused an unusually high storm surge (6-8 feet above normal) in the Chesapeake Bay and Potomac River Basin. Storm surge in the Chesapeake Bay and the Potomac River reached the highest levels since the Chesapeake/Potomac Hurricane of 1933. In Georgetown at the foot of Wisconsin Ave., the water level reached 8.72 feet. The headquarters of the police and fire harbor patrol at Water Street were also flooded. (Schwartz, 2007)

Hurricane Isabel caused a system malfunction in the 14th Street pumping station. The Incident closed 395 in both directions for 48-Hours. One motorist required helicopter rescue and three cars were completely submerged under water. $125M in property damages, and winds 75-80 mph flooding on Potomac and Anacostia Rivers were reported. (Columbia, 2011)

3.24. Flood of 2006

On June 22-23, 2006, a low-pressure front caused heavy precipitation, resulting in localized flooding throughout the region. On June 19, 2006, a wet weather pattern started in Washington. Soon thereafter, from June 25 through June 27, intense tropical downpours inundated the District. The heaviest rainfall fell from early evening on Sunday, June 25, through the early morning hours of June 26, with a total recorded accumulation of 7.09 inches on June 25. The extensive flooding shut down operations at four key federal office buildings—IRS Headquarters, the Commerce Department, the Justice Department, and the National Archives. Several Smithsonian museums along Constitution Avenue also closed their doors. The National Gallery of Art closed due to a weather-related steam outage, and the National Zoo banned cars because of flooding in the parking lot. Rock Creek Parkway became impassable and had to be closed when Rock Creek overflowed its banks and flooded the road. (NCPC, 2008)

Constitution Avenue flooded on Sunday evening, June 25. Rainwater poured down the driveways of the 7th and 9th street sides of the building and flooded the transformer vaults and the subbasement areas. The two transformer vaults were submerged in up to eight feet of water. The freshly renovated (2004) William McGowan Theater, located under the Constitution Avenue steps, was also significant damaged. Flood water flowed down the theater steps, submerging the stage and the first two rows of seats. Electrical power went out immediately, but the sprinkler and security systems remained operational. Sump pumps continued to operate because of the emergency generator, but they were overwhelmed and had no place to pump the water. Fortunately, no original records were affected by the flood. (NCPC, 2008)

The IRS Building sustained the greatest amount of water damage, most likely because it has the lowest elevation. Rainfall flowing down Constitution Avenue spilled into the moats surrounding the building. The IRS subbasement, which holds all of the building's electrical and maintenance equipment such as electrical transformers, electrical switchgears, and chillers, was submerged in over 20 feet of water. Virtually all major building systems were affected and most of the equipment either had to be extensively rebuilt or replaced. The basement flooded with five feet of water. The fitness center, cafeterias, offices, systems furniture, carpet, ceiling tiles, computer equipment and vehicles garaged in the building were all destroyed. (NCPC, 2008)

The Smithsonian's Natural History Museum, American History Museum, the Smithsonian Institution Building and the Castle also were closed. PEPCO shut off power to those large government buildings because some basements containing electrical switch gears were flooded, and the buildings all share the same electricity network. The National

Gallery of Art also closed because flooding cut off the building's steam supply, which maintains air humidity levels necessary to preserve the artwork. (NCPC, 2008)

Shortly after the June flood, the General Service Administration (GSA) retained an independent, private consultant to ascertain its causes and to recommend solutions to prevent future flooding. The study was recently completed, although the results are not public. GSA summarized the report so that we could include the consultant's initial findings here. (NCPC, 2008)

In short, after interviewing DC WASA, the GSA consultant was unable to determine conclusively why the Federal Triangle area flooded so badly and so quickly. DC WASA was unable to provide an explanation as to why the flooding occurred. In categorizing the rain event, the consultant determined that over a 24-hour period the rainfall was equivalent to the expected rainfall for a 50-year storm event. However, over the most intense 6-hour period of the storm, the rainfall was equal to a 200-year storm. The capacity of the DC sewer system in the Federal Triangle area is unknown, as it was constructed before such standards were typically adopted. As a result, it would be easy to conclude that the storm exceeded the capacity of the sewer. However, the consultant noted that flooding started before the rainfall should have exceeded the sewer's capacity.

In addition, when the flooding dissipated, it also did so at a speed greater than what would be expected. Power outages caused the 12th Street pumping station to be inoperable, but DC WASA concluded that while a fully functioning pumping station would have offered some relief, it would not have completely ameliorated the severe flooding. The main pumping stations were operational during the entire storm. The Potomac River remained below flood stage during the entire storm, so backflow was not a contributing cause to the interior flooding. In summary, the flooding may have been caused by the extreme intensity of the rainfall over a very short period of time, but no one can be sure. The report to GSA includes recommendations for future flood prevention at each of the buildings that flooded. The report and these recommendations are under consideration by GSA management. This flooding caused $10 million in damages (NOAA NWS, 2008)

4. Past Flood Protection Measures

As introduced in chapter 3, flooding in Washington are categorized in three main groups: tidal and storm surge flooding, riverine flooding, and pluvial or drainage flooding. This chapter presents some of the historical measures undertaken to protect the city from these types of flooding. Protections include any preventive acts against flooding include National Mall levee, emergency acts and temporary closures at the Potomac River and west side of the Anacostia River.

4.2. Permanent portion of the National Mall Levee

Baltimore District Corps of Engineers has stated that three federal levees within the southern District of Columbia have not been maintained properly. These levees consist of levees between the Lincoln Memorial and the Washington Monument and the raised section of P Street, S.W. adjacent to Fort McNair. These levees either have not been maintained very well or they cannot protect city from flooding. Consequently, the levees do not meet the NFIP regulations anymore. Therefore, the risk of flooding and its destruction have been increased.

USACE began developing a solution for the National Mall overbank issue after flooding of 1936. They constructed a levee between the Lincoln Memorial and the Washington Monument in 1940 (NCPC, 2008). This levee was designed for a discharge of 700,000 cubic feet per second (cfs) in the Potomac River. It is estimated that the Potomac River's discharge during the 1942 Great Flood was 450,000 cfs when the maximum flood stage was attained. The maximum discharge of record for the Potomac River is 484,000 cfs, which occurred in March 1936 (USGS National Water Information System, 2011).

USACE estimated that an overbank flood of 700,000 cfs has a larger percentage chance of annual occurrence (two percent) than the 15.0-foot tide, which has less than a one percent change of annual occurrence. Consequently, Congress deemed that the USACE Washington, DC flood control measure (the levee) should be built to the 700,000 cfs design standard (NCPC, 2008). According to USGS, the maximum tidal gauge height was recorded at 17.72 ft (DC MLW) on Oct. 17, 1942 (see section 4.3).

According to USACE, a considerable portion of the levee was removed during World War II for Navy Department construction. Consequently, it is necessary to construct as much as 1,500 feet of temporary levee in three segments to provide protection to the height of the permanent works now in place.

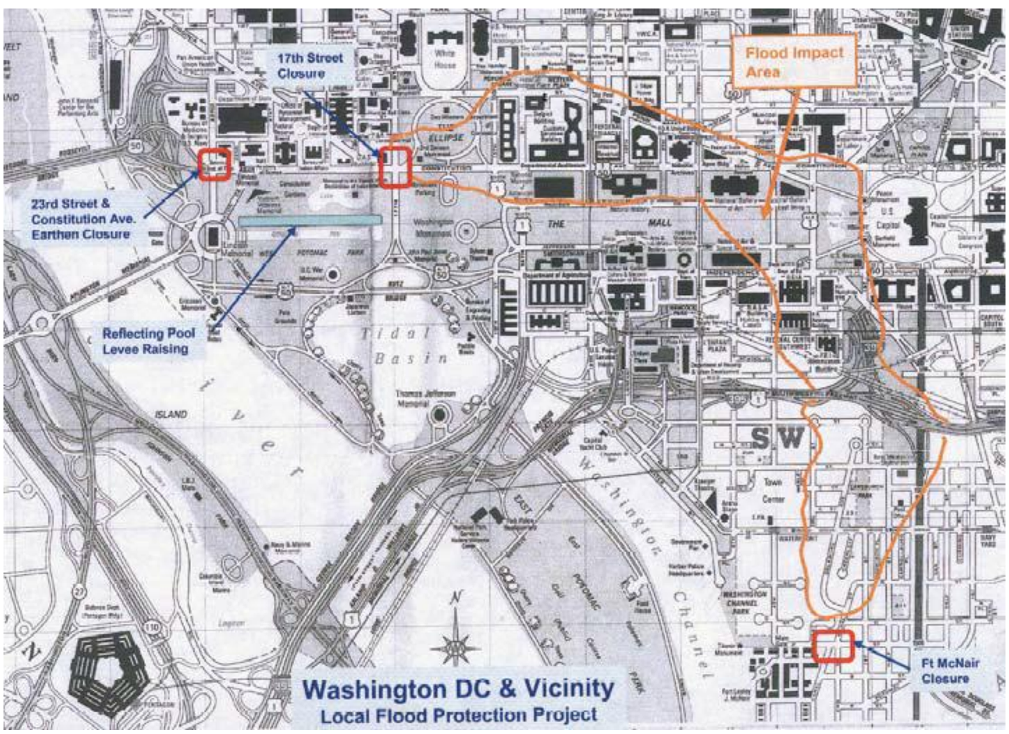
After Washington flooded again in 1942, new regulations authorized improvements to the levee to restore the level of protection and improve the levee's operation. The levee's overall effectiveness depends on implementing the 1946 improvements; however, due to lack of funding the levee improvements is remained incomplete (NCPC, 2008). At present, the project is unable to provide the level of protection it was designed to provide because in a flood emergency the levee's effectiveness relies on timely, complete, and correct construction of the three temporary barriers.

4.3. Temporary Closures of the National Mall Levee

To keep water from the Potomac and Anacostia River systems out of the downtown business district, the USACE erected an earthen levee along the north side of the mall, running from the Lincoln Memorial to the Washington Monument. This flood control measure relies upon temporary closures of several north-south streets, which constitute gaps in the levee.

The first opening is located at 17th Street and Constitution Avenue, N.W. In order to close this opening, a flood wall designed by USACE is currently in the construction phase. This flood wall is located at 17th Street, between the World War II Memorial and the Washington Monument. Other openings are at 23rd Street and Constitution Avenue, N.W.; and at 2nd and P Streets, Southwest. Figure 8 indicates the location of these temporary closures by red boxes and the boundary of the floodplain in orange.

Figure 8, Temporary Protection In Flooding (NFIP, 2008)



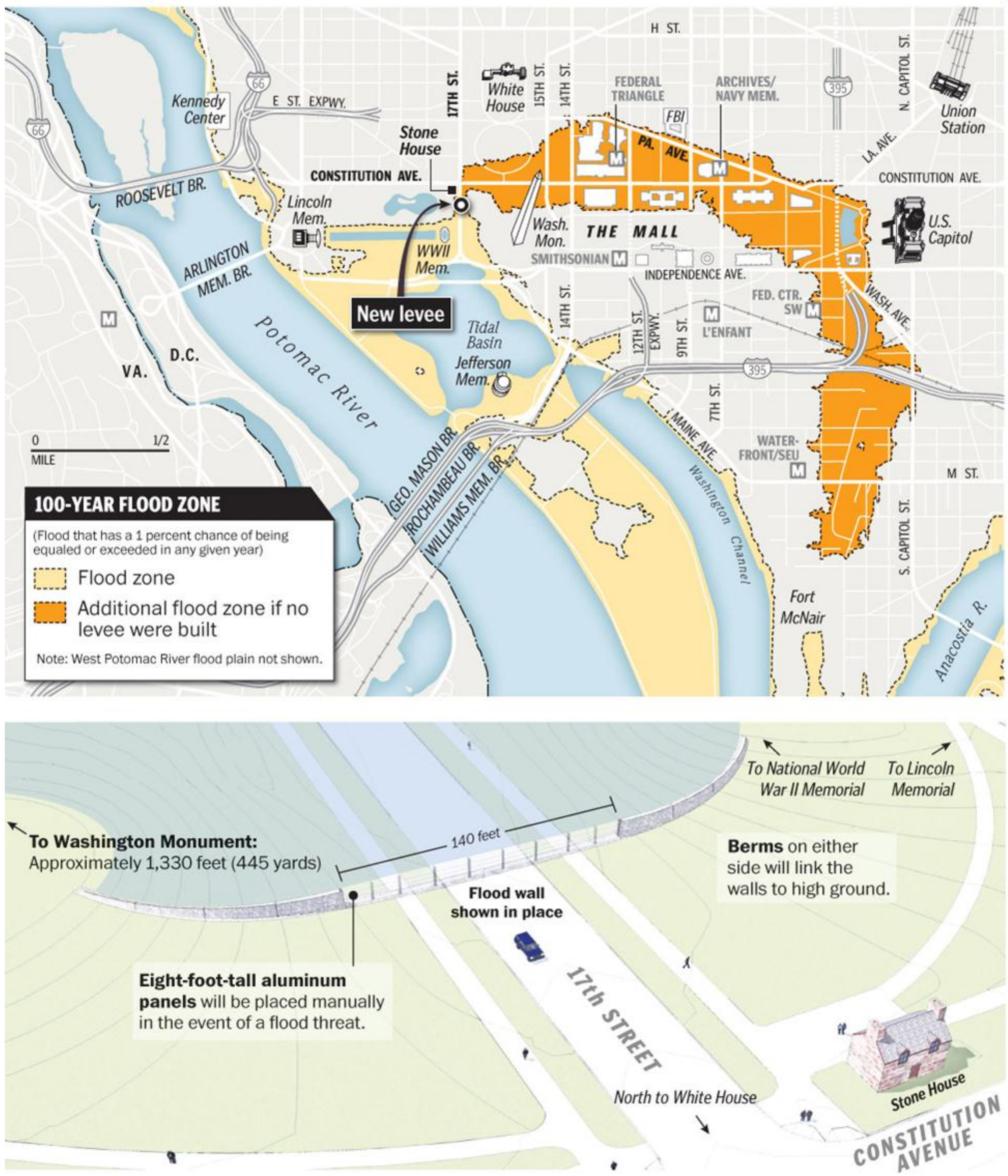
To make the levee more reliable, USACE proposes making two of the temporary closures permanent by extending the levee to meet the higher topography to the north. To ensure the continued flow of cross-mall vehicular traffic, the 17th Street closure would remain temporary, but the barrier would be redesigned to improve its effectiveness and ease of assembly. (NCPC, 2008) Following is more discussion about details of these temporary closures

4.3.1. 17th Street Floodwall

For the 17th Street USACE is now in the construction phase and they plan to finish the construction by the end of 2011. This wall provides protection for about 20 feet MLW. After construction of the earthen berm through Constitution Avenue between the Lincoln Memorial and the Washington Monument, a gap in the levee still existed at 17th street just south of Constitution Avenue. NPS was made responsible for a temporary barrier and sandbag wall during flood events at this location. After Hurricane Katrina, regulations became stricter. Consequently, FEMA proposed to create a 100-year flood protection barrier on 17th Street which would provide 100-year protection to Federal Triangle. Figure 9 shows the threat of flooding in the study area and the barrier which would prevent floods from going through 17th Street (the orange zone is the proposed flood area).

USACE, NPS, National Capital Planning Commission, and the District of Colombia joined together to decide on a permanent barrier at this point. Two major scenarios were considered: installing an inflatable dam, and elevating the land with an earthen berm (CE, 2011). The decision was a combination of temporary and permanent structures. The permanent portion is on both sides of the street and the temporary portion is across 17th Street and will be erected during flooding events to link the permanent floodwalls on both sides.

Figure 9 FEMA flood zones and the 17th Street wall location (washingtonpost)



The permanent walls consist of 24 caissons, each 32 inches in diameter, extending 30 feet to bedrock. The wall is concrete with a height of eight feet. The temporary portion is made by steel posts and aluminum panels which can be assembled quickly. The panels are 9ft tall at their highest points and 140ft long, and they have been designed to be assembled in flood events on the street. In normal conditions the temporary portion is open to let the traffic pass. The total length of the temporary and permanent wall is 450ft (Figures 10 and 11).

Figure 10 seventinth Street Flood Wall Location (National Park Service, Dec 31, 2008)

Figure 11 Schematic view of the 17th Street Flood Wall (National Park Service, Dec 31, 2008)

It is assumed that this flood wall will protect Federal from a 100-year flood. The Corps also proposes to fortify the portion of the levee along the Reflecting Pool by eliminating low spots. When all of the modifications are complete, the levee would have less than a one percent chance of being overtopped in any one year. The modifications will bring the top of the existing levee along the Reflecting Pool (between 23rd and 17th Streets) to a uniform elevation and increase the level of freeboard7 protection provided. (NCPC, 2008)

4.3.2. Fort McNair Closure

The Fort McNair is a temporary closure located in at 4th streets, DC Southwest, neat the Waterfront/Marina (see figure 6). The DC Emergency Management Agency is responsible for sandbag closure at P and Canal Streets when the Wisconsin Ave. river stage exceeds 23 feet MLW. In order to improver the reliability of Fort McNair closure, USACE proposed a permanent earth berm that would be 1.2 feet high and extend for 570 feet. (FEMA FIS, 2010)

4.3.3. 23rd Street Closure

NPS is to construct the emergency levee at 23rd Street when the Potomac River stage of 19.0 MLW or greater is predicted at the Wisconsin Avenue gauge. In 2000, USACE proposed making the temporary closures at 23rd Street permanent to improve the levee's design and reliability. USACE proposed a 600-foot earth embankment with a maximum height of 3 feet that would run along 23rd Street until it met the existing embankment for the Route 50 ramp. The topographic modifications would then complete the protection line at 23rd Street. (NCPC, 2008)

4.4. Anacostia River

The Anacostia River originates in Bladensburg, Maryland, where the Northwest and Northeast Branches meet, and flows southward for 8.4 miles until it runs into the Potomac River at Hains Point in Washington, DC. (NCPC, 2008)

Historically, the Anacostia was broad, deep, and meandering with thousands of acres of fully functional freshwater tidal marshes. In 1790, Bladensburg was a deep water port receiving ocean-going vessels. But less than 100 years later, sediment from agricultural activities in the surrounding area clogged the river channel and closed the river to navigation. During the past century, channel dredging and the consequent wetlands "reclamation" significantly altered the tidal river system's morphology. A stone seawall was built along much of the river's edge creating a hard line between the dredged river channel and the deposited fill material behind the seawall. (NCPC, 2008)

Currently, the hydrology of the Anacostia tributary system has a quick flow response to rainfall. In other words, stormwater or even moderate rainfall events can lead to intense flow conditions .Channelization of the Anacostia's tributaries, along with urbanization, results in higher runoff volumes that flow quickly into the mainstream. Conversely, in dry weather, the tidal river portion is sluggish, and water can languish for 100 to 110 days in drought periods. (NCPC, 2008)

There is less historical flood data and river flow measurements for the Anacostia River in comparison with the Potomac River because the Anacostia is tidal for its entire length. Due to the tidal effect on the Anacostia River's water level, the USGS can not collect stream flow data from the river's rise in the way that it is collected for a non-tidal river channel. The reason is that because Flooding along the Anacostia River usually only occurs when the Potomac floods and not independently. Potomac River flooding, because of the far greater size and reach of its watershed and stream volume, is a far greater threat to its surrounding area. Therefore, it has been monitored more closely in the past. (NCPC, 2008)

4.4.1. Anacostia sedimentation

Over the years, the riverbed has been silted in with dirt and debris carried by stormwater runoff from the river upstream. Sedimentation of the stream channel means that the riverbed can only contain a small volume of water. Rainfall or river flow displaced by the sedimentation will flood over the top of the riverbank. Therefore, even moderate rainfall has the potential to cause overbank flooding because the excess stormwater can not be conveyed carried by the river channel. Anacostia's tendency for sedimentation, and the significant upstream development in Prince George's County, that have resulted in more sedimentation in the Anacostia would likely result in higher flood levels in a storm event than previous events would indicate. (NCPC, 2008)

4.4.2. Anacostia dredging

In the late 19th century ACOE began channelization of the river and seawall construction to aid navigation and control flooding. Poor agricultural practices throughout the upper watershed reduced the Bladensburg seaport blocked and created extensive mud flats densely covered with grasses that trapped sewage and other waste. Because of water pollution and its contributed diseases, Congress directed the USACE to dredge the River and deposit the sediment on the mud flats to reclaim the land, provide sanitation, and promote navigation and commerce. (NCPC, 2008)

As a result, channelizing the Anacostia increased the speed and volume of the water during heavy rainfall. Increased river flow, in combination with a stone seawall has increased the severity of flood events in heavy rainfall events. Consequently, these changes cause flashy storm flows with a low base flow between storm events.

Urbanization increases impervious surfaces, which causes the storm flow to have higher peaks and greater volumes. Greater stream flow, in combination with channel modifications, increasingly deepens the stream channels, and cuts the stream off from the floodplain and its flood-mitigating functions. The increased flow and the deeper channel within the tributaries have an even greater capability to mobilize stream sediment and reduce or eliminate river bed features that help dissipate flow energy and slow the water down. However, because the Anacostia River is flatter in elevation than the Potomac River, alterations to its tributaries that cause sediment to become waterborne are a more significant problem. The sediment remains in the Anacostia River's streambed rather than washing further downstream, and, therefore, increases the flooding risk in the surrounding communities. (NCPC, 2008)

USACE built three levee systems in the District, as a result of the legislation. In the District, the Fort McNair levee, discussed in Section 4.3.1, protects the downtown business area from flood waters rising from the Anacostia. Fort McNair also is surrounded by an USACE-built seawall. In addition, there are two levees on the east side of the Anacostia that protect upland areas from Anacostia River flooding which is outside of the flood prone areas of this study. (NCPC, 2008)

4.5. Washington DC Emergency Flood Procedures

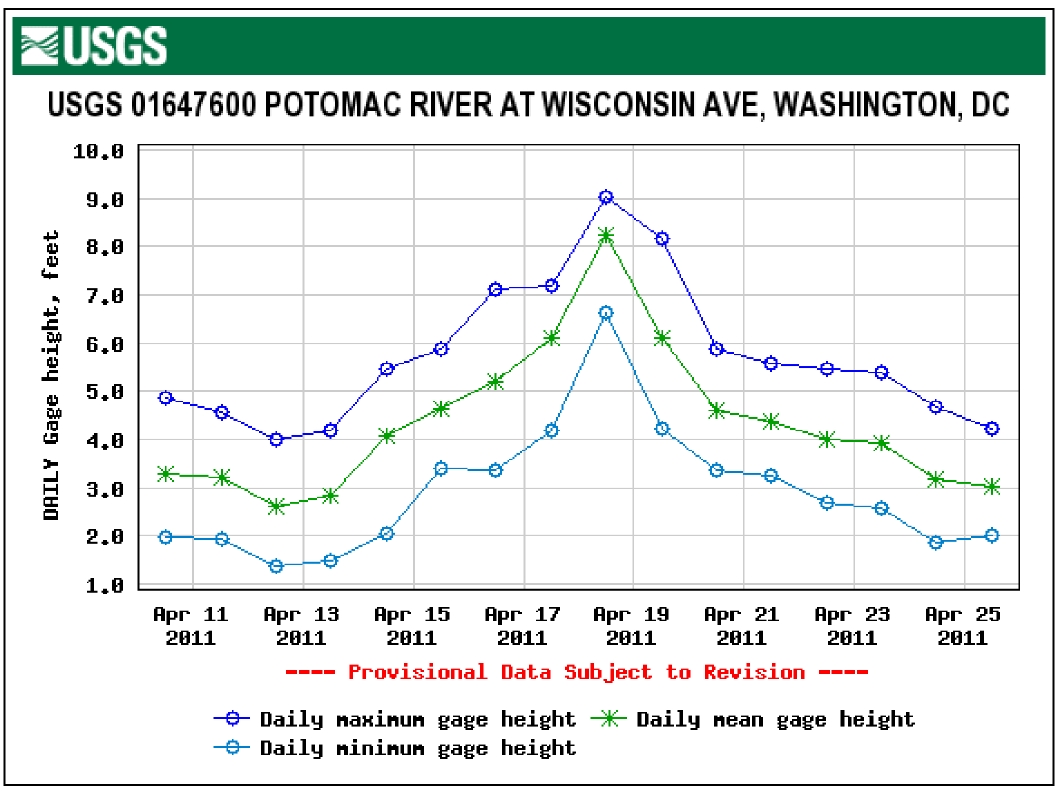
In the event of a storm, National Weather Service (NWS) forecasts are posted on the Washington Area Warning Alert System (WAWAS) and the National Oceanic and Atmospheric Administration (NOAA) Weather Radio whenever a Potomac River Stage of 7.0 feet mean low water (MLW) or greater is predicted at the Wisconsin Avenue gauge. MLW is the average of all the low water heights observed over the National Tidal Datum Epoch (Tides Currents, 2011). Simultaneously, the National Park Service (NPS) is responsible for placing temporary closures at 23rd Street, NW and at 17th Street, NW (see figure 6).

One of the most important components of this emergency system there is a water-stage recorder at Potomac River, along the Wisconsin Ave. This gage measures the mean low water level of the Potomac river located on the left bank at upstream end of Georgetown Waterfront Park, 0.6 mile upstream from mouth of Rock Greek, 0.08 mile downstream from Key Bridge, and at river mile 112.5.

The Georgetown harbor is just downstream of the Georgetown Waterfront Park. The harbor floodwall is privately owned and operated. As discussed in chapter 3 a failed emergency response led to overbank flooding in Georgetown waterfront in 2011 .Figure below shows this event following by the MLW information from USGS that shows how the water risen in May 18, 2011. Figure 8 shows the MLW records before and after the flood event.

Figure 12 Georgetown Overbank Flooding April 18, 2011 (www.tbd.com, 2011)

Figure 13 MLW of April 18th 2011, at Wisconsin Ave. Station (USGS National Water Information System, 2011)



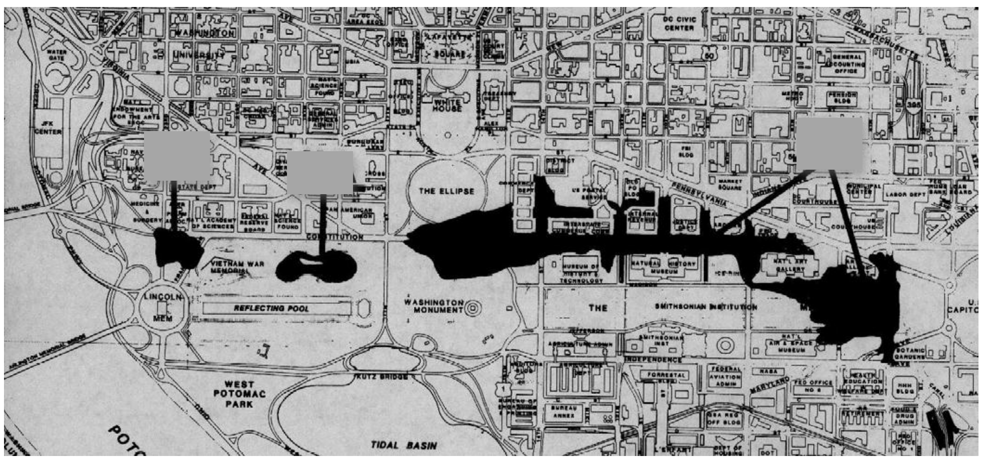
4.6. Drainage Flooding

When flooding occurs, the downtown Washington combined sewer system carries both raw sewage and storm water. This can easily exceed the capacity of the system. When it does, water spreads through the city. Furthermore, if the combined flow exceeds the capacity of the city's Blue Plains Treatment Plant, the sewage is not completely treated, water can flow through to the river, and thus violate the rules of Clean Water Act. The construction of storage tanks and tunnels is the primary solution for this problem and is both time consuming and expensive, but is underway.

Moreover, excess stormwater may be so great that that the sewer system can not even collect it, and then it floods the streets. The storage tunnel solution described above would not prevent street flooding caused by excess rainfall because the capacity of the sewers under the streets remains unchanged. The storage tunnel merely holds the water for future treatment once it is in the system; not increase the actual capacity of the old receiving sewer tunnels. One additional predicament is that when the river level rises above the outfall pipes, water can back up into the system and cause reverse flooding. This should be resolved by the gates that DC WASA installed at the outfall pipes, but there have been problems with the gates in the past either being open during a storm or not functioning completely. The tide gates at the outfall pipes specifically prevent backflow of river water to Blue Plains Wastewater Treatment Plant during high river levels. This protects the plant against treating extraneous river water. However, tide gates are not typically relied upon to protect life or property during river floods.

In those situations, a positive means of shutting off flow is used, such as sluice gates or stop logs. For example, in the current USACE Flood Emergency Manual for DC, locations are identified where stop logs are to be inserted in sewers to prevent backflow during river floods. USACE developed a map to illustrate the areas that would experience street flooding in a storm event that produced rainfall greater than what the sewer system could handle. This map (Figure 12) delineates the flooded areas corresponds almost exactly to the areas that flooded in June 2006. Consequently, it appears that interior flooding is a separate, persistent issue that needs a separate solution.

Figure 14 1990 USACE Map Showing Areas of Residual Flooding (NCPC, 2008)



4.7. Tidal Flooding Measures

Washington, DC is severely vulnerable to tidal surges and tidal flooding damage. Tidal flooding at Hains Point can produce the highest possible water levels in the city. The elevation of this water may exceed the current and future levees designed for the Potomac and Anacostia Rivers.

In 1955, a year after three successive hurricanes ravished the northeastern seaboard, Congress directed USACE to evaluate cost effective structural measures to reduce the human and property losses from future hurricanes. USACE prepared a report that evaluated the risk of tidal flooding in the Washington, DC metropolitan area and concluded that while the area was vulnerable to severe damage from hurricanes, the relief from tidal flooding by structural means could be accomplished by protective works needed for overbank flooding control. (NCPC, 2008). Based on conclusion section of this report, “The continuing encroachment on the tidal flats and floodplains of the Potomac River in the Washington area has seriously reduced the capacity of the stream to pass fluvial floods and absorb tidal floods without losses. Zoning regulations to stem the encroachment on the waterfronts and to establish future structures at safe elevations are needed.” (USACE Baltimore, 1963)

5. Approach and Framework of the research

5.2. Goal

The main goal of this study is to employ a standard method for estimating flooding hazards in Washington in order to make data available for planning purposes, such as reducing natural hazard losses and preparing emergency response and recovery. In order to get to this point integrated functions are practiced to make different scenarios. The aim of this study is to supply additional input data to the HAZUS-MH 2.0 program to get more practical information through Geographic Information System (GIS) functions for the study region.

5.3. Software Applications

There are a limited number of software programs that can be used for flood loss estimation. Among them, Flood Information Tool (FIT) and HAZUS-MH 2.0 are the most well known programs to make loss estimates for natural hazards, including floods, hurricanes, and earthquakes. FIT is designed by FEMA to process and convert locally available flood information to data that can be used by the HAZUS Flood Module (FEMA, www.fema.gov, 2011). These programs contain risk mitigation methods to analyze all aspects of different types of losses in the built environment. These aspects include population, building types, occupancies and specifications, traffic aspects, essential facilities, and any other inventories that can be damaged through flooding events.

These calculations always have some uncertainty because of incomplete knowledge of details and actualities that may happen in a real event. There are also some approximations in our analysis that depend on the accuracy of the input data. The input data used for this study has been adjusted for the DC area in order to get the best estimation of actual inventories and enhance the result's precision.

HAZUS is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes (FEMA, www.fema.gov, 2011). This study has taken advantage of HAZUS-MH 2.0 methods in order to utilize a modular approach to the loss estimation methodology. Version 2.0 is the last version of HAZUS which was released in April 2011 and updated in June of the same year. This software provides flexibility in supplying input data at various levels of analysis to get loss estimation results with different degrees of precision. The easy implementation, appropriate terminology and global definitions, user oriented structure, and GIS compatibility are the main features of HAZUS that make this software stand out in comparison to previous methods.

Although this software is the best and most reliable software that is available to date, it has limitations. However, these limitations do not have a significant impact on the methodology, as they will only affect a details of the analysis, and have a negligible impact on this study.

5.4. Standardization

This method follows all standard methods, most of which are described in the HAZUS definitions. The list below shows these standards.

1. Inventory data based on census block area data collection
2. Using the database Digital Elevation Maps (DEM) of terrain elevations
3. Arranging occupancy of buildings and facilities
4. Categorizing building structure type by occupancy and structure
5. Evolving building damage functions
6. Collecting, grading and analyzing lifelines
7. Using global terminology
8. Considering last updates and changes in the topography of study region
9. Delivering numerical results

5.5. Inputs of Method

A large amount of inventory data for the study region, southern Washington, is available by default with HAZUS software. Depending on the level of analysis, more accurate or detailed inventory data can be added or replaced with default data from the program. The more detailed the input inventory data, the more truthful the generated loss estimation results will be. A complete discussion of data inventory, sources, and classification of data is available in chapter 6.

The main inputs in the method part in flood maps. There are two flood maps discussed in the chapter 2 which derived from FEMA and USACE. The FEMA map shows the 100-year flood inundation area due to riverine flooding. The storm surge map shows the four different types of hurricane categories which can occur in the study region. The other important input is Digital Elevation from the USGS. This map provides ground elevation with one meter resolution.

5.6. Level of Analysis

In this study, the level of analysis is improved by providing more detailed information than normally available in HAZUS using the default settings. The purpose of doing this analysis is reaching the best estimates of flood damage losses. Using standardized methods, parameters from published reports and maps have helped this research create more comprehensive data in order to go beyond the previous analyses.

In some cases limitations had to be accepted because of the lack of detailed information. For example, damage/loss due to ground failure or erosion (riverine), damage/loss due to earthquake driven flooding such as tsunamis or seiche, and damage/loss due to dam failure are excluded from this method.

5.7. Loss Estimation Overview

Loss estimation analysis is estimating direct physical damage to buildings and their contents, exposure of facilities to flooding, and displacement of people by evacuation from inundation areas. Flood hazard and flood loss estimation analyses are two basic steps for estimation of flood loss that are discussed in the following sections. The first step is to identify the characteristics of flood and depth of flooding, which has been discussed in the following sections of this chapter. The identifying flood characteristic procedure include defining the study region, identify flood hazard, determining the topography and Study region, Generate stream network, develop scenario, and delineate floodplain.

The second step is to identify the damages of this flooding to all inventories in the study region. Flood model considers the number of units impacted by flooding. These units are called census blocks. The flood inundation is directly related to damage loss. In order to find the associated damage loss for each depth of flooding damage, functions have been used. These damage functions are developed by the Federal Insurance and Mitigation Administration (FIMA) cooperated with the US Army Corps of Engineers (USACE). The elements will be discussed in detailed in chapter 6.

5.8. Defining the Study Region

The first step of any run the analysis is defining the study region, the geographic area that will be analyzed. The study region contains all census tracts and census blocks in the southern area of the Washington. The method is based upon using census blocks as the smallest geographic unit, the smallest Census Bureau geographic entity. These blocks are generally areas bounded by streets, streams, and the boundaries of legal and statistical entities. Discussed effort in chapter 4 is made to make the census block as homogeneous as possible in terms of inventory data. Table 3 include all the census tracts and the blocks that have been selected for the study region.

5.9. Flood Hazard

The next step is to select flood hazard in examining for the DC community. This involves importing topography data, calculating stream networks for riverine hazard, and defining the flooding hazard. The riverine and coastal hazards have different requirements in terms of the development of the hazard and the digital elevation data required to support the analysis. Because DC in not in direct touch with the shorelines, it will be classified as

Table 3 Census Blocks Considered for the study region

Census Tracts & Blocks
110010057011000-1007, **110010057012**000 – 2008, **110010057015**000 - 5007
110010057021000-1013
110010058001000-1063
110010059001000-1012, **110010059002**000-2021
110010060011000-1027
110010060021000-1006
110010061001000-1024
110010062011000-1023
110010062021000-1167
110010063011000-1005
110010063021000
110010064001000-1007**, 110010064002**000-2032
110010065001000-1012, **110010065002**000-2024
110010072001000-1072

riverine hazard. Riverine flood hazard type will require a DEM that covers both the study region and all the watersheds that intersect that study region and will require developing stream network.

The Hazard of flooding in Washington refers to both the frequency and the magnitude of flooding. The frequency is measured by the return period of floods of a given size (the reciprocal of probability or chance). The chance of a flood occurring is determined by the probability of occurring flood in a given period. The magnitude of flooding is measured by discharge value, flood elevation and depth of the water. The relationship between flood depth and annual chance of flooding is called the depth-frequency curve which is the primary output of flood hazard modeling.

5.10. Defining Topography

Topography is the most critical element to the Flood Model. In this step we need map in order to identify the ground elevation and determine potential water flows through the area. The map should be in Digital Elevation Map (DEM) format. The most reliable source for an accurate DEM map is the United States Geological Survey (USGS). USGS gives us the National Elevation Dataset (NED) in different levels of detail for different regions. Due to the high level of importance of the DC area, a detailed map of this area can be found through this organization. The map available for DC is 1/9 arc-second map derived from Light Detection And Ranging (LIDAR) technology with an resolution of three meter contours.

LIDAR (Light Detection And Ranging, also LADAR) is an optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light, often using pulses from a laser. Generally the map is created by spacecraft's LIDAR mapping technology (Cracknell & Hayes, 2007).

The National Elevation Dataset (NED) is the primary elevation data product of the USGS. The NED is a seamless dataset with the best available raster elevation data. The NED is updated on a nominal two month cycle to integrate newly available, improved elevation source data. All NED data are public domain. The NED is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. NED data are distributed in geographic coordinates in units of decimal degrees, and in conformance with the North American Datum of 1983 (NAD 83). All elevation values are in meters and, over the conterminous United States, are referenced to the North

American Vertical Datum of 1988 (NAVD 88). The vertical reference will vary in other areas. NED data is 1/9 arc-second, resolution of about three meter (USGS, National Elevation Dataset, 2011).

5.11. Grid and Cells

As discussed before, DEM contains equally sized square grid points arranged in rows and columns. For example, a one Arcsec DEM map contains 30-by-30 meter-sized cells. The area of each of these cells would be 900 square meters, which is relatively large. In previous studies this kind of grid was used to determine the floodplain and run estimation an analysis, which might not lead to the accurate results. In this study the 1/9 Arsec DEM map is used to determine grid cells in 3-by-3 meters (3 meter resolution). This map is derived from the USGS.

Each cell has its associated elevation. The elevation of cells shows the ground level of the area. In flooding events, the difference between the water surface and the ground level of each cell is to be considered. As a result, we will be able to determine the mean difference of the census blocks. Choosing smaller dimensions for the cells will end in having more cells for each census block. Consequently, increasing the number of cells in the census block will give us the best mean estimations for the entire census block.

5.12. Determining the watershed

The present study has used detailed stream network and associated watersheds by applying 3-meter resolution DEM. It affects the study region drainage area that will be identified for hydraulic and hydrology analyses. The threshold drainage area depends on the accuracy of the DEM map. The more detailed map identifies the more precise stream reaches within the study region.

The watershed is divided into units called polygons. After specifying the polygons correlated to the watersheds in the drainage area we will define the chosen reaches. All non-defined watersheds will be eliminated from the calculation. The remaining default reaches are potential source reaches for flooding. These sources are parts of our stream that are located outside the study region area but which still affect the study region. There are some different reach categories used to run the hydrologic modules and formulas that all contributed to the water resources science but that are outside of my research study.

5.13. Generate a Stream Network

The next step is to generate a stream network, For developing the stream network it is required to chose a stream drainage area, which affects the stream density. Selection a small number for the drainage area such as 0.25 square mile in this research is led to a highly defined stream network. This value represents the total land area, in square miles, that drains into any given reach excluding that drainage at the starting node of the reach. The smaller the drainage area input, the more processing time required and the more detailed stream network will be resulted. As long as, the main focus of this study is only on the land area, not the river parts mainly, improper impacts of choosing this small number on Potomac River and Anacostia River would not affect the stream network.

5.14. Defining Scenario

A scenario defines the specific stream reaches and the hydrologic and hydraulic characteristics that are included in one analysis run. The reaches identify the positional waterways in flooding. Therefore, all the reaches that are located in the proposed floodplain by the SLOSH model have been selected.

5.15. Delineate Floodplain area

The goal of this part is to develop a stream network through the river and create flood depth and flood depth frequency information by giving essential data to the software. The result would be a GIS model which is in a grid format and specifies the flood depth for each cell. After selecting the goal reaches in the study region, the next step is to spread water through the area. The method of spreading water is a way of comparing the ground elevation with the water surface level. For those cells in which this amount is rationally close to zero we identify them as the flood plain boundaries. For those cells in which the water elevations are higher than the ground elevations, the model considers them as flooded cells. Gathering all of the flooded cells will result in the floodplain area.

This step has been done for both storm surge model and 100-year flood identified by FEMA. Identifying the floodplain area in each of these flooding is done by visual inspection method. In this method by identifying the boundaries of inundation area the similar flood has been translated into the HAZUS with all similar characteristics regarding depth of flooding and floodwater elevations.

Flood depth of each cell means the elevation of flood water surface minus the elevation of land in each grid cell. Both flood and ground levels are determined by the grid cell in the DEM map. HAZUS uses an algorithm to run the calculation for each grid cell and then determining the average flood level in each census blocks. The procedure is determining the land elevation at the center of each grid cell and then comparing that to the flood elevation. The difference between these two elevations would be the mean flood depth of a specified cell. This procedure would be repeated for all cells within a census block to determine the floodplain. The floodplain area is the area containing cells with flood surface elevations higher than their attributed ground surface. There are also some cells at the borders of the floodplain area that have a zero difference between flood and ground elevations. Those cells are known as floodplain boundaries.

6. Loss Estimation Mechanisms

This chapter describes estimating methods for damage to buildings, facilities, and vehicles located at the floodplain area. The discussion is mainly about the HAZUS loss estimation process for the flood model and parameters that has been considered throughout the process. The analysis includes calculation methods of flood damage to buildings and contents according to data such as occupancy types and first floor elevation. Generally, the estimation methodology is based on applying appropriate depth-damage curves to each inventory, such as buildings, facilities, and transportation systems, in order to calculate the dollar loss for each inventory type.

6.2. Input and Output Information

One of the most influential portions of the loss estimate methodology is the comprehensive inventory data for the study region. This information defines and evaluates building stock, infrastructure, and population of the floodplain area. These data are available for each census block in the software. Whenever more detailed data is available for the region it can be put manually into the software. Following sessions focuses on the classifications and types of data that are used in the method, followed by data that are added for the analysis.

In order to run the loss estimation model there are two groups of information needed for buildings; the first group is occupancy class, foundation type, and first floor elevation, and the second one is the depth-damage function for the associated census block.

Combining these two groups of information gives us the percentage of damages inflicted on each building.

As mentioned previously, the smallest unit of the study region is a census block. Therefore, rather than calculating the depth of flooding for each individual building, the average flood depth of each block is applied evenly to all of the buildings located in that census block. This process is called the area-weighted damage estimation method, which considers the variation of flood depth throughout the entire block to determine the average flood depth in the census block. This process also applies to the dollar exposure value of inventories in each unit. The total value of the buildings (inventory dollar exposure) in each unit is distributed evenly throughout the census blocks. Using these two data enables the software to use damage curves to determine the percentage of buildings damaged the block.

Comprehensive Data Management System (CDMS) is a tool developed for collecting and generating building inventory data to make an input for the HAZUS. This tool gives different inventory data for the region according to specified hazard types. For flood hazards, the most important information is about the first floor, foundations, garages and equipments. Therefore, using this tool helps us to classify data in order to import a large amount of data into HAZUS. Fortunately, CDMS has more suitable data specifically for floods, as opposed to earthquakes or hurricanes.

6.3. General Building Stock

The most important parameters used to estimate building losses from flooding include age of the building, foundation and first floor elevation, and building model type. It should be mentioned that the other parameters of buildings such as structure specifications, construction quality and design levels are not necessarily good measurements for vulnerability for building in flooding. In flooding, buildingss will not get damaged from their structures. Many times structures remain free of damage after inundation, more than 50% of the building survive even though their contents are damaged.

6.3.1. Building Age

One of the most important parameters that can affect a building's resistance against flooding is the age of the building. The performance of buildings decreases over time. Therefore, older buildings will probably suffer from flooding more than new ones. In this study there are lots of old buildings that developers have not really consider for flood resistance during their construction period. Therefore, in the DC area, it can be predicted that there will be relatively more residential building damage loss because of the number of old buildings remaining from the mid 1900's, especially in southwest DC.

Information about the age of buildings is derived from the U.S. census and Dun & Bradstreet (D&B) data. These data show the range of built years for the entire set of buildings in each census block. Therefore, analysis for all types of buildings such as commercial, residential, and industrial are done using the same distributed age throughout a census block. This analysis would work concurrently to take the age parameter into account evenly through each census block.

6.3.2. Model Building Types

For estimating the damages for these building, it is assumed that the value of the whole buildings in each census block is evenly distributed through the block. Therefore, by determining the percent of damage according to the average inundation of census block the damage can be calculated. The building stock contains five different types of data; Square footage by occupancy, full replacement value by occupancy, building count by occupancy, general occupancy mapping, and demographics.

Building structure is another parameter that usually used in hurricane and earthquake loss estimation methods; however, they can still be used in flood calculations. Generally buildings are divided into five structural systems: Wood, Steel, Concrete, masonry, and mobile homes are all various types of structures that are framed these buildings.

Wood structures usually are used in single family and multi-family houses. HAZUS consider two analyses for the wood buildings category. First category is houses that have area less that 5,000 square feet, which are classified in masonry type because they are usually constructed based on "conventional construction" provision rather than engineering calculation. Category two is wood structure buildings with area more than 5,000 might usually have some steel framing for strengthening the structure. The following section shows the detailed classification of these buildings.

6.3.3. Building Count by occupancy

Previously the building count data by occupancy was calculated by dividing the total square footage of buildings in each census block by average area of each occupancy type. This method could not give the exact numbers of houses exposed to the flood in the study region. Therefore, the new version of counting replaces the old one. In the new version the exact count of houses are considered and their number of units are available for residential buildings type I and II. For all other occupancy classification the building count derived from total square footage, by occupancy and by census block, regards to their associated assumed typical building size.

6.3.4. Building Classification

In the HAZUS flood model buildings are classified into 33 categories. The idea of this categorizing is grouping buildings with same valuation, damage, and loss characteristics in pre-defined groups. Table 4 shows all building categories and their associated Standard Industrial Codes (SIC). SIC is a classification code used in the development of the non-residential facilities.

Table 4 HAZUS Building Occupancy Classes

HAZUS Label	Occupancy Class	Standard Industrial Codes (SIC)
	Residential	
RES1	Single Family Dwelling	
RES2	Mobile Home	
RES3A	Multi Family Dwelling – Duplex	
RES3B	Multi Family Dwelling – 3-4 Units	
RES3C	Multi Family Dwelling – 5-9 Units	
RES3D	Multi Family Dwelling – 10-19 Units	
RES3E	Multi Family Dwelling – 20-49 Units	
RES3F	Multi Family Dwelling – 50+ Units	
RES4	Temporary Lodging	70
RES5	Institutional Dormitory	
RES6	Nursing Home	8051, 8052, 8059
	Commercial	
COM1	Retail Trade	52, 53, 54, 55, 56, 57, 59

COM2	Wholesale Trade	42, 50, 51
COM3	Personal and Repair Services	72, 75, 76, 83, 88
COM4	Business/Professional/Technical Services	40, 41, 44, 45, 46, 47, 49, 61, 62, 63, 64, 65, 67, 73, 78 (except 7832), 81, 87, 89
COM5	Depository Institutions	60
COM6	Hospital	8062, 8063, 8069
COM7	Medical Office/Clinic	80 (except 8051, 8052, 8059, 8062, 8063, 8069)
COM8	Entertainment & Recreation	48, 58, 79 (except 7911), 84
COM9	Theaters	7832, 7911
COM10	Parking	
	Industrial	
IND1	Heavy	22, 24, 26, 32, 34, 35 (except 3571, 3572), 37
IND2	Light	23, 25, 27, 30, 31, 36 (except 3671, 3672, 3674), 38, 39
IND3	Food/Drugs/Chemicals	20, 21, 28, 29
IND4	Metals/Minerals Processing	10, 12, 13, 14, 33
IND5	High Technology	3571, 3572, 3671, 3672, 3674
IND6	Construction	15, 16, 17
	Agriculture	
AGR1	Agriculture	01, 02, 07, 08, 09
	Religion/Non-Profit	
REL1	Church/Membership Organizations	86
	Government	
GOV1	General Services	43, 91, 92 (except 9221, 9224), 93, 94, 95, 96, 97
GOV2	Emergency Response	9221, 9224
	Education	
EDU1	Schools/Libraries	82 (except 8221, 8222)
EDU2	Colleges/Universities	8221, 8222

Each of these 33 building categories is also defined in five different construction groups. Wood, Concrete, Masonry, Steel, and Manufactured Housing are five general construction classifications. The height of the buildings and number of stories is one of the most important parameters for the damage curve functions. In order to classify the height of buildings in each construction types, they are classified in three sub-categories regarding Low-Rise, Mid-Rise, and High-Rise. Table below shows the range of stories for each category and their associated height.

Table 5 HAZUS Building Construction types

Number	Label/Description	Height Name	Range of Stories
1	Wood Frame	All	All
2		Low-Rise	1-3
3	Steel Frame	Mid-Rise	4-7
4		High-Rise	8 & up
5		Low-Rise	1-3
6	Concrete Frame	Mid-Rise	4-7
7		High-Rise	8 & up
8		Low-Rise	1-3
9	Masonry	Mid-Rise	4-7
10		High-Rise	8 & up
11	Manufactured Housing	All	All

Data available for each census block derives from the US Census and Dun & Bradstreet (D&B) data. In aggregating data process some of the reports from Department of Energy (DOE) are also used to define the more detailed characteristics of buildings, such as number of garages, type of foundation, and number of stories. HAZUS also use the information of the US Department of Commerce's Census of Housing in order to create final data usable in analysis inventory for residential structures,. For commercial and industrial structures the main database is from D&B, which is aggregated by Standard Industrial Classification (SIC).

6.3.5. Building Foundation Type

Foundations and associated first floor heights are among the parameters that could have a significant effect on estimation analysis. Foundations are generally developed in seven different types; pile, pier, solid wall, basement or garden level basement, crawlspace, and Slab-on-grade. Each of these foundations can have different behavior in a flood event. The information about building's foundation can be found from either the Housing Characteristics report or the Residential Energy Consumption report. Data used in this research is from the Residential Energy Consumption report which is relatively new (1997) and accurate.

6.3.6. Building and Contents Damage states

The methodology of the direct physical damage to buildings is relatively straightforward. Each census block has its own appropriate damage functions according to the occupancy classes. The depth of flooding is also calculated in hydraulic and hydrologic analyses in each census block. Using the damage curve function will give us the percentage of damage on the building. Multiplying this percentage to the cost of replacing the whole building will give us the final result that is known as estimated dollar loss.

There are different numbers of damage state ranges that are defined for the rescued buildings. These damage states are derived from the percent damage; for example 1-10% damage is considered slight, 11-50% damage is considered moderate, and 51-100% is considered substantial damage.

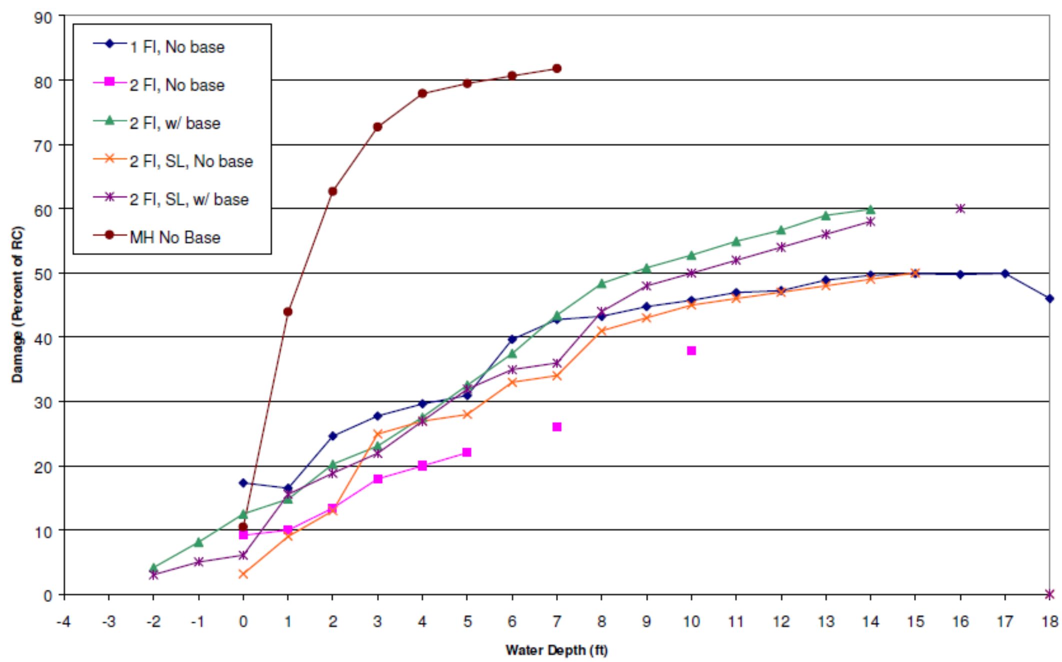
6.4. Damage Functions

As mentioned before, damage functions are tools to determine percentage of damages to buildings based on the depth of flooding. These functions may vary for different buildings according to their structural systems, architectural, mechanical, electrical components, and finishing. This study uses the available depth damage functions that have been created by different sources. The basic source of these functions is coming from Federal Insurance and Mitigation Administration (FIMA), and they have been developed and improved by the U.S. Army Corps of Engineers (USACE), and Institute for Water Resources (IWR) (DHS, 2011).

Damage curves are based on actuarial rate setting process which has been done by Federal Insurance Administration (FIA) and post-flood surveys conducted by Corps of Engineers. Some of the other initial Statistical damage curves has been developed from the early 1970 and created theoretical base tables. During years the actual cash value of losses to buildings and their contents are recorded by gathering flood insurance claims.

In some cases lack of enough information in one the two mentioned methods may cause to use them interchangeably. But generally, these functions are combined to each other and updated annually to verify most accurate damage curves. The following figure is an example of different damage curves based on damages occurred to the different stories of buildings.

Figure 15 Building Depth-Damage Curves according to different number of stories (DHS, 2011)



Damage curves are coming from seven different districts with different criteria that have been compiled by USACE. The structure and contents vulnerability are the factors that are considered in most of the districts. There are some other interesting factors like salt water and fresh water that may have different behavior in corrosions. There is also a variety of occupancy classifications that has major focus on important inventories like multi-family residence, professional businesses, public, groceries, gas stations, electric power substantial, schools and any other public areas that gives services to the public. These data are gathered by USACE Institute for Water Resources (IWR), and then they are used as an input to the HAZUS software. Table below shows different HAZUS's damage curve sources based on classification of building occupancy.

Table 6 Damage Function for Estimation of Structure Damage

Damage Functions for Estimation of Structure & Contents Damage			
HAZUS Occ. Class	**Flooding Type/Zone**	**Curve Source**	**Curve Description for Structures, and Contents**
RES1	Riverine/ A- Zone	FIA "credibility-weighted" depth-damage curves (CWDD)	Residential contents – 1st floor only (for 1 floor, no basement) Residential contents – 1st floor and above(for 2 floor no basement, and 2 floor, split level, no basement)
	Riverine/ A- Zone	Modified FIA CWDD:	EQE-modified versions of FIA CWDD: Residential contents – 1st floor and above (for 2 floor, w/ basement, and 2 floor, split level, w/basement)
	Coastal/ V- Zone	FIA V-Zone Damage function	Combined curve (average of with and without obstruction)
	Coastal/ A-Zone	FIA V-Zone Damage function	Contents – Residential – Mobile Home
RES2	All Zones	FIA CWDD	Contents – Residential – Mobile Home
RES3	All Zones	USACE Galveston	Apartment contents
RES4	All Zones	USACE – Galveston	Average of "Hotel – Equipment" and "Motel Unit - Inventory"
RES5	All Zones	N/A	No RES5 curves available – use RES6
RES6	All Zones	USACE – Galveston	Nursing Home –Equipment
COM1	All Zones	USACE – Galveston	Average of 47 retail classes – equipment and inventory, when available

COM2	All Zones	USACE – Galveston	Average of 22 wholesale/warehouse classes – equipment and inventory, when available
COM3	All Zones	USACE – Galveston	Average of 16 personal and repair services classes - equipment and inventory, when available
COM4	All Zones	USACE – Galveston	Average of “Business – inventory” and “Office, equipment”
COM5	All Zones	USACE – Galveston	Average of Bank inventory and equipment
COM6	All Zones	USACE – Galveston	Average of Hospital inventory and equipment
COM7	All Zones	USACE – Galveston	Average of 4 medical office/clinic classes, inventory and equipment, when available
COM8	All Zones	USACE – Galveston	Average of 13 entertainment & recreation classes, inventory and equipment, when available
COM9	All Zones	USACE – Galveston	Average of 3 theatre classes, equipment
COM10	All Zones	USACE – Galveston	Garage, inventory
IND1	All Zones	USACE – Galveston	Average of 16 heavy industrial classes, inventory & equipment, when available
IND2	All Zones	USACE – Galveston	Average of 14 light industrial classes, inventory & equipment, when available
IND3	All Zones	USACE – Galveston	Average of 10 food/drug/chemical classes, inventory & equipment, when available
IND4	All Zones	USACE – Galveston	Average of 4 metals/mineral processing classes, inventory & equipment, when available
IND5	All Zones	N/A	No IND5 curves available – use IND3
IND6	All Zones	USACE – Galveston	Average of 8 construction classes, inventory & equipment, when available

AGR1	All Zones	USACE – Galveston	Average of 3 agricultural classes, inventory & equipment, when available
REL1	All Zones	USACE – Galveston	Average of "Church" inventory and equipment
GOV1	All Zones	USACE – Galveston	Average of "City Hall" and "Post Office" equip.
GOV2	All Zones	USACE – Galveston	Average of "Police Station" equipment and "Fire Station"
EDU1	All Zones	USACE – Galveston	Average of "School," Equipment and "Library,"
EDU2	All Zones	USACE – Galveston	Average of "School," Equipment and "Library,"

The damage caused by the velocity is more than the damage only caused by the inundation. HAZUS classifies velocity damages only when velocity is more than two feet per second. Fortunately, the most severe potential floods in the DC would not have a considerable velocity; therefore, damages will be caused only by inundation. There are some functions based on the amount of velocity, depth of flooding, building material and number of stories that determines the collapse thresholds for the buildings; consequently, if the parameters exceed the thresholds buildings will collapse and the damage loss for those buildings would be 100 percent.

6.5. Induced Damage for Debris

Debris disposal include any scattered remains of destroyed buildings and their contents from flooding. Therefore, major content of debris is coming from building finishes, structural components, and foundation materials, and any types of furniture.

The methodology of damage estimation for debris is to identify components that are needed to be replaced in various depth of flooding. The next step is estimating the weight of destroyed components. These weights are considered as an average weight of typical model building types. These analysis are highly depends on the buildings and data input that are discussed in previous sections for building classifications.

This model uses tables that determine weight of debris in tons per thousand square foot based on the depth of water, occupancy type and foundation type. Finishes, structures and foundations are three different categories of debris that their weights are specified for each flood depth and building type. Foundation is also classified into two types, slab-on grade, and footing. It should be mentioned that HAZUS doesn't calculate vegetation, sediments and other natural debris loads that are carried by flooding.

6.6. Lifeline Facilities

Transportation and utility infrastructures makes a healthy economic and continual contribution to the United States with communication, water, power, mobility and other public necessities. These facilities are extremely important because any interruption or collapse in one of their elements will cause an extended issue to public and they will require urgent supplement to solve solutions.

Lifeline components include bridges, water and wastewater systems, electrical power, communications, natural gas, and petroleum lifeline system components. Each type of lifeline components has various treatments towards different sources of damages. For example, bridge foundations and pipelines would not be damaged because of inundation, but scour and erosion will have a serious impact on them.

There are three different damage sources that have impacts on the system functionality. Inundation, scour or erosion, and Debris impact are different sources of damage to this type and each one has different estimation methodologies.

Generally, the method used for damage estimation on lifeline components is same as what was for buildings. It considers depth of flooding and assigned damage curve to calculate the percentage of damage to the component. The main difference is that some lifeline systems are uniquely vulnerable to inundation and some others are difficult to be repaired or replaced.

HAZUS software contains some fragility functions for the facilities that are suffering from inundation. Electrical and mechanical equipment exist in the floodplain area will damage based on two different scenarios, dike/protected and un-diked/unprotected. if the elevation of the water exceeds the dike for protected components and for all un-diked components the facility would be submerged. Usually for electrical components being submerged means requiring the whole replacement. Therefore, thresholds and diking for essential facilities could have considerable impact on the dollar loss.

6.7. Essential Facilities

All facilities that should be functional after flood events to provide service to the public are included in the essential facilities. Hospitals, Police stations, fire stations and schools are grouped in essential facilities. In order to calculate site specific damage assessment of these facilities we need to determine their occupancy classes and building structure type according to their design level (same as general building stock). There are three major occupancy classification system consist of medical care, emergency response, and schools. Each of these groups has some subcategories which are shown in the table below. This table contains some other columns that represent assumptions for each subcategory. Column contains information about enclosing basement, first floor elevations, number of stories, and damage functionality.

Table 7 Essential Facilities Classification

Hazus Label	Occupancy Class	Description	1st Floor Height	Story Hieght
		Medical Care Facilities		
MDFLT	Default Hospital	Assigned features similar to EFHM	3	Mid
EFHS	Small Hospital	Hospital with less than 50 Beds	3	Low
EFHM	Medium Hospital	Hospital with beds between 50, 150	3	Mid
EFHL	Large Hospital	Hospital with greater than 150 Beds	3	Mid
EFMC	Medical Clinics	Clinics Labs Blood Banks	3	Low
		Emergency Response		
FDFLT	Default Fire Station	Without Basement	0	Low
EFFS	Fire Station	Without Basement	0	Low
PDFLT	Default Police Station		0	Low
EFPS	Police Station		0	Low
EDFLT	Default EOC		0	Low
EFEO	Emergency Operation Centers		0	Low
		Schools		
SDFLT	Default School	Assigned features similar to ESF1	0	Low
EFS1	All Schools	Without Basement	0	Low
EFS2	Colleges/University	Without Basement	0	Low

For the functionality depth there is a general rule that says whenever the depth of water in facilities such as hospitals reaches to half feet the facility should be closed; therefore, they would not be functional anymore if the depth of water exceeds 0.5 ft of their floor elevation.

6.8. Transportation Systems

Classification of the transportation components is based on different characteristics of each system in damage loss of flooding. Transportation systems include all highways, railways, light rail, bus, ports, ferries, and airports. The effort of this section is to differentiate various category systems by their vulnerability to flooding. The HAZUS transportation raw data is derived from 2001 update information of the National Transportation Atlas. It should also be mentioned that for the transportation systems, excepting vehicles, there is no comprehensive damage curves and it depends on parameters that are at times unknown and/or unpredictable. Therefore, only the dollar exposure of this system to flooding is going to be estimated.

6.8.1. Highway Systems

This system is the most important component of transportation can be severely influenced by flooding. This system consists of roadways, bridges and tunnels. In order to have a dollar exposure of this system to the flooding, HAZUS assumes different values for various subcategories. The assumption of this categorizing is shown in the table below. The valuation of each component is thousands dollar per kilometer for each type.

Table 8 Highway system classification

Flood Label	General Occupancy	Specific Occupancy	Valuation ($1000)
HRD1	Highway Roads	Major Roads (1km 4 lanes))	10,000
HRD2	Highway Roads	Urban Roads (1 km 2 lanes)	5,000
HTU	Highway Tunnel	Highway Tunnel	20,000
HWBM	Highway Bridge	Major Bridge	20,000

HWBO	Highway Bridge	Other Bridge (include all wood)	1,000
HWBCO	Highway Bridge	Other Concrete Bridge	1,000
HWBCC	Highway Bridge	Continuous Concrete Bridge	5,000
HWBSO	Highway Bridge	Other Steel Bridge	1,000
HWBSC	Highway Bridge	Continuous Steel Bridge	5,000

6.8.2. Railway Systems

Inventory data required for the railway systems includes the geographical location, and repair and replacement cost of system components. Components of the railway system include tracks, bridges, stations, fuels, dispatches and maintenance facilities.

Table 9 Railway System Classification

Flood Label	General Occupancy	Specific Occupancy	Valuation ($1000)
RTR	Railway Tracks	Railway Tracks (per km)	1,500
RBRU	Railway Bridge	Railway Bridge Unknown	5,000
RBRC	Railway Bridge	Concrete Railway Bridge	5,000
RBRS	Railway Bridge	Steel Railway Bridge	5,000
RBRW	Railway Bridge	Wood Railway Bridge	5,000
RTU	Railway Tunnel	Railway Tunnel	10,000
RSTS	Railway Urban Station	Steel Railway Urban Station	2,000
RSTC	Railway Urban Station	Concrete Railway Urban Station	2,000
RSTW	Railway Urban Station	Wood Railway Urban Station	2,000
RSTB	Railway Urban Station	Brick Railway Urban Station	2,000
RFF	Railway Fuel Facility	Railway Fuel Facility (Tanks)	3,000
RDF	Railway Dispatch Facility	Railway Dispatch Facility (Equip)	3,000
RMFS	Railway Maintenance Facility	Steel Railway Maintenance Facility	2,800
RMFC	Railway Maintenance Facility	Concrete Railway Maintenance Facility	2,800
RMFW	Railway Maintenance Facility	Wood Railway Maintenance Facility	2,800
RMFB	Railway Maintenance Facility	Brick Railway Maintenance Facility	2,800

Like the highway system classification, the dollar value of each subcategories of this system is defined by kilometer units of the facility.

6.8.3. Light railway Systems

This system is relatively similar to the railway system, but the difference is in its power sources. The light railway uses DC power substations. Therefore, in valuation process the electric power should be taken into account. Table 10 shows classification data of this system.

Table 10 Light rail System Classification

Flood Label	General Occupancy	Specific Occupancy	Valuation ($1000)
LTR	Light Rail Track	Light Rail Track (per km)	1,500
LBRU	Light Rail Bridge	Light Rail Bridge Unknown	5,000
LBRC	Light Rail Bridge	Concrete Light Rail Bridge	5,000
LBRS	Light Rail Bridge	Steel Light Rail Bridge	5,000
LBRW	Light Rail Bridge Wood	Light Rail Bridge	5,000
LTU	Light Rail Tunnel	Light Rail Tunnel	10,000
LDC	DC Substation	DC Substation (equip)	2,000
LDF	Dispatch Facility	Dispatch Facility (equip)	3,000
LMFS	Maintenance Facility	Steel Maintenance Facility	2,600
LMFC	Maintenance Facility	Concrete Maintenance Facility	2,600
LMFW	Maintenance Facility	Wood Maintenance Facility	2,600
LMFB	Maintenance Facility	Brick Maintenance Facility	2,600

6.8.4. Other Transportation Systems

Other transportation systems that have not been discussed in this study (Ports and Harbors, Ferries and airports) are excluded from this study region. However, the classification of these types is available in the HAZUS technical manual.

6.8.5. Direct Damage to Vehicles

This section develops a procedure to estimate direct damages to motor vehicles. The first step of this estimation is to calculate the vehicle inventory of the study region and then distribute vehicles through different locations of the city according to the day or night times. The second step is to estimate the value of the vehicles and calculate the percentage of damage by applying loss functions according to the flood depth.

In order to estimate the location of vehicles, the building inventory, parking generation rates, parking supply, parking occupancy, and vehicle population by age group and type are required. These data will help us to estimate the number of vehicles by parking structure, vehicle age, and vehicle type by time of day. Following is the input data required for this estimation which is discussed in detail.

6.8.6. Building's Parking Inventory

The purpose of this data is to find the number of vehicles that are potentially at risk of being flooded. The building category is based on occupancy types, exactly what was used for building stock direct damages. The other most important information required is the number of vehicles per square foot by different occupancy types.

The number of vehicles in different places can be differents from day to night. These are factored using parking generation rates. The most comprehensive data available of this parameter is gathered by the Institute of Transportation Engineering, which was updated in 2002. The other source that can be used is available at American Planning Association (APA), which generated Off-Street Parking Requirements manual for land use purposes.

6.8.7. Parking Supply and Parking Occupancy

Because of denser populations in urban areas like Washington DC, there are more multi-story and underground parking areas. The elevation of the story on which the vehicle is parked is considerable, because those vehicles parked in the underground levels assumes fully submerged. On the other hand, vehicles parked above the flood level will not receive any damages. In order to determine this difference, parking locations are categorized into four groups. Table 11 shows this category and the distribution of vehicles in different places.

Table 11 Estimated Parking Distribution by Parking Area Type

Urban	On-Street	Parking Lot	Garage	Underground
Parking Spaces	12.5%	31.5%	33.6%	22.4%
Occupancy	78%	65%	45%	45%
Distribution	18%	37%	27%	18%

While the actual number of levels varies, a parking garage can be represented by a five-floor structure, with the roof also available for parking. To estimate the impact of flood damage to vehicles in urban areas, it is assumed that 18% of vehicles are below ground level and under water during all flood events and, therefore, total losses. Another 60% of the vehicles (18% (on-street) + 37% (surface lot) + 5% (first floor from garage)) are subject to damage based on the appropriate flood damage equation. The remainder is located at least one level above ground and are assumed to receive no damage.

6.8.8. Vehicle Population by Age Group and Type

The National Personal Transportation Survey (NPTS) keeps track of the total amount of vehicles owned by people in different areas. In order to differentiate the number of cars and trucks and vehicles with different ages, the National Automobile Dealers Association (NADA) data is one of the most developed data available in this region. Department of Transportation's comprehensive Truck Size and Weight Study (TSWS) is also in charge of compiling data about different truck types. All the above organizations have some different sort of data that is gathered by FEMA and is determined in the table below.

Table 12 Vehicle Age Distribution by Vehicle Classification

Age	Car	Light Truck	Heavy Truck	Total
0-2	8.438%	4.631%	0.459%	13.53%
3-6	17.500%	6.703%	1.969%	26.17%
7-10	15.625%	5.241%	0.919%	21.78%
10+	20.938%	7.800%	9.778%	38.52%
Sum	62.500%	24.375%	13.125%	100%

6.8.9. Vehicle Value Estimation

In order to estimate the value of the total dollar loss of vehicles, the average value of vehicles is represented by NADA. The average price for brand new light vehicles is $24,923, and for used light vehicles the average price is $13,648. According to the number of new cars in dealerships, FEMA estimates that the average used vehicle values are about 50% value of the average new vehicle. NADA also has information about the actual dealer selling prices that can be useful in calculating the total car values of the region. For the total cars in the region, it has been considered that the 7% of the total light cars and 9% of the total light and heavy trucks are brand new and the remain are used cars. (FEMA, 2011)

6.8.10. Damage Factors to Vehicles

Motor vehicles are one of the systems in this study that are most susceptible to flooding. These damages depend highly depend on warning systems. The main factor in vehicle damages is the time that they are in the floodplain. Based on this fact the location of the vehicles has the major importance. Therefore, vehicles are classified in some categories. They may be parked at residencies, structures, parking or transportation facilities, business locations, dealership parking or repair centers, and they are maybe in use at site. The probability of getting damaged for these categories is totally different from what were for the buildings.

This damage also depends on the time gap between warning and the flood event and the chance of availability of the vehicle owner to relocate them. For those vehicles that are parked in facilities like airport or metro parking the likelihood for availability of owner is relatively small. However, for those vehicles that are parked in the business parking operators usually are available at the work site, so they can relocate vehicles. In multi-story parking just first floors and basement are at risk. The most severe damages can be to parking of vehicle sales, repair centers and retail facilities that there would not be enough time to remove all of them from the floodplain.

Vehicles that are at risk of flooding include all types of passenger cars, heavy trucks, and light trucks. However, the heavier vehicles will damage less than light ones. Damage to the private and business vehicle owners doesn't limited only to the cost of the vehicle. It may cause some unemployment because of property loss of firms. These costs will be considered as indirect cost estimation for the study region.

6.8.11. Vehicle Damage Function

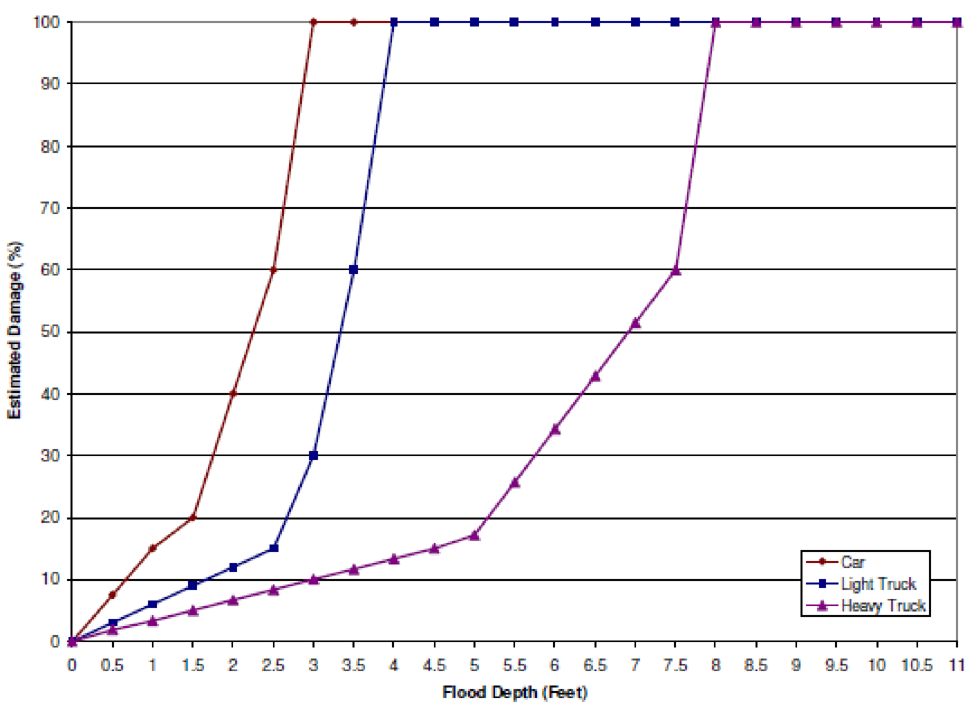
Cars are classified into three major groups, passenger cars, light trucks and heavy trucks. For each type the specific heights has been determined as the thresholds. Two specific levels of heights are carpet and dashboard. The percentage of damage to the car depends on the level of flooding according to the three zones of car heights. For example, if the engine submerged in the water, total electronic and computer components will be damaged therefore the car is considered for the total loss. Consequently, if the depth of flooding exceeds the height of dashboard (engine) in each vehicle categories, it will be known as hundred percent damage loss. The height of each category is the average heights for various vehicles brands of each type. Below is the table of function that is used to determine the damage percentage to the cars.

Table 13 Vehicle Depth Damage Relationship

Flood Level (ft)	Car	Light Truck	Heavy Truck	% of Damage
Below Carpet	<1.5	<2.7	<5	15%
Between Carpet and Dashboard	<2.7	2.7 - 3.7	5 – 7.5	60%
Above Dashboard	>2.4	>3.7	>7.5	100%

There are also some depth damage functions similar to those that existed for buildings. Below is the default depth damage function that is used in the model. There are two breaking points in the damage curves. These points shows the elevation of carpet and dashboard of cars. As the water rise up to these elevations the damages would dramatically increase in a faster pace manner. The discussed warning parameter can change the number of exposed vehicles in the region and it can decrease the dollar exposure of vehicle in the region.

Figure 16 Vehicle Damage Functions (DHS, 2011)



6.9. Direct Social Losses

6.9.1. Casualties

Usually flood events do not have significant fatalities similar to earthquake or hurricane events. Therefore, the data available for casualties in flooding is limited and is not enough to make a good fatality model. Drowning may lead to death because of either “rapid rise” or “very rapid rise” flooding. In order to collect data and gather information about fatalities because of flooding the history of flood casualties are studied. Based on the NIBS studies these casualties are categorized into three types:

Casualties that occur in floodwaters: This casualty determines the number of deaths per 100,000 in exposed community. It totally depends on the speed of water rising and demographic characteristics of the community such as gender and age.

Casualties that occur within buildings: This casualty divides into two different phases, during the flooding and during the flood cleanup. In the flood event the number of casualties depends on the type of building, warning system, and depth of flooding. During the cleanup phase it depends on the occupancy type and electric power service interruption.

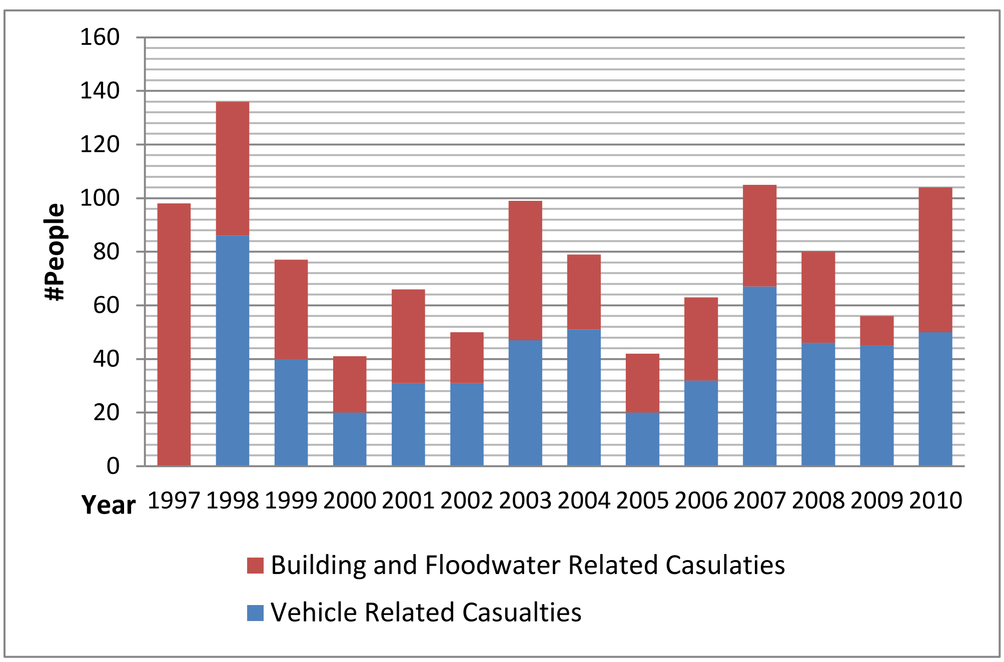
Vehicle Related casualties: In this type the most important factor is motor vehicle accidents and injuries because of too much raining. The casualty rate is defined as low, medium and high rainfall rates based on casualties per 100,000 populations. The source data is coming from “El Nino” phenomenon that has been conducted by UCLA School of

Public Health. Based on the history available at NOAA about 56% of the flood casualties are because of rain-related motor vehicle accidents.

The Table below shows the growing trend of the flood casualties of these recent years. The reason of the trend rising is because of growing population and increasing of the flood magnitudes in the recent years. As discussed in section 1.6. Hurricane and flood events have a growing trend according to the history. The data is collected from NOAA Hydrologic Information Center. In the Table the number of fatalities for each month and year and also separately fatalities related to motor vehicle accidents are shown below:

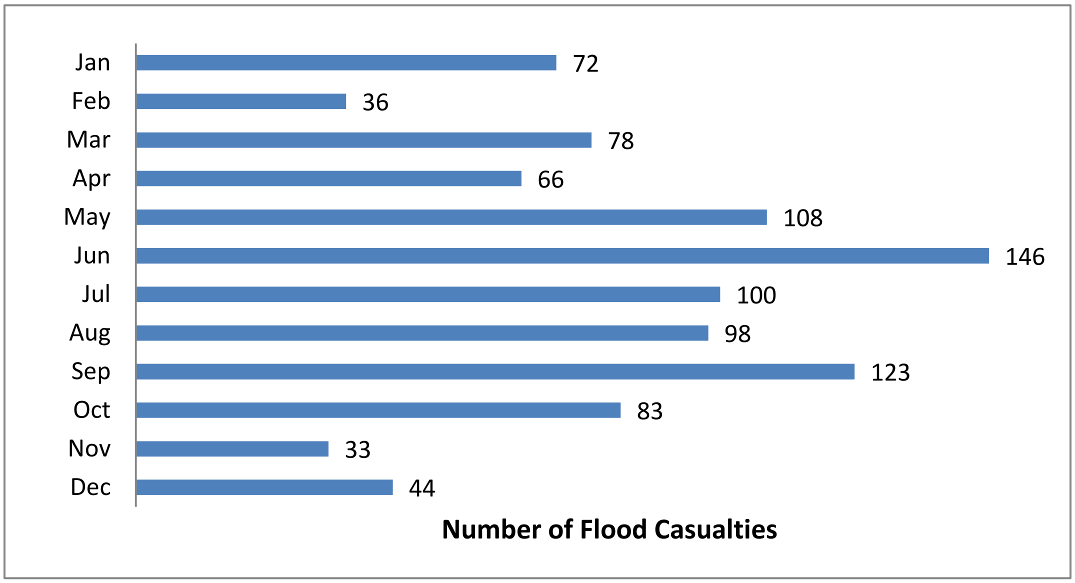
The recent rate of flood casualties in the US has been about hundred deaths due to the information of flood casualties per year. Figure 17 shows the number of casualties du to flooding through the US.

Figure 17 Flood Casualty history of the US



The chart below shows related to the number of casualties based on NOAA research and data collections. These casualties are defined for different months. Therefore, it can be concluded that the most fatal flooding in the US has been occurred during months of June and September and generally during summer.

Figure 18 Flood casualties in the US from 1997 – 2010 by month



Due to lack of enough information about flood casualties and unknown parameters that cannot be predicted for the study region, it is not possible to calculate the number of fatalities in the region. But the data above can help decision makers to develop rules and regulations in order to decrease number of fatalities due to flooding in this region.

6.9.2. Displaced Households & Move to Temporary Shelters

After flooding events households and individuals from properties that have been significantly damaged will need a short-term shelter. Not all of these people go to the governmental shelters. The number of individuals that will use governmental shelters depends on the income, age, and having any families around of the population.

Data that is considered to count this factor is number of households in the flooding area, population of the area, distribution of households by income, and distribution of population by age. Generally, younger and older families usually choose to live in government provided shelters. These categories are in the lower income brackets.

There are some equations and pre-prepared probabilities for determining the displaced individuals as a result of inundation and utility damages. Some social factors also have an impact on the displaced individuals. Research has shown that the income factor to choose government shelters is four times more important than the age factor. For those who will live in their family and friends' home the model can just allocate a probability of having families or friends immediate to the area. For the other factors the weighting method has been used to get more accurate results.

6.10. Direct Economic Losses

Most of the methods are limited to estimate the repair and replacement cost of damaged inventories, but this method also considers immediate economic loss impacts to people in flooding area. This session is about the conversion of percent damage into dollar loss. The actual estimates of direct economic losses are financial consequences of damaging to buildings and properties. Building losses could become causes some Financial issues like business interruption, loss of financial resources to cover damages, and lost of job and housing. These losses all can be categorized as immediate economic impact to the community.

In economic terms buildings, inventories and public facilities are values that are being sources of income to people. If the sources (buildings) be destroyed, people will lose their source of funding. It is the reason that this type of losses is named direct economic losses. In order to calculate these sorts of economic impacts, FEMA has developed studies to evaluate mitigation strategies and budgets. The real strategies to determine all aspects of socio-economy losses exactly are too much complex and they will need a huge amount of accurate data that usually is unavailable for such big areas. Therefore, with an acceptable proximity we can estimate the direct losses due to damage to the inventories with reasonable and available database.

Direct economic losses due to the damage to buildings include capital stock losses (cost of removing damaged buildings and contents), relocating expenses, income losses (capital related, wage, output and employment losses), and rental income losses. The analysis for estimating damage is based on percentage of damages relative to full replacement cost. Estimating damages module are determined for each building occupancy types.

6.10.1. Building Replacement Costs

The input information available for this estimation is all based on 2006 dollar expenses. Full replacement and depreciated cost model are two basic models used to calculate this type of loss estimation. The full replacement cost is industry- standard cost that is published by R.S. Means as means square foot costs.

The Buildings full replacement costs are categorized in different occupancy types first. There are also some sub-categories for these occupancy types to calculate the more accurate loss estimation. The area of these categories and sub-categories also specifies for each census block. Therefore, by multiplying the areas of each specific category to the

Means cost per square foot. Applying damage curves will give us the percentage of damages to each category and then we can calculate the damages for them. Summing up all these costs is the final loss estimation for buildings in each census block.

R.S. Means has two depreciation models for Single Family Residential and commercial/industrial/institutional structures. The model for residential structures is based on its age and general conditions. General conditions are defined in three categories; good, poor, and average. For the certain age and condition of the building there is a depreciation percentage than can be found in Means depreciation Diagrams. For the Non-residential buildings this models based on the age and framing material of structure. Similar to the previous model there are diagrams for each framing material and relevant depreciation percentage according to the age of buildings.

6.10.2. Contents Replacement Costs

Contents of building include all furniture, non-structural equipment and other supplies in buildings. Mechanical and electrical equipment and fixtures are excluded from these contents. The value of contents is determined as a percentage of the whole value of building in each occupancy types. Table 14 by National Institute of Building Sciences that determines contents value ratios according to different occupancy types.

6.10.3. Building Relocation Expenses

Relocation expenses include shifting, transferring, and the rental of temporary space. This cost is for all buildings that has been damage more than 10%. It should be mentioned that this expenses are not calculated for entertainment, theaters heavy industries and parking

Table 14 Contents Value Percent of Structure Value

No.	Type Code	Occupancy Type	Contents Value (%)
1	Residential RES 1- 6	Single Family Dwelling, Mobile Home, Multi Family Dwelling, Temporary Lodging, Institutional Dormitory, Nursing Home	50
2	Commercial COM 1-5,8,9	Retail Trade, Wholesale Trade, Personal and Repair Services, Professional/Technical/Business Services, Banks, Entertainment & Recreation, Theaters	100
3	COM 6,7	Hospital, Medical Office/Clinic	150
4	COM 10	Parking	50
5	Industrial IND 1-5	Heavy, Light, Food/Drugs/Chemicals, Metals/Minerals Processing, High Technology,	150
6	Industrial 6	Construction	100
7	Religion 1	Religion, Non/Profit, Church, Membership Organization	100
8	Governmental 1	General Services	100
9	Governmental 2	Emergency Response	150
10	Educational 1	Schools/Libraries	100
11	Educational 2	Colleges/Universities	150

facilities. HAZUS has some tables that define the distribution of owner occupied buildings for each category. Therefore, it is easy to calculate the number of relocation required in each census block and for the whole flooding area.

6.10.4. Loss of Income

Loss of income totally depends on the time needed to restore the buildings. Restoration time include any process to make the flooding area as well as how it was before. This process could be inspections, permit, clean-up, approval, and rebuilt the damaged buildings. Flood damage restoration model has been developed in order to calculate the time period. This amount of time has been determined for each occupancy class and for different flood depth.

Time of restoration also depends on the amount of damage occurred to building. For example, if the flood water level exceeds the lower level of the finished floor, damage will occur to the wall, therefore, the whole wall should be restored. Also if the damage is more than 50% to a building, that building is assumed as totally destroyed. Therefore reconstruction for these types is required. Reconstruction time is approximately assumed 24 month. 6 months is to remove, buy-out, and do some administrative tasks; 6 month is for permits, approval, and calculations; at last it takes about a year to get the physical construction done. For the building outside of the 100-year floodplain area this time will decrease about 6 month because it is allowed to do the reconstruction to the original configuration at the same location. Therefore, the total amount of time would be 18 months.

The capital related, wage, and employment losses uses “loss of function” within the time period required to restoration. Having the time period and determining each of these items exists in default HAZUS database can give us the total loss of income for the floodplain area.

7. Results

7.2. Summary of Results

This section covers the results of the loss estimation analysis of the storm surge for flood prone areas in Washington. The results include the dollar exposure of building in both study region and floodplain. It also shows the estimation damages to the buildings and their contents, damage to the vehicle in night and day time, Transportation systems dollar exposures, social impact, and direct economic loss in the study region. The tidal storm surge, category 4 hurricane, considered as the scenario for this region has a 210-year return period. The geographical size of the region is about 5 square miles and contains 549 census blocks. The region contains over 12 thousand households with about 24 thousands of residents. Table 15 is a summary of Region Statistics..

Table 15 Region Statistics

Region Statistics		
Area of the Study Region	5	Square Miles
Number of Census Blocks	549	
Number of Buildings in the study Region		
Residential	3,614	
Total	6,968	
Number of residents in the region	24	(× 1000)
Building Exposure	$1,736	Million Dollar
Total	$6,049	Million Dollar

7.3. Total Losses

Table 16 is a summary of total losses due to the flooding in inundation area.

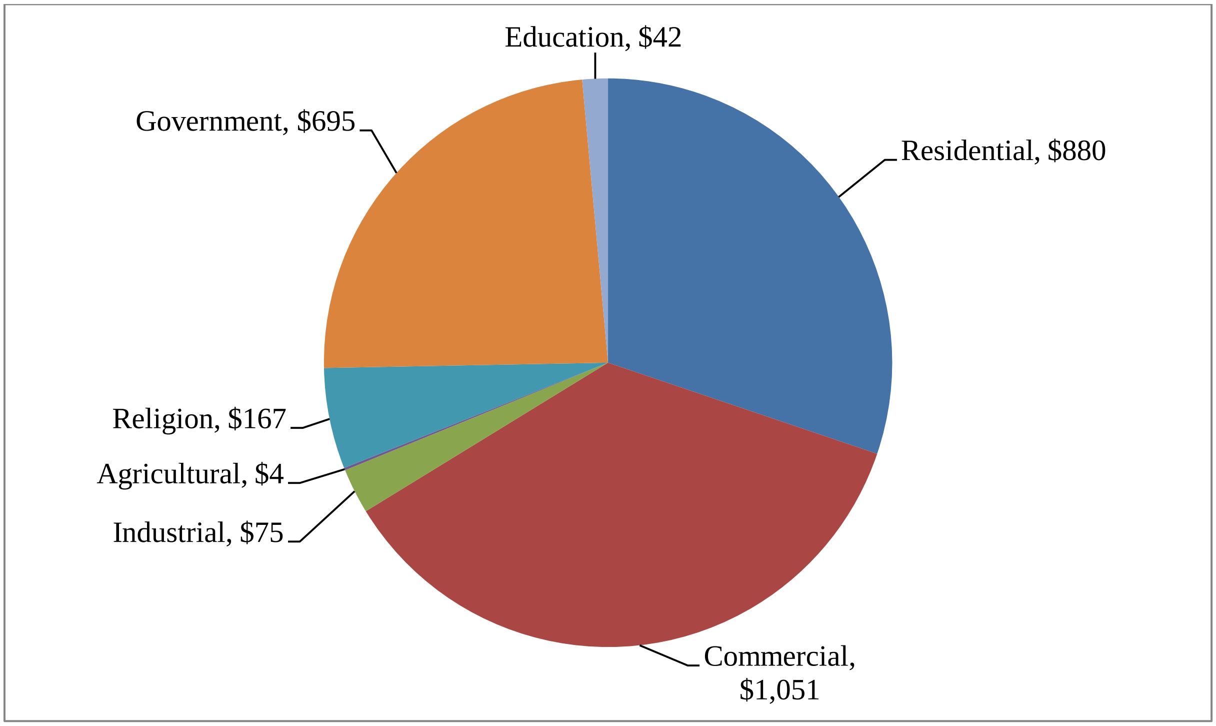
Table 16 Quick Assessment Report

Scenario Results		
Shelter Requirements		
Displacement Population	3,333	(# of Households)
Short Term Shelter	9,932	(# of People)
Debris Generated		
Debris Amount	135.7	(1000 * Tons)
Truckload Required to Remove Debris	5430	(# @25 ton/truck)
Building Related Losses		
Residential Related Losses	$280.8	Million Dollar
Commercial Related Losses	$596.0	Million Dollar
Total Property (Capital Stock) Losses	**$1,003.9**	Million Dollar
Essential Facility Losses		
Building Loss	$1.4	Million Dollar
Content Loss	$7.0	Million Dollar
Vehicle Damages		
Flood During Day	276.9	Million Dollar
Flood During Night	91.3	Million Dollar
Total Losses	**$1289.2**	**Million Dollar**

7.4. General Building Stock Inventory

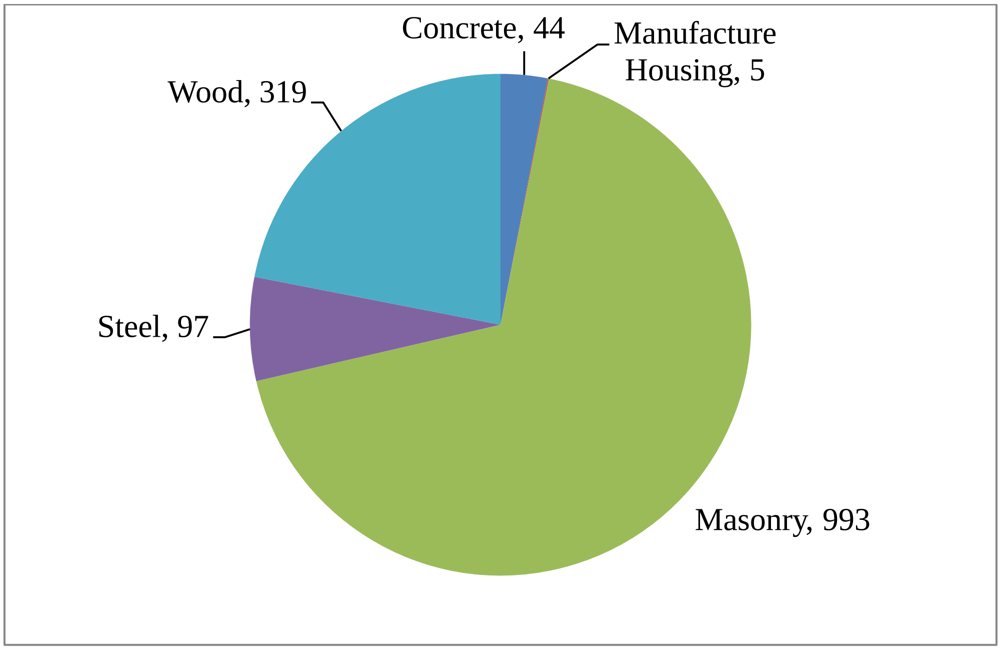
HAZUS estimates that there are 1,454 buildings in the inundation area which have an aggregate total replacement value of about three million dollars. Figure 19 presents the relative distribution of the value with respect to the general occupancies for the inundation area. These amounts represent the total value of the buildings that are exposed to the flooding, and they will not necessarily get damaged.

Figure 19 Building Value Exposure in Inundation Area by General Occupancy Type



Information about buildings is also available based on their structure types. It is estimated that more fourteen hundreds of buildings will be exposed to flooding. Figure 20 presents the relative distribution of the building count with respect to the structure types for the inundation area.

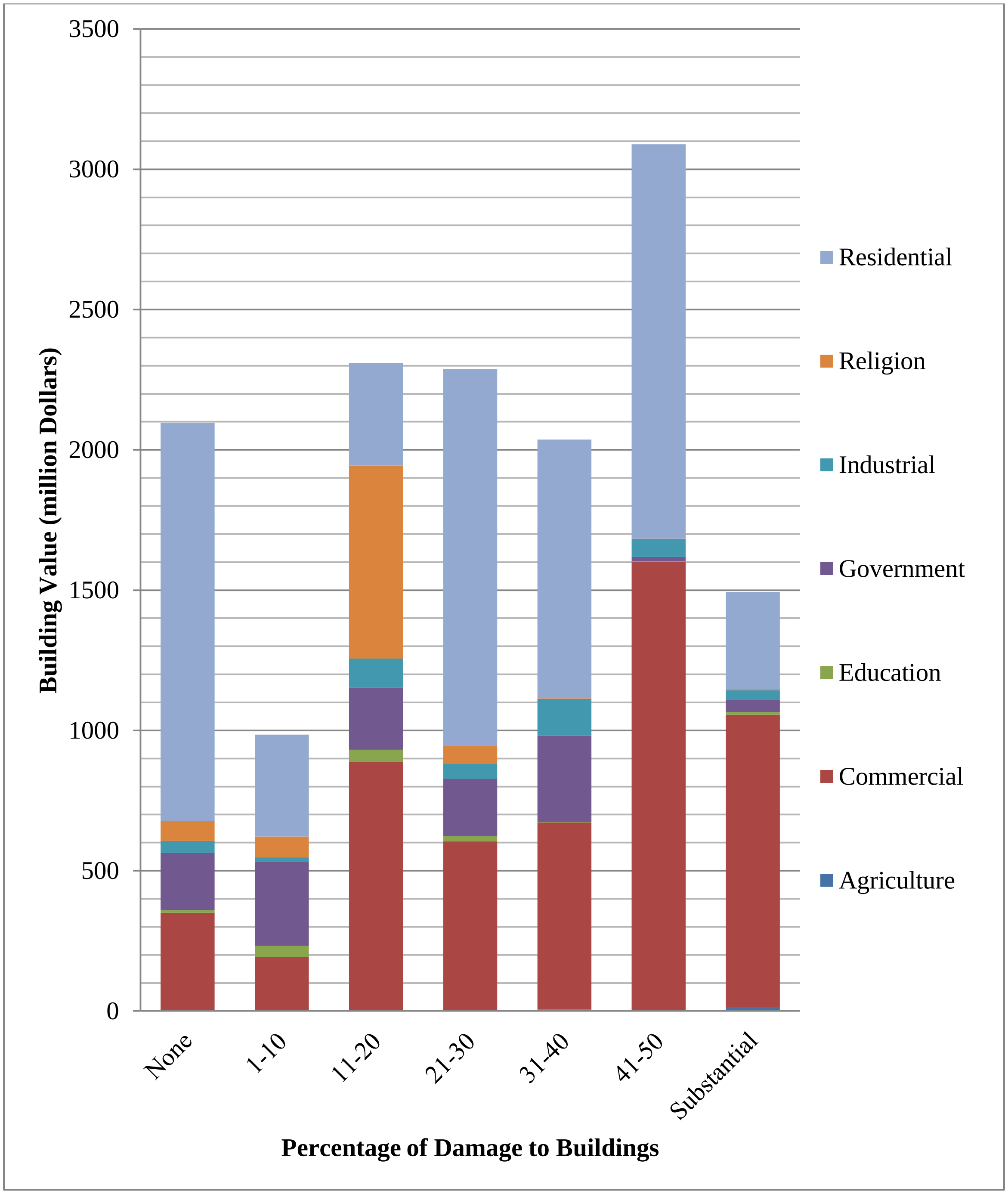
Figure 20 Building Count Exposure in Inundation Area by Structure Types



7.5. Building Damage

HAZUS estimates that about twelve hundred of buildings will be at least moderately damaged. This is over 33% of the total number of buildings in the floodplain area. There are an estimated 100 buildings that will be completely destroyed. Table below summarizes the number of damaged buildings by general occupancy for the buildings in the region. The ranges shown at the bottom of each column categorize buildings based on the percent of damages that apply to those buildings. For example, the First column at the left hand side shows the total value of buildings that has been damaged between one through ten percent. The buildings that are damaged more than fifty percent are identified as substantial damaged.

Figure 21 Expected Building Damages Based on General Occupancy



7.6. Essential Facility Inventory

For essential facilities, there are no hospitals in the region without any clinical centers. There are 15 schools, no fire stations, 10 police stations and no emergency operation centers. Tables 17 and 18 show the damage assessment of police stations and schools.

Table 17 Police Stations Building and Content damages in the inundation area

Police Station Name	Building Loss (1000 $)	Content Loss (1000 $)	Total Loss (1000 $)	Restoration Time (days)
Metropolitan Police Boys Club	275.23	1,872.37	**2,147.60**	630
Washington DC Police Department	567.92	2,163.00	**2,730.92**	720
Washington DC Police Department	146.62	497.87	**644.49**	480
Total	989.77	4533.24	**5,523.01**	610

Table 18 School Building and Content damages in the inundation area

School Name	Building Loss (1000 $)	Content Loss (1000 $)	Total Loss (1000 $)	Restoration Time (days)
SMITHSONIAN EARLY ENRICHMENT C	69.34	162.57	**231.91**	900
ST ALBANS SCHOOL	29.93	162.13	**192.06**	480
AMIDON ELEMENTARY SCHOOL	10.52	56.82	**67.34**	480
BOWEN ELEMENTARY SCHOOL	238.34	1,611.79	**1,850.13**	630
VAN NESS ELEMENTARY SCHOOL	69.89	476.8	**546.69**	630

7.7. Induced Flood Damage (Debris Generation)

HAZUS estimates the amount of debris that will be generated by the flood. The model breaks debris into three general categories:

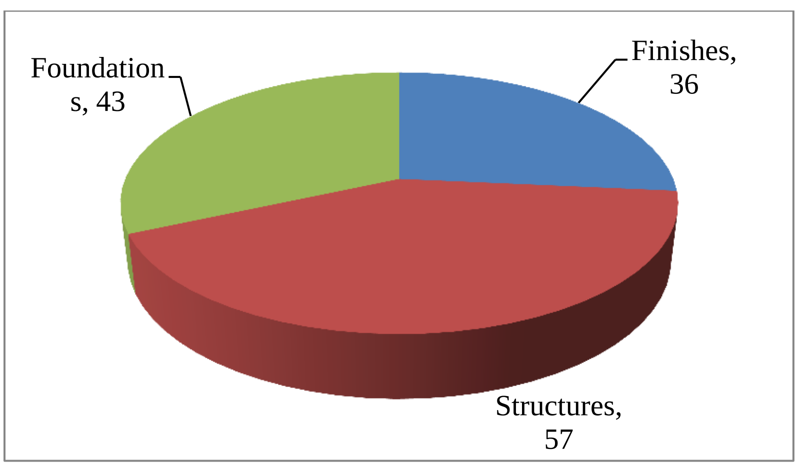
1) Finishes: dry wall, insulation, etc.

2) Structural: wood, brick, etc.

3) Foundations: concrete slab, concrete block, rebar, etc.

This distinction is made because of the different types of material handling equipment required to handle the debris. The model estimates that a total of 135,755 tons of debris will be generated. Of the total amount, Finishes comprises 26% of the total, Structure comprises 42% of the total and the rest of 34% belongs to the building's foundations. If the debris tonnage is converted into an estimated number of truckloads, it will require 5,430 truckloads (@25 tons/truck) to remove the debris generated by the flood. Figure 22 shows the debris percentage for each type.

Figure 22 Different types of Generated Debris by Kilo Tons



7.8. Vehicle

The numbers of vehicles is varying during day and night. Therefore, the damages to vehicle have a significant impact on the estimation loss for the study region. Figure 23 shows the dollar exposure of the cars for each type of vehicles.

Figure 23 Dollar Exposure of Vehilce in the Inundation Area by day and night

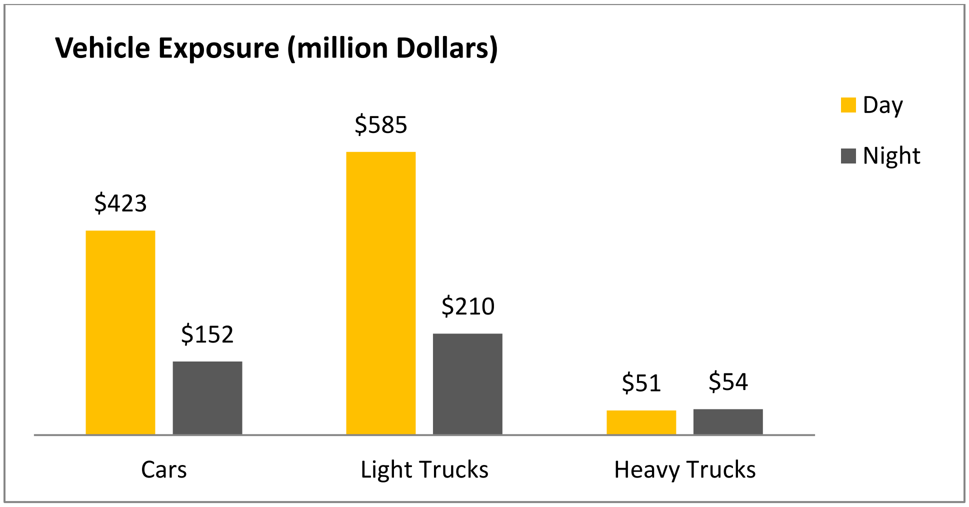
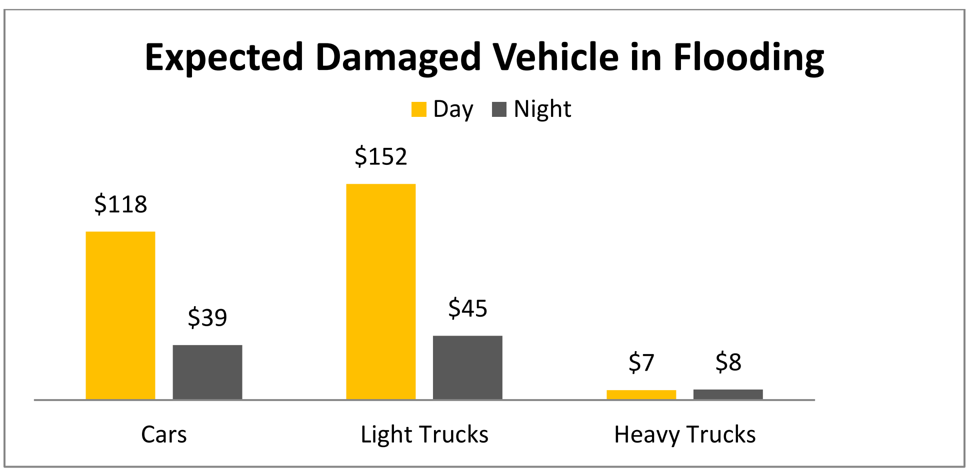


Figure 24 shows the Amount of damages to the cars in both day and night. This significant amount can be decreased by managing a good warming system.

Figure 24 Damaged Vehicle in the Inundation Area by day and night



7.9. Transportation Systems Dollar Exposure

Table 19 presents the dollar exposure of different transportation systems that data are available for them. These amounts are in thousand dollars and represent the value of systems that may be located in the inundation area. Due to the insufficient information about the mechanisms of these systems and their limited available information the damage assessments cannot be implemented for them.

Table 19 Transportation Systems Dollar Exposure

Types	Highway	Railway	Light Rail	Bus Facility	Total
Segments	513,127	8,940	37,796	N/A	559,864
Bridges	294,798	N/A	N/A	N/A	294,798
Tunnels	N/A	N/A	N/A	N/A	N/A
Facilities	N/A	N/A	31,956	2,245	34,201
Total	807,925	8,940	69,752	2,245	888,863

7.10. Social Impact

HAZUS estimates the number of households that are expected to be displaced from their homes due to the flood and the associated potential evacuation. Those displaced people that will require accommodations in temporary public shelters. The model estimates 3,333 households will be displaced due to the flood. Displacement includes households evacuated from within or very near to the inundated area. Of these, 9,932 people (46% of the population in the region) will seek temporary shelter in public shelters.

7.11. Building Related Loss

The total economic loss estimated for the flood is 1,003.87 million dollars, which represents 34.45 % of the total replacement value of the scenario buildings.

The building losses are broken into two categories: direct building losses and business interruption losses. The direct building losses are the estimated costs to repair or replace the damage caused to the building and its contents. The business interruption losses are the losses associated with inability to operate a business because of the damage sustained during the flood. Business interruption losses also include the temporary living expenses for those people displaced from their homes because of the flood.

The total building related losses were 969.38 million dollars. 3% of the estimated losses were related to the business interruption of the region. The residential occupancies made up to 28% of the total loss. Figure 25 presents summary of building related losses.

Figure 25 Building Related Losses

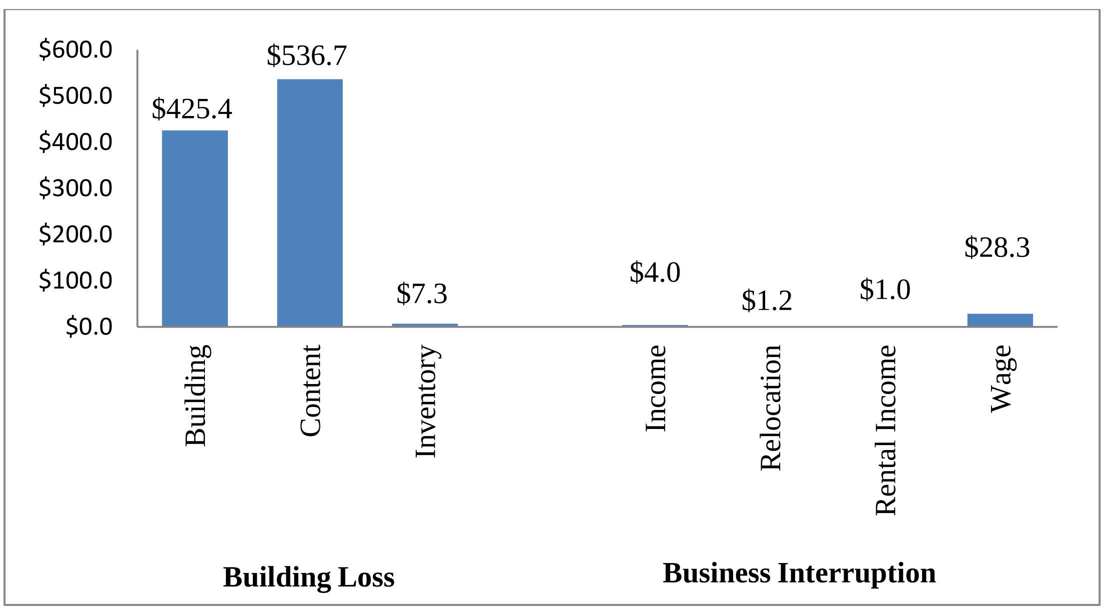


Table 20 provides a summary of the losses associated with the building damage, both building and business-related losses.

Table 20 Building-Related Losses (million Dollars)

Building Loss (Millions of Dollars)

Category	Area	Residential	Commercial	Industrial	Others
Building	168.83	232.54	11.94	12.05	$425.4
Content	111.09	354.57	31.53	39.54	$536.7
Inventory	0	2.04	4.91	0.33	$7.3
Subtotal	$279.9	$589.2	$48.4	$51.9	$969.4

Business Interruption (Millions of Dollars)

Area	Residential	Commercial	Industrial	Others	Total
Income	0.07	3.54	0	0.36	$4.0
Relocation	0.27	0.85	0	0.11	$1.2
Rental Income	0.37	0.64	0	0.04	$1.0
Wage	0.17	1.84	0.01	26.24	$28.3
Subtotal	$0.9	$6.9	$0.0	$26.8	$34.5

All building-Related Losses (Millions of Dollars)

Total	**$280.8**	**$596.0**	**$48.4**	**$78.7**	**$1,003.9**

8. Conclusion

This chapter provides a summary of this research, and elaborates on the results in order to arrive at an overall. Afterward, there is discussion about physical remedial actions for the floodplain in order to reduce the damages associated with the flood risk within the floodplain followed by limitations of this study and potential further study opportunities for future research.

8.2. Summary of the research

In summary, this research has used the USACE hurricane storm surge predictions for an extreme storm (category IV hurricane). The flood map of this study has been used to inspect elevations of flooding throughout the region, and to translate them into depths. Afterwards, the HAZUS-MH 2.0 is applied to estimate damages of a variety of types in the inundated area by relating them to their depth-damage curves. In essence, this means that what has been done is to find one point on the curve of hazard probability vs. damages, and this point is the one associated with the largest credible hurricane that is considered to occur. The return period of the category IV hurricane through the Chesapeake Bay is roughly 210-years. This hurricane on its worst condition may lead to raising stormwater up to 24 feet above sea level. According to the binomial distribution the probability that such flood happens at least once in 100 years is 38 percent. Currently, FEMA has considered 100-year riverine flooding to develop FIRM maps and regulations for the floodplain; however, the water level of this flood is only about 15 ft. The probability that such a flood happens at least once in 100 years is 63 percent. Comparing the potential damages of the two floods shows that current flood protection plans are not sufficient for the predicted flooding.

8.3. Overall Conclusion

Flooding is a risk to the national cultural and historic resources around the National Mall as well as residential properties in the Southwest area. Flooding not only poses a financial risk for property damage, but also a security risk given the concentration of key federal functions in the region.

Comparing storm surge in the region with the 100-year overbank flooding has shown that the predicted flooding by FEMA has not considered the hurricane impacts and storm surges, which has led to the inadequate protection planning for the region. In other words, the actual risk of flooding in the area is more than what FEMA has projected by this date. The similar analysis has been run for 100-year flood based on FEMA maps which resulted to only $700 million dollar loss. This amount is about half of the loss estimated for the storm surge category 4, which is roughly $1300 million dollars. Consequently, decision–makings for managing the floodplain have been based on an underestimated predictions which will not efficiently protect the capital of the nation against flood risk.

Chesapeake Bay sea levels are forecast to rise approximately two to three feet within the next 50 years. The combination of rising sea levels in conjunction with the storm surge can have a severe flooding effect in the area. The 1933 flooding event in its storm track, tidal surge, maximum sustained wind speed, and minimum pressure was relatively similar to the proposed storm surge that has been discussed in this study. Over years, global warming increases the intensity of hurricanes and storm surges. Additionally, rising sea levels in the Potomac River combined with climate changes will increase the probability of flood risk in the area. Hence, within decades the return periods currently estimated for the respective storm surge categories will shorten. In other words, the risk of a severe surge (a category IV hurricane) is increasing. Therefore, risks of this magnitude will need improved emergency response measures.

The most destructive combined hurricane and flooding in the DC area occurred in 1933. The concern is that over the past 100 years the hazard from storm surge has likely increased. Therefore, it may be more probable severe flooding such as what was experienced in August 1933 will occur. In conclusion, if the sea level continues to rise at its current pace, in the near future even relatively weak storms could produce enormous damage to the area.

8.4. Possible remedial actions for Floodplain

This section discusses recommendations for the next steps for reducing flooding risk in the study region. There are many potential remedial actions to reduce flooding risk and damages through the study region. There is no absolute solution that can keep Washington completely safe of flooding, but taking a combination of actions will minimize risk by decreasing the probability of flooding occurrence.

8.4.1. Enhance Potomac River's Levee Protection

River overflow and urban drainage have been thought to be the most frequent types of flooding in Washington. The factor that makes flood control more difficult is that storm surge must be added to these flood types. The current levees are designed to keep water from the Anacostia River systems out of the downtown business district. These levees are generally designed to protect the city against 100-year overbank flooding which dose not protect the city against hurricane category 4.

According to the NCPC, in riverine flooding events the Anacostia River flooding is less of a threat to the Washington metropolitan region than the Potomac River because of the greater watershed of the Potomac River. This fact can hold validity only when the overbank flooding has been considered. Considering the storm surge model shows that on the left hand, the storm surge pushes the water from the Hains Point to Potomac River and 17^{th} street toward National Mall. On the right hand, at the Anacostia River near the Hains Point water will come up through Ft McNair and north across the Mall at 3d Street toward the Southwest DC. These two paths of waters will fill the floodplain gradually and may join together at the south of the US Capitol building. In conclusion, in addition to make a flood barrier at 17th street protective actions are needed for the Southwest. In addition, the designed floodwall for the 17^{th} street protects flooding up to 20ft above sea level; however category 4 storm surge flooding could exceed this amount and pass the barrier. Therefore, all the protection levees should be adjusted to the new estimated flood. These adjustments include increasing the height of the levees and inspecting any defects along the levee in order to assure correspondence to post-Katrina regulations.

8.4.2. Enhance and Improve Anacostia River's Levee Protection

The levees along Anacostia River are at the right hand side of the river, which is out of the study region. The flood maps show that the temporary closure at the Fort McNair is not adequately prevent water to enter the Washington. Therefore, a new levee at the left boundary of the Anacostia River should be designed. The levee can begin from the Fort McNair, goes toward the river boundary, surrounding the Southwest and reach to the United States Navy Yard. The river height of this levee should be designed according to the new proposed flooding regulations. Two main alternatives for the type of this levee include earthen berm levee and I-walls. This project will not require extensive land purchase because most of the lands in the Washington Southwest area and especially the river boundaries are owned by the government.

8.4.3. Improve Drainage System

The proposed study region, the downtown area of Washington DC, has a relatively low ground level. In addition, this area contains old buried waterways that interrupt its drainage system.

According to the DC WASA overflow predictions, in an average year, less than 0.5” of rain can cause more than three hours of untreated sewage to flow into the Anacostia River. This fact happens usually more than 50 times each year. This is due to the inadequate capacity of the sewer system. Inadequate capacity also makes the area susceptible to pluvial flooding. One of the most important causes of this type of flooding is a primary sewer system that collects water through the entire city in the National Mall area.

Renovation of the primary sewer system has been suspended for many years because of the disruption and cost. The project has an estimated cost of $1.9 billion. Because of the severe impact of this poor drainage system on flooding for the area, identifying practical alternatives is a crucial action. One alternative is renovation of the current sewer system in order to increase the drainage capacity and consequently decrease the probability of the occurrence of urban drainage flooding. Separating this system into smaller ones and making outputs through the different points of the conduits to the Anacostia tributaries can direct large amounts of rainfall through the Anacostia River. This action needs a comprehensive study in order to identify the most critical waterway splitting points and the type and capacity of the transferal channels.

8.4.4. Solution to Urban Drainage flooding at Anacostia River

Urban drainage flooding is typically caused when the sewer system's capacity is exceeded (see section 4.5). A portion of the District along the west side of the Anacostia River has a combined sanitary and stormwater system. Presumably this area would be more susceptible to flooding from excess stormwater. However, there have not been reports of urban drainage flooding in this area. This sewer system should be separated into two independent piping systems: One system for sanitary sewage and one system for stormwater. Separate systems for stormwater and sanitary sewage can't ensure that an area will not flood, but the additional sewer capacity can help mitigate heavy rainfall.

8.4.5. Anacostia River Sedimentation Issue

Sedimentation has been an ongoing problem of the Anacostia River. In severe flood events, large amounts of debris flow through this river. The capacity of the river is not enough to tolerate this discharge. Sedimentation and debris hinder floodwater from draining easily. Emergency responses are required to remove the debris from the Anacostia River following such flooding. It would be worthwhile to evaluate alternatives for this sedimentation problem.

One possible solution is to dredge sediment from the riverbed of the Anacostia and restore a wider and deeper channel. Potential financial assistance is an important advantage of this recommendation. The US Navy might support dredging in the Analcostia because existing sedimentation prevents larger naval ships from reaching existing Naval facilities on the river.

8.4.6. Enforce Land Use Restrictions

Numerous laws, policies, and executive orders are in place to reduce property loss and environmental degradation caused by flooding, but there are two main challenges in flood management for Washington. First, Lack of clarity or uniformity in the division of responsibilities among various federal and local authorities has leaded to rely only on the local DC government to manage, regulate, and otherwise control stormwater (NCPC, 2008). Stormwater control is an ongoing issue for which there is not a long-term federal or local management plan in this important area. NCPC could play a leadership role in the development of such a plan, if the Commission chooses. Afterward, the Commission can consider revisions to the project review procedures and adding stormwater considerations to planning initiatives.

There are first main actions that NCPC can consider as the first steps of its effort on stomwater control. First, NCPC may review its own agency's guidelines and policies to increase the level of scrutiny for proposals within or near the floodplains. Second, NCPC may undertake a number of planning initiatives and local and regional partnerships to further evaluate flooding and stormwater issues and research new and innovative measures for stormwater management. Third, NCPC may encourage more proactive stormwater management tactics to improve the water baseline and ensure that future development does not exacerbate the situation. No one solution can eliminate the potential problem entirely, but a strategic combination, weighed by the costs and benefits, could help minimize the risk by lowering the frequency and magnitude of flooding that does occur.

8.5. Limitations

1. The results of HAZUS are considered as average damage losses to a group of similar buildings. However, there are different types of especial buildings such as museums and governmental buildings with different resistance functionalities against floods.
2. Due to the lack of inventory data, damages to transportation systems and utilities have not been calculated. Results only show their dollar exposure to flooding.
3. The most detailed available data for the region was 1/9 Arcsec DEM map which has derived from USGS. This map does not work well for identifying levee protections.
4. The flood model is more sensitive to the damages in census blocks that have few buildings because of their small measurement scale.
5. HAZUS cannot calculate the damage loss due to ground failure or erosion, and damage loss through earthquake-driven flooding events, like tsunamis; however, these two mechanisms are not important in the present study region.
6. The flood model performs its analysis at the census block level. This means that the analysis starts with a small number of buildings within each census block and applies a series of distributions necessary for analyzing the potential damage. The application of these distributions and the small number of buildings make the flood

model more sensitive to rounding errors that introduces uncertainty into the building count results.

8.6. Further Research Opportunities

This chapter addresses the limitations of this study and gives recommendations to improve the loss estimation analysis. The results shown in section 5 reflect data for those census blocks included in the study region. The estimates of social and economic impacts contained in this report were produced using HAZUS loss estimation software which is based on current scientific and engineering knowledge. There are uncertainties inherent in any loss estimation technique. Therefore, there may be significant differences between the modeled results contained in this report and the actual social and economic losses following a specific flood. These results can be improved by using enhanced inventory data and flood hazard information.

8.6.1. Delineate Flood map using FIT & What-if Functions

One of the best suggestions to improve the accuracy of these analyses is to develop what-if functions to the Flood Model including: testing various types of future levee protections, calculating the velocity of floodwater, taking floodplain regulations into account, and restudying flood mappings. Moreover, adding a levee alignment and attribute the levee with a level of protection would help to evaluate levee's level of protection and differentiate various types according to their heights in order to fine proper levee for the region.

8.6.2. Apply ADCIRC and SWAN storm surge modeling

SLOSH model is a simple software program that can be used for identifying storm surges. The data derived from SLOSH is conservative with a large amount of uncertainties because this model is a fairly unsophisticated tool with respect to the physics of surge and waves and does not handle complex topography well. The following paragraphs introduce two alternatives for simulating the storm surge of Washington.

ADCIRC is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids. Typical ADCIRC applications have included: (i) modeling tides and wind driven circulation, (ii) analysis of hurricane storm surge and flooding, (iii) dredging feasibility and material disposal studies, (iv) larval transport studies, (v) near shore marine operations (www.adcirc.org, June 22, 2010). This program is very complicated and also gives the best possible predictions of storm surges.

The other applicable program is SWAN Model. SWAN Model is the most widely used computer model to compute irregular waves in coastal environments, based on deep water wave conditions, wind, bottom topography, currents and tides (deep and shallow water). SWAN explicitly accounts for all relevant processes of propagation, generation by wind, interactions between the waves and decay by breaking and bottom friction. Diffraction is included in an approximate manner in SWAN. One of the advantages of SWAN-DHH is that it provides options to produce pictures of the computed wave parameters directly from the program itself. Using PostScript it also has become possible to generate colored pictures which can be used for presentation to principals, managers and the general public (DHH, 2011).

8.6.3. Increase Accuracy of Inventory Data

All inventory data used for running this loss estimation analysis is based on data available in the census blocks as the smallest units of the region. The smallest units that can be used to increase the accuracy of estimating dollar exposure to flooding is exact information of buildings in the floodplain. This information can be gathered by conducting the field research to identify the types of buildings and their associated prices. This research will be very sensitive to essential buildings such as museums and important governmental buildings

8.6.4. Define Specific Damage Curves For Essential Inventories

The discussed depth damage curves in this thesis are limited to the typical buildings that are classified through all the US. This region contains uncommon inventories, including museums and important governmental buildings, which can be considered as individual buildings that should be added to the study region. Each of these buildings may have different characteristics leading to different vulnerability against flooding.

Within the HAZUS Model there is an opportunity to select alternative depth damage functions from the extensive library of functions. Additional depth damage functions can also be found at the USACE Baltimore District or floodplain manager that develop post-flood surveys for depth-damage relationships. In conclusion, future research can develop a custom depth damage curve which follows the unique characteristics of the associated defined buildings. There is also an opportunity to create the damage function in order to identify specific depth damage curves for each of these buildings.

8.6.5. Estimate Indirect Economic Losses

Indirect Economic Loss Estimation encompasses valuating any economic disruption or ripple effects that follow from direct losses due to flooding in the area. Research should be done in order to develop a relationship between the Indirect Economic Loss Module, the traditional modeling approach for tracing indirect losses, and supply and demand shocks that occur in such events. Therefore, it would be beneficial to run the HAZUS Indirect Economic Loss Module by applying all the extensive economic status of the region.

8.6.6. Considering Lifeline Utility Systems Individually

Utility systems include potable water, wastewater, oil, natural gas, electric power, and communication systems. In the model used for this study these types of facilities have been calculated as attached mechanisms to buildings. For future studies the lifeline systems should be considered as separate components that makeup the system into a set of pre-defined classes. The classification system used in this method considers all these lifelines as building components. In order to generate a more detailed analysis than this study the model should differentiate between varying lifeline system components with substantially different damage and loss characteristics because the malfunctioning of these utilities can lead to significantly more direct and indirect costs and unidentified consequences.

In conclusion, an effort should be made to classify these components based on their vulnerability to flooding. In order to calculate the dollar exposure of these facilities to flooding, required database for the analysis should be gathered. The inventory data required for the damage analysis includes the geographical location and classification of system components. The analysis also requires the replacement cost and repair cost for utilities. Applying proper damage functions provides precise results such as cost to clean-up, repair or replace and the overall costs and time of recovery. The new Flood Model can also consider flood borne debris impact, or water borne debris loads, which can cause significant clean-up efforts for utility systems.

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