STOCHASTIC ANALYSIS OF STORM-SURGE INDUCED INFRASTRUCTURE LOSSES IN NEW YORK CITY

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ABSTRACT

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Hurricanes are among the most catastrophic types of natural hazards, with the potential to cause serious losses in lives and property. While hurricanes rarely have a huge impact on the New York City area, they do have the potential to cause major damage to the city’s transportation infrastructure. This research will deal with two main considerations—fragility curves and exceedance curves of vulnerable points in that infrastructure.

The primary objective of this study is to provide a model for predicting future hurricane related storm surge patterns and for estimating possible levels of damage from future events in order to develop planning strategies to mitigate against possible damage. The first step is to describe the frequency of past storm surge events in New York City from 1920 to 2012 and determine a probability distribution for hurricane hazard about the maximum daily and yearly storm surges. The second step is to estimate potential probabilistic models by looking at the empirical data on storm surges in New York City. The last step is to
concentrate on the reliability assessment for several infrastructures subjected to hurricane loading and storm surges.

No significant studies have been conducted using the available empirical data on storm surge heights in New York City, despite the fact that since an observation station was installed in the Battery, New York in 1920, daily and yearly maximum water levels at that location have been documented by the National Oceanic and Atmospheric Administration (NOAA). Considering the available daily maximum sea water levels from 1920 to 2012 yields a total of 31,148 data points (2,394 days of maximum height data are unfortunately missing); 92 data points of maximum sea water levels are also available. This is the first study to utilize the nearly century’s worth of empirical data obtained by the observation station at the Battery.

Extensive goodness of fit testing (including the use of various probability papers) is performed on the empirical daily maximum sea water level data. It is concluded that the daily maximum sea water levels at the Battery from 1920 to 2012 follow closely a logistic distribution, with a mean value of 8.10 feet and a coefficient of variation (COV) of 9.63%. The methodology of analyzing the yearly maximum sea water levels is quite similar to that used for the daily sea water levels (and the analysis is performed independently). It is found that the yearly maximum sea water levels at the Battery from 1920 to 2012 follow closely a generalized extreme value (GEV) distribution with a mean value of 10.72 feet and a COV of 10.07%. Then, applying exact and asymptotic Extreme Value
Theory, the parent GEV distribution is used to determine the probability distributions for maximum sea water levels over a range of different multi-year periods including 1, 10, 50, 100, 200, and 500 years.

Finally, the total volume of flood-vulnerable infrastructure is generated and flood damage probabilities when related to the established probability distributions for sea water levels are considered. The flood vulnerabilities of different parts of the built infrastructure in New York City are studied; specifically, the subway system and the tunnel system. The concept of fragility curves is used to express these vulnerabilities. Conclusions and recommendations are provided for estimating losses probabilistically over different periods, retrofitting and strengthening the infrastructure to reduce future potential losses, and determining repair priorities. This is very useful for cost-benefit analysis.
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Chapter 1. Introduction

1.1 Background of Hurricane Loss and Preparedness

On August 29, 2005 Hurricane Katrina virtually destroyed the city of New Orleans, killing many residents and displacing hundreds of thousands. As of early August 2006, the death toll exceeded 1,800 and total damages/costs were estimated to be around $125 billion (Graumann and Center, 2006). Katrina was one of the strongest storms to impact the United States in 100 years, 127-mile-an-hour winds (NOAA, 2012) as it made landfall. It was a Category 3 hurricane on the Saffir-Simpson scale. The hurricane's storm surge was 29-feet high, which was the highest ever measured in the United States (Graumann and Center, 2006).

Economists have said that damage and loss from hurricane Sandy in 2012, which blasted the U.S. Mid-Atlantic Coast and shut down New York City, could hit $50 billion (Walsh and Schwartz, 2012). The damage in lower Manhattan and the loss from two days of financial market blackout and bank closures make for a significant proportion of the loss. Sandy was the second most costly natural disaster in the U.S., following hurricane Katrina in 2005. Eqecat, a catastrophe risk modeling company, indicates that the high damage estimate is partly due to the large electrical blackouts and transportation infrastructure losses–transit and road closures. Much of the city was shut down many days longer than expected.
At least 75 people died in cities along the coast, most of them centered in the New York City area. Many homes were destroyed by flooding and winds; power failures affected more than 8 million customers (Searcey, 2012). Transportation in much of New York City was a disaster due to suspended subway service, closed bridges and tunnels, and prolonged power failure in all of lower Manhattan. The largest losses will come from the financial industry, heavily concentrated in the lowest-lying, most flood-vulnerable areas in lower Manhattan, and in the heavy-hit suburbs in New Jersey.

Lower Manhattan, including the Battery Park area, is easily flooded due to the fact that it is at critical lowest elevation (CLE) and is adjacent to the sea. Since the South Ferry Station of the number 1 subway line has a CLE of 4 feet, it can succumb to flooding very easily. Even though Sandy did not bring significant rainfall to New York City, the Battery was flooded by the storm surge. Although the storm was a Category 1 hurricane on the Saffir-Simpson scale (OEM, 2009), its impact was similar to that of Hurricane Donna (1960), Category 2 hurricane.

People in other U.S. coastal cities, such as New York, Miami, and Boston, should prepare for possible future disasters equivalent to Hurricane Katrina and Sandy.
1.2 Literature Review

Many researchers have studied hurricane wind speeds but less research has been done on water level rise associated with hurricanes. According to Walton (Walton, 2000), early research on extreme water levels focused on analyzing observations of astronomical tide data and meteorologically driven levels. Researchers have recently begun recognizing the importance of the difference between meteorological and astronomical components in water level data, trying to estimate separately the stochastic components (meteorological surges) from deterministic components (astronomical tides). In this research, however, the previous two methods are analyzed simultaneously to determine an accurate trend.

In recent years, due to climate change, the world has suffered much more extreme climatic and hydrological events. There are several studies of risk assessment of hurricanes for New York City. Lin (Lin et al., 2010) developed a model-based study of hurricane storm surge levels using the SLOSH (sea, lake, and overland surges from hurricanes) model simulation. Gornitz (Gornitz et al., 2001) analyzed sea level rise scenarios for different return periods with several global climate model (GCM) simulations.

Also, the ClimAid initiative (ClimAid, 2010) New York state’s assessment project for climate change adaptation strategies has published an overview of the vulnerabilities of the New York’s transportation system as climate change takes place. They have concluded that hazards, risk, and potential
future losses from climate change to transportation systems and the economy are likely to increase.

1.3 Motivation and Objective of Research

Hurricanes rarely have a significant impact on the New York City area, but when they become severe they can produce high winds, heavy rainfall flooding, and coastal flooding. The rise in sea water levels from a hurricane’s storm surge may last for only a few hours, but in the case of a serious storm that can be enough time to flood New York City’s transportation infrastructures—tunnels, subways and train systems (Colle et al., 2010). Because hurricanes have not caused severe damage and losses in New York City prior to Hurricane Sandy (2012), hurricane studies relevant to New York City are not common. However, New York City is a hub of finance and economy, and flooding can bring tremendous damage. This study will focus on lower Manhattan, as it relies on water level data obtained from an observation station in that area. The lower Manhattan area has also proven to be especially prone to flood damage. This area includes the Battery, as the southern tip of Manhattan is known, Battery Park, Battery Park City, which is a planned community built on low-lying landfill along the coast, and the financial district, which is located in the vicinity of Battery Park City.
During the last century, New York City has been hit by only a small number of hurricanes. Yet 2011’s Hurricane Irene and 2012’s Hurricane Sandy suggest that hurricanes may become annual events in the area and that the possibility of damage and loss from hurricane events are likely to increase over time. Therefore, analyzing sea water levels and estimating simulated loss are key in planning and preparing mitigating actions for major hurricane events.

This research examines the long-term changes in water levels in New York City to estimate the adequacy of fit testing of a variety of probability distributions of hurricane events in New York City. The first step is to collect past storm tide data in New York City from 1920 to 2012. After analyzing these data, the next step is to determine a probability distribution for storm surge hazard. Finally, using these distributions, exceedance curves and fragility curves of the infrastructure are described to assess the risk for uncertain future events.

**Figure 1.1 Flow Chart for Risk Assessment from Future Hurricane Events.**
Also, this research is important in that it uses historical data from the last century; no previous research has been done using the full 93 years of water level observations that have been available for New York City.

1.4 Organization of Dissertation

The organization of the dissertation is described as follows:

Chapter 1 contains a background introduction on historical hurricane losses, followed by a brief literature review. It answers questions such as why hurricane loss estimation is necessary, who is interested in it.

Chapter 2 provides more detailed descriptions of water height data for New York City from 1920 to 2012. It explains how to measure water levels, how to use the data from NOAA and determines the distribution of frequency about the maximum daily/yearly water heights. Also, future risks are established through a probabilistic model of water level heights derived from the empirical data available for New York City.

Chapter 3 estimates a calculation of flooding of the infrastructure in New York City. A history of the flooding in New York City during the last century is detailed in this chapter. Methods of calculating the flood volume of the infrastructure with each storm surge are suggested and shown.
Chapter 4 develops a Monte Carlo simulation to estimate the vulnerabilities of different parts of the infrastructure in New York City. Using the established probability distributions for sea water levels, the vulnerabilities of different parts of the infrastructure in New York City are studied. Also, methodological developments in both hurricane hazard modeling and damage risk assessment are described, and the development of a structural damage vulnerability model is explored.

Chapter 5 wraps up the entire dissertation and highlights the basic assumptions and major capabilities of the methodology of hurricane loss estimation using Monte Carlo Simulation. Future works are discussed at the end.
Chapter 2. HURRICANES IN THE NEW YORK CITY METROPOLITAN AREA

2.1 History of Hurricanes

The vulnerability of an infrastructure can be defined in relation to the categories of hurricanes (OEM, 2009). Hurricanes are categorized according to their wind strength through the Saffir-Simpson Hurricane Scale. A Category 1 storm has the lowest wind speed, while a Category 5 has the highest. Table 2.1 shows the storm surge levels and wind speeds for hurricanes in each category in New York City (from OEM, New York City Coastal Storm Plan (CSP, 2008) NYC Office of Emergency Management). Table 2.2 details predicted damage levels associated with each storm category (OEM, 2009).

Table 2.1 Saffir-Simpson Hurricane Scale with Predicted Storm Surge Levels for New York City (OEM, New York City Natural Hazard Mitigation (2009)).

<table>
<thead>
<tr>
<th>Category scale</th>
<th>Max. Sustained Wind (MSW)</th>
<th>Storm Surge in NYC NAVD88 (Station Datum)</th>
<th>Damage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Depression</td>
<td>&lt; 39 mph</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tropical Storm (TS)</td>
<td>39 - 73 mph</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Category 1 (H1)</td>
<td>74 - 95 mph</td>
<td>6.1-10.5ft (12.17 – 16.57)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Category 2 (H2)</td>
<td>96 - 110 mph</td>
<td>13.0-16.5ft (19.07 – 22.57)</td>
<td>Moderate-Severe</td>
</tr>
<tr>
<td>Category 3 (H3)</td>
<td>111 - 130 mph</td>
<td>14.8-25.0ft (20.87 – 31.07)</td>
<td>Extensive</td>
</tr>
<tr>
<td>Category 4 (H4)</td>
<td>131 - 155 mph</td>
<td>24.6-31.3ft (30.67 – 32.00)</td>
<td>Extreme</td>
</tr>
<tr>
<td>Category 5(H5)</td>
<td>&gt; 155 mph</td>
<td>Not predicted</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>
Table 2.2 Saffir-Simpson Hurricane Scale with Predicted Damage Descriptions (OEM, New York City Natural Hazard Mitigation (2009)).

<table>
<thead>
<tr>
<th>Category</th>
<th>Damage Description</th>
</tr>
</thead>
</table>
| 1        | • Damage primarily to trees and unanchored homes  
           • Some damage to poorly constructed signs  
           • Coastal road flooding |
| 2        | • Some roofing material, door, and wind damage to buildings  
           • Considerable damage to shrubbery and trees  
           • Flooding of Low-lying areas |
| 3        | • Some structural damage to residences and utility buildings  
           • Foliage blown off trees and large trees blown down  
           • Structures close to the coast will have structural damage by floating debris |
| 4        | • Curtain wall failures with utilities and roof structures on residential buildings  
           • Shrubs, trees, and signs all blown down  
           • Extensive damage to doors and windows  
           • Major damage to lower floors of structures near the shore |
| 5        | • Complete roof failure on many residence and industrial buildings  
           • Some complete building and utility failures  
           • Severe, extensive window and door damage  
           • Major damage to lower floors of all structures close to shore |

According to Office of Emergency Management (OEM), when New York City experiences a Category 1 hurricane, it is expected to experience moderate damage. However, 2012’s hurricane Sandy shows that the data in Table 2.1 are serious underestimations of loss and damage that occur in the event of a Category
1 hurricane. The *New York Times* reported that Hurricane Sandy was a Category 1 hurricane with 80 mph winds on Oct. 29, 2012. However, New York City suffered considerable damage from Sandy—greater than that estimated in the event of a Category 2 hurricane.

Since 1900, there have been 31 hurricanes (Figure 2.1) within a 80-mile radius of New York City (NOAA, 2012). The 80-mile radius was selected and implemented so that the strongest hurricane, Donna, which passed 80 miles southeast of the city, could be included in this research. There have also been four significant nor’easters, which we will also consider for the high levels of flooding they generated. The following map (Figure 2.2) shows the paths of hurricanes that recorded wind speeds greater than Category 1 from 1920 to 2012. Although hurricane Irene did not make landfall as a Category 1 hurricane, and Hurricane Sandy did not pass through 80-mile radius, these two hurricanes are included in this figure because they were very recent and because they caused significant flooding. Hurricane Irene did hit New York City directly as a tropical storm, and Hurricane Sandy caused tremendous damage and loss in New York City.
Figure 2.1 Historic Hurricanes within a 80-mile Radius from New York City (NOAA, 2012).

Figure 2.2 Paths of Hurricanes which Recorded as Greater than Category 1 and Irene (NOAA, 2012).
Table 2.3 List of Significant Hurricanes in New York City (within the 80-mile radius) (source from NOAA, 2012).

<table>
<thead>
<tr>
<th>No</th>
<th>Year</th>
<th>Name</th>
<th>Date</th>
<th>Max. Cat.</th>
<th>wind speed (mph)</th>
<th>Arrival in NYC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max. Surge (ft)</td>
<td>Cat.</td>
</tr>
<tr>
<td>1</td>
<td>1902</td>
<td>Not named</td>
<td>Jun.12-Jun17</td>
<td>TS</td>
<td>58</td>
<td>_</td>
</tr>
<tr>
<td>2</td>
<td>1903</td>
<td>Not named</td>
<td>Sep.12-Sep.17</td>
<td>H2</td>
<td>98</td>
<td>_</td>
</tr>
<tr>
<td>3</td>
<td>1904</td>
<td>Not named</td>
<td>Sep.8-Sep.15</td>
<td>ET</td>
<td>86</td>
<td>_</td>
</tr>
<tr>
<td>4</td>
<td>1915</td>
<td>Not named</td>
<td>Jul.31-Aug.5</td>
<td>H1</td>
<td>75</td>
<td>_</td>
</tr>
<tr>
<td>5</td>
<td>1916</td>
<td>Not named</td>
<td>May13-May18</td>
<td>H1</td>
<td>58</td>
<td>_</td>
</tr>
<tr>
<td>6</td>
<td>1924</td>
<td>Not named</td>
<td>Sep.27-Oct.1</td>
<td>ET</td>
<td>75</td>
<td>_</td>
</tr>
<tr>
<td>7</td>
<td>1929</td>
<td>Not named</td>
<td>Sep.22-Oct.4</td>
<td>H4</td>
<td>138</td>
<td>10.10</td>
</tr>
<tr>
<td>8</td>
<td>1934</td>
<td>Not named</td>
<td>Jun.4-Jun21</td>
<td>H1</td>
<td>81</td>
<td>8.10</td>
</tr>
<tr>
<td>9</td>
<td>1934</td>
<td>Not named</td>
<td>Sep.5-Sep.9</td>
<td>H2</td>
<td>98</td>
<td>9.10</td>
</tr>
<tr>
<td>10</td>
<td>1938</td>
<td>Not named</td>
<td>Sep.10-Sep.22</td>
<td>H5</td>
<td>161</td>
<td>10.90</td>
</tr>
<tr>
<td>11</td>
<td>1939</td>
<td>Not named</td>
<td>Aug.7-Aug.20</td>
<td>H1</td>
<td>81</td>
<td>9.00</td>
</tr>
<tr>
<td>12</td>
<td>1944</td>
<td>Not named</td>
<td>Sep.9-Sep.16</td>
<td>H4</td>
<td>138</td>
<td>11.20</td>
</tr>
<tr>
<td>13</td>
<td>1945</td>
<td>Not named</td>
<td>Sep.12-Sep.20</td>
<td>H4</td>
<td>138</td>
<td>9.54</td>
</tr>
<tr>
<td>14</td>
<td>1952</td>
<td>Able</td>
<td>Aug.18-Sep.2</td>
<td>H2</td>
<td>104</td>
<td>9.00</td>
</tr>
<tr>
<td>15</td>
<td>1954</td>
<td>Carol</td>
<td>Aug. 25-Sep.1</td>
<td>H2</td>
<td>85</td>
<td>10.30</td>
</tr>
<tr>
<td>16</td>
<td>1955</td>
<td>Diane</td>
<td>Aug.7-Aug.21</td>
<td>H3</td>
<td>121</td>
<td>9.28</td>
</tr>
<tr>
<td>17</td>
<td>1960</td>
<td>Brenda</td>
<td>Jul.28-Aug.1</td>
<td>TS</td>
<td>58</td>
<td>8.80</td>
</tr>
<tr>
<td>18</td>
<td>1960</td>
<td>Donna</td>
<td>Aug.29-Sep.14</td>
<td>H5</td>
<td>161</td>
<td>13.30</td>
</tr>
<tr>
<td>19</td>
<td>1961</td>
<td>Unnamed</td>
<td>Sep.12-Sep.15</td>
<td>TS</td>
<td>40</td>
<td>8.10</td>
</tr>
<tr>
<td>20</td>
<td>1971</td>
<td>Doria</td>
<td>Aug.20-Aug.29</td>
<td>TS</td>
<td>63</td>
<td>8.92</td>
</tr>
<tr>
<td>22</td>
<td>1976</td>
<td>Belle</td>
<td>Aug.6-Aug.10</td>
<td>H3</td>
<td>121</td>
<td>9.80</td>
</tr>
<tr>
<td>23</td>
<td>1985</td>
<td>Gloria</td>
<td>Sep.16.-Oct.2</td>
<td>H4</td>
<td>144</td>
<td>11.32</td>
</tr>
<tr>
<td>24</td>
<td>1985</td>
<td>Henri</td>
<td>Sep.21-Sep.25</td>
<td>TS</td>
<td>58</td>
<td>8.68</td>
</tr>
<tr>
<td>25</td>
<td>1988</td>
<td>Chris</td>
<td>Aug.21-Aug.30</td>
<td>TS</td>
<td>52</td>
<td>9.52</td>
</tr>
<tr>
<td>26</td>
<td>1996</td>
<td>Berths</td>
<td>Jul.5-Jul.17</td>
<td>H3</td>
<td>115</td>
<td>9.88</td>
</tr>
<tr>
<td>27</td>
<td>1999</td>
<td>Floyd</td>
<td>Sep.7-Sep.16</td>
<td>H4</td>
<td>155</td>
<td>9.52</td>
</tr>
<tr>
<td>28</td>
<td>2000</td>
<td>Gordon</td>
<td>Sep.14-Sep.21</td>
<td>H1</td>
<td>81</td>
<td>10.3</td>
</tr>
<tr>
<td>29</td>
<td>2008</td>
<td>Hanna</td>
<td>Aug.28-Sep.8</td>
<td>H1</td>
<td>86</td>
<td>9.88</td>
</tr>
<tr>
<td>30</td>
<td>2011</td>
<td>Irene</td>
<td>Aug.24-Aug.29</td>
<td>H2</td>
<td>115</td>
<td>12.71</td>
</tr>
<tr>
<td>31</td>
<td>2012</td>
<td>Sandy</td>
<td>Oct. 26-Oct.31</td>
<td>H2</td>
<td>110</td>
<td>17.27</td>
</tr>
</tbody>
</table>

* Cat. = Category Scale (Table 2.1)
Table 2.4 List of Significant Nor’easters in New York City.

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Name</th>
<th>Surge (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dec. 2, 1992</td>
<td>Nor’easter</td>
<td>12.99</td>
</tr>
<tr>
<td>2</td>
<td>Jan. 3, 1999</td>
<td>Nor’easter</td>
<td>10.64</td>
</tr>
<tr>
<td>3</td>
<td>Apr. 15, 2007</td>
<td>Nor’easter</td>
<td>10.95</td>
</tr>
<tr>
<td>4</td>
<td>Dec. 26, 2010</td>
<td>Nor’easter</td>
<td>9.96</td>
</tr>
</tbody>
</table>

Table 2.3 lists the dates, maximum wind speeds (mph), and category of hurricanes that have hit New York City (within the 80-mile radius) between 1900 and 2012, along with wind speed and storm surge upon arrival in the city. Even though the original strengths varied, depending on other factors such as the radius of the storm, the route, and the origination, the damage and devastation that each hurricane caused were as severe as described in Table 2.5, which shows data obtained from OEM for the 13 coastal storms in New York City from 1938 to 2007.
Table 2.5 Historic Occurrences of Coastal Storms in New York City (OEM, 2009).

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Location(s)</th>
<th>Description</th>
</tr>
</thead>
</table>
| Sep. 21, 1938 | Hurricane   | Citywide    | • Category 3  
• Most Powerful Hurricane to make landfall near New York City  
• Eye crossed over Long Island living its name, the Long Island Express  
• Killed nearly 200 people total; 10 in New York City  
• Electricity Knocked out north of 59th street in Manhattan  
• 100 Large trees in Central Park were destroyed |
| Aug. 30, 1954 | Hurricane   | Citywide    | • Made landfall in eastern Long Island and SE Connecticut  
• Sustained winds more than 100 mph and gusts 115 to 125 mph  
• Most destructive hurricane to hit the northeast coast since the 1938 hurricane  
• Major flooding throughout the City |
| Aug. 19, 1955 | Hurricanes  | Citywide    | • Leftover rains from hurricanes dropped nearly 12 inches of rain at LaGuardia Airport  
• In just over one week, the remnants of 2 hurricanes passed over the City  
• Created an 11-foot storm tide in New York Harbor and caused extensive pier damage |
| Sept. 12, 1960 | Hurricane   | Citywide    | • Agnes fused with another storm system in the northeastern U.S., flooding areas from North Carolina to New York State  
• Caused 122 deaths  
• More than $6 billion in damage (when adjusted for inflation) |
| June 22, 1972 | Tropical Storm | Citywide | • Category 3  
• Made landfall on Long Island at 80 mph  
• Produced a modest storm surge of 4-7 feet above normal across the Atlantic |
<table>
<thead>
<tr>
<th>Date</th>
<th>Type</th>
<th>Location</th>
<th>Event Details</th>
</tr>
</thead>
</table>
| Dec. 21, 1992 | Nor'easter     | Citywide       | • Could have produced a much stronger and intense storm surge if it happened during high tide  
• Caused the largest single power loss in U.S. history at the time  
• Total damage estimated at $900 million in 1986 |
| June 17, 1995 | Hurricane Felix | Citywide       | • Flooding and coastal erosion, debris  
• Damage to residential and commercial structures, utility lines, roads and other infrastructure |
| June 18, 1996 | Tropical Storm Bertha | Citywide | • Hurricane Felix lingered off the East Coast for nearly a week, menacing the northeastern U.S. before it finally drifted out to sea |
| Jan. 3, 1999 | Nor'easter      | Citywide       | • Weakening storm brought heavy rain to the City |
| Sept. 16, 1999 | Tropical Storm Floyd | Citywide | • Flooded subway tunnels across the City causing service disruptions  
• Dropped 10-15 inches of rain in a 24-hour period  
• Public schools closed for the day |
| Sept. 18, 2003 | Tropical Storm Isabel | Brooklyn, Bronx, Queens, Staten Island | • One fatality in the NY area – a man drowned while bodysurfing off Long Beach, Long Island  
• A fallen tree branch in the Bronx seriously injured a man  
• 640 trees and 801 tree limbs were downed across the City  
• Total damage exceeded $1 billion along the East Coast |
| Apr. 15, 2007 | Nor'easter      | Citywide       | • More than 7.5 inches of rain in Central Park  
• More than 500 flights cancelled  
• Disrupted power to 18,500 customers in three states |
Table 2.6 counts the number of occurrences of hurricanes in each decade in New York City. Although historically New York City has had few hurricanes, it has already suffered two hurricanes since 2012.

There was a significant hurricane that passed near the city in 1960. It was Hurricane Donna, which recorded the highest surge and the greatest amount of flooding prior to hurricane Sandy. Hurricane Donna moved across Puerto Rico, Hispaniola, Cuba, the Bahamas and many states on the east coast of the United States. It was a Category 3 or greater on the Saffir-Simpson Hurricane Scale in the Atlantic Basin from September 2 to September 11. Donna roamed the Atlantic from August 29 to September 14, a total of 17 days and, during that period, briefly achieved Category 5 strength. Donna’s storm surge measured 13.3 feet in the Battery Park area of lower Manhattan.
In 2011, the storm surge breached the seawall at several points in lower Manhattan, including near the Staten Island Ferry Terminal. Roadways became flooded, including the Henry Hudson Parkway, the West Side Highway and the Franklin Delano Roosevelt Drive in Manhattan, as well as the Belt Parkway in Brooklyn.

In 2012, New York City suffered tremendous loss and dreadful damage from Hurricane Sandy. The high winds and heavy rain caused damage to the city unlike that seen from any hurricane before. The highest storm surge (17.27 feet), broke the old record, hit New York Harbor and flooded New York’s financial district, located very closely to the Battery at the southern tip of Manhattan, Battery Park, and Battery Park City, all areas located along the Hudson river and extremely vulnerable to flooding from storm surges.
Figure 2.3 After being hit by Hurricane Donna, the Intersection of West and Cortlandt Streets is turned into a Wind-tossed Lake by the passing Storm (Courtesy of The New York Times, Sept. 13. 1960).

Figure 2.4 A New York City Taxi is stranded in Deep Water on Manhattan’s West Side after Hurricane Irene passed through the City (Courtesy of CTV News, Aug. 28. 2011).
Figure 2.5 A Taxi Driver was pulled out of his cab at 51st and FDR Drive City (Courtesy of New York Times, Oct. 30, 2012).
2.2 Definitions of Reference Levels for the Analysis of the Data

There are 251 water level observation stations in the United States (including offshore islands). New York State has 4 stations at the following locations: Montauk, Kings Point, the Battery, and Bergen Point. New Jersey has 6 stations: at Sandy Hook, Atlantic City, Cape May, Ship John Shoal, Tacony-Palmyra Bridge, and Burlington. This study uses the data from the Battery Station in New York City.

Since an observation station was installed in the Battery in 1920, replacing the preceding station on Governor’s Island, water levels in lower Manhattan have been documented by the National Oceanic and Atmospheric Administration (NOAA). This research focuses on Station Datum in the Battery, New York between 1920 and 2012. In general, a datum is a base elevation used as a reference from which to reckon heights and depths. A Station Datum is the permanent base elevation at a tide station to which all water level measurements are referred, and is unique to each station. It is established at a lower elevation than the water is ever expected to reach. It is referenced as the primary benchmark at the station and is held constant regardless of changes to the water level gauge or tide staff (NOAA, 2012).

Figure 2.6, shows the definitions of various elevations with respect to the Station Datum at the Battery. Mean high water level, MHW, is the average of all
the high water levels observed over what is known as the National Tidal Datum Epoch. National Tidal Datum Epoch refers to the specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values for tidal data. Mean sea level, MSL, the arithmetic mean of hourly water levels observed over the National Tidal Datum Epoch. Mean low water, MLW, is the average of the low water levels of each tidal day observed over the National Tidal Datum Epoch. The surge thresholds for flooding are calculated relative to a determined baseline. New York City has set values: a mean low water level of 3.49 feet, a mean sea level of 5.86 feet, and a mean high water level 8.02 feet. All storm surge heights in this research are measured with respect to the Station Datum.

Figure 2.6 The Elevations on Station Datum at the Battery (NOAA, 2012).
Table 2.7 Elevations on Station Datum for Two Different Epochs at the Battery (NOAA, 2012).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MHW</td>
<td>7.85 feet</td>
<td>8.02 feet</td>
<td>Mean High Water</td>
</tr>
<tr>
<td>NAVD88</td>
<td>-</td>
<td>6.07 feet</td>
<td>North American Vertical Datum of 1988</td>
</tr>
<tr>
<td>MSL</td>
<td>5.65 feet</td>
<td>5.86 feet</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>NGVD29</td>
<td>4.95 feet</td>
<td>4.95 feet</td>
<td>National Geodetic Vertical Datum of 1929</td>
</tr>
<tr>
<td>MLW</td>
<td>3.29 feet</td>
<td>3.49 feet</td>
<td>Mean Low Water</td>
</tr>
<tr>
<td>STND</td>
<td>0.00 feet</td>
<td>0.00 feet</td>
<td>Station Datum</td>
</tr>
</tbody>
</table>

The Geodetic Glossary (NOAA, 2012) explains that the National Geodetic Vertical Datum of 1929 (NGVD29) is the name given, as of May 10, 1973, of what was previously called the Sea Level Datum of 1929, which is a vertical control datum established for vertical control in United States through the general adjustment of 1929, made by what is today the National Ocean Service. The name change was made to reflect the fact that the datum was set respective to the geoid, the hypothetical shape of the earth based on global mean sea level and its extension across land. Also, the North American Vertical Datum of 1988 (NAVD88), which fixed the height of the primary tidal bench mark, was established in 1991 by the minimum-constraint adjustment of Canadian-Mexican-U.S leveling observations (Table 2.7). The NAVD88 value for the 1983-2001 epoch was calculated to be 6.07 feet above the Station Datum at Battery Station.
The superseded geodetic value of NGVD29 was calculated for NAVD88 to be 4.95 feet above Station Datum at the Battery Station for the 1960-1978 epochs.

2.3 Correlation between Maximum Storm Surge Height and Its Duration for a Hurricane

There have been four critical hurricanes in New York City during the last century—Hurricane Donna (1960), Hurricane Gloria (1985), Hurricane Irene (2011), and Hurricane Sandy (2012). Usually, typical tidal curves have simple cosine waves and a period of 12 hours and 25 minutes (12.42 mean solar hours) (Boon, 2004). When a hurricane hits the city, its tidal curves change. Figure 2.7 shows the evolution of the tide height during these four events. These are time histories of storm surge levels before and after each hurricane has made landfall. The maximum water level is the difference between peak amplitude and lower amplitude associated with each hurricane and the period is the duration between two successive low water points when the water has the highest value.

Until Hurricane Sandy occurred, Hurricane Donna had held the record for severity of hurricane impact, generating a maximum surge of 13.3 feet within 10 hours (Bureau, 1960). Hurricane Sandy created a new record surge into New York City; 17.27 feet was set at the Battery within 13 hours. Hurricanes Gloria and Irene also had significant storm surges, at 11.32 feet and 12.71 feet, respectively.
These four critical hurricanes considered here have different ratios between hourly water heights at the Battery Station and their durations. This ratio reflects how quickly the storm surge rises. Hurricane Donna has the highest ratio (0.98) among the four hurricanes (Table 2.8) and hurricane Donna exhibits the largest slope. These slopes are used to introduce some uncertainty in generating random slopes, as we will explore in Chapter 3.
Figure 2.7 The Hourly Storm Surge levels at the Battery during Hurricanes Donna, Gloria, Irene and Sandy.
Table 2.8 Ratios of Peak Storm Surge Height to Duration (Height/hours) during the Hurricane.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Heights (ft)</td>
<td>13.30</td>
<td>11.32</td>
<td>12.71</td>
<td>17.27</td>
</tr>
<tr>
<td>Heights (ft)</td>
<td>9.80</td>
<td>8.57</td>
<td>8.33</td>
<td>10.19</td>
</tr>
<tr>
<td>Period (hrs)</td>
<td>10</td>
<td>14</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Ratio (ft/hrs)</td>
<td>0.98</td>
<td>0.61</td>
<td>0.70</td>
<td>0.78</td>
</tr>
</tbody>
</table>

2.4 Analysis of Maximum Daily Water Heights in New York City (Battery Station)

2.4.1 Fitting and Statistics

A time series of the maximum daily water heights from June 1920 to October 2012 in New York City is shown in Figure 2.8 (NOAA, 2012). A time series can be used by management to make plans based on long-term forecasting (Von Storch and Zwiers, 2002). It assumes that past patterns will continue into the future. With a statistical analysis of the storm tide data, the probability distribution of the maximum daily storm tide heights can be obtained. The mean of the maximum daily water heights at the Battery is 8.1 feet with a standard deviation of 0.78. Figure 2.8 also shows a linear trend: a steadily upward sloping line. This shows that the mean value of maximum daily water levels is increasing linearly with a computed constant standard deviation over time at the Battery.
Figure 2.8 Time Series of the Maximum Daily Storm Water Heights at the Battery between 1920 and 2012 (sources from NOAA, 2012).

Figure 2.9 Histogram of the Maximum Daily Storm Water Heights at the Battery between 1920 and 2012.
The typical time history of the maximum daily tide heights is shown in Figure 2.10 from June 1, 1920 to Dec. 10, 2012 with an applied linear regression. For a statistical analysis of this time series, a moving average can be applied by creating a series of averages of different subsets of the full data set. A moving average is commonly used with time series data to smooth out certain period trends or cycles. In this case, 4 periods: 1 year, 3 years, 5 years and, 10 years (Figure 2.11, Figure 2.12, Figure 2.13 and Figure 2.14) - are considered to find the moving average.

![Figure 2.10 Time Series and Linear Regression Line about Maximum Daily Storm Water Heights.](image)
Figure 2.11 Moving Average Plot of Maximum Daily Storm Water Heights for a 1-Year Smoothing Window.

Figure 2.12 Moving Average Plot of Maximum Daily Storm Water Heights for a 3-Year Smoothing Window.
Figure 2.13 Moving Average Plot of Maximum Daily Storm Water Heights for a 5-Year Smoothing Window.

Figure 2.14 Moving Average Plot of Maximum Daily Storm Water Heights for a 10-Year Smoothing Window.
Figure 2.15 Moving Standard Deviation Plot of Maximum Daily Storm Water Heights for a 1-Year Smoothing Window.

Figure 2.16 Moving Standard Deviation Plot of Maximum Daily Storm Water Heights for a 3-Year Smoothing Window.
Figure 2.17 Moving Standard Deviation Plot of Maximum Daily Storm Water Heights for a 5-Year Smoothing Window.

Figure 2.18 Moving Standard Deviation Plot of Maximum Daily Storm Water Heights for a 10-Year Smoothing Window.
The moving standard deviation is a measure of volatility. It makes no predictions of event direction, but it shows as a confirming indicator. There are moving standard deviations with the 4 different intervals. Figure 2.15, Figure 2.16, Figure 2.17 and Figure 2.18 show the moving standard deviations in a time series from 1920 to 2012 with 1 year, 3 years, 5 years, and 10 years smoothing windows, respectively. These plots indicate that the standard deviation remains essentially constant in time, while the mean value exhibits a linear increase. After subtracting the linearly increasing mean, the standard deviation was found to be a constant. Therefore, we can generate a unique distribution for the maximum daily storm surge levels from 1920 to 2012.

Table 2.9 Statistics for the Maximum Water Heights.

<table>
<thead>
<tr>
<th>Max. Daily Height</th>
<th>Number</th>
<th>Minimum (ft)</th>
<th>Maximum (ft)</th>
<th>Mean (ft)</th>
<th>Std. Deviation</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>31,148</td>
<td>3.33</td>
<td>17.27</td>
<td>8.10</td>
<td>0.78</td>
<td>9.63%</td>
</tr>
</tbody>
</table>

These maximum daily data are used for the goodness of fit testing which is used to find the parent distribution. The goodness of fit of a statistical model is a measure of how well data from a set of observations comply with a specified probability distribution. In order to estimate this, the probability paper plot is generated through statistics programs such as Minitab, SPSS and the computation program MATLAB. The probability plots are used to assess how well empirical
data approximates a particular theoretical distribution (Wilk and Gnanadesikan, 1968).

Plots using probability papers are used for each distribution of water levels in Figure 2.19 and Figure 2.20. The goodness of fit is selected for closeness of fit in the upper tail of the distribution function. The blue lines are the theoretical distributions. When the red dots closely follow the blue lines, then the data can be said to follow closely the specific distribution. Applying various types of distribution formats: normal distribution, lognormal distribution, Weibull distribution, exponential distribution and so on, it becomes clear that the logistic distribution is the most suitable as the parent distribution for the set of maximum daily water heights.
Figure 2.19 Plots of Data on Various Different Probability Papers.
Figure 2.20 Plots of Data on Various Different Probability Papers.
### 2.4.2 Logistic Distribution

Eq 2.1 is the cumulative distribution function (CDF) of the Logistic distribution (Balakrishnan, 1992),

\[ F(x; \alpha, \beta) = \frac{1}{1 + \exp\left\{-(x - \alpha)/\beta\right\}} \quad (2.1) \]

where \( \alpha \) and \( \beta \) are location and scale parameters, respectively. The probability density function (PDF) of the Logistic distribution \( x \) is

\[ f(x; \alpha, \beta) = \frac{\exp\left\{-(x - \alpha)/\beta\right\}}{[1 + \exp\left\{-(x - \alpha)/\beta\right\}^2]} \quad (2.2) \]

The mean and variance of the logistic distribution are given by

\[ \mu = \alpha \quad \text{and} \quad \sigma^2 = \frac{\pi^2 \beta^2}{3}, \beta > 0 \quad (2.3) \]

To establish a logistic distribution, we consider the mean and variance, which are obtained from the empirical data for the maximum daily water levels. Figure 2.21 illustrates a histogram of maximum daily water levels and a probability density function (PDF) of the maximum daily water levels of logistic distribution. It can express how logistic distribution fits the histogram of the observed maximum daily water levels. The cumulative distribution function (CDF) of the parent probability distribution and the observed data are shown in Figure 2.22.
Figure 2.21 Histogram of Maximum daily Water Heights and PDF of Logistic Distribution.

Figure 2.22 CDF of Maximum Daily Water Heights and Logistic Distribution CDF.
Figure 2.23 Probability Plot for the Logistic Distribution and Recorded Data (circles).

The probability plot for logistic distribution (Figure 2.23) demonstrates that the parent distribution of the empirical daily data at the Battery follows a logistic distribution. The circles are the recorded data in the Battery and the red line is the logistic distribution. Figure 2.23 also shows a circle at a point significantly off the tail; this is Hurricane Sandy. The circle representing Hurricane Donna also signals a trend off the tail, but is still closer to the logistic distribution. If the high height values are modelled with high accuracy in this plot, we might have to select a different distribution. However, overall, this logistic curve fits for all the points from the beginning point to end. It was thus concluded that the maximum daily water levels follow a logistic distribution. An effort to
better fit the right tail was abandoned in favour of fitting the maximum yearly storm surge heights.

2.5 Analysis of Maximum Yearly Storm Surges in New York City (Battery Station)

In this section, the maximum yearly water levels are analyzed to find their parent distribution from 1920 to 2012. The methodology for analysing yearly maximum water levels is quite similar to the method for daily water heights but the analysis is performed independently. Table 2.10 provides the statistics about the maximum yearly storm tide heights during the 89-year span. The total number of years from 1920 to 2012 is, of course, 93. However, since the data from 1922 to 1925 are absent, we have only 89 data points.

Figure 2.24 is the time history of the maximum yearly water heights in New York City from 1920 to 2012 with 17.27 feet (October 2012) being the highest. For example, in 1944, the maximum yearly storm tide height is 11.2 feet. This means that maximum height of every day is measured for 365 days in 1944 and then the highest value, 11.2 feet among the 365 data is selected for the maximum yearly water height in 1944. The maximum is the maximum of 365 days. So, the mean value of maximum yearly tide heights is calculated to be 10.73 feet with a COV of 10.07%.
Table 2.10 Statistics about the Maximum Yearly Storm Surge Heights.

<table>
<thead>
<tr>
<th>No.</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>8.74 feet</td>
<td>17.27 feet</td>
<td>10.73 feet</td>
<td>1.08</td>
<td>10.07 %</td>
</tr>
</tbody>
</table>

Figure 2.24 Plot of Maximum Yearly Storm Surges at the Battery.

To obtain the parent distribution, goodness of fit testing is applied for the yearly maximum, as it was for the daily maximums. Plots using probability papers are used for each distribution of maximum yearly water levels and are illustrated in Figure 2.25 and Figure 2.26. Applying various types of distribution functions, it is clear that the generalized extreme value (GEV) distribution is the most suitable as the parent distribution for a set of maximum yearly water heights.
Figure 2.25 Plots of Data on Various Different Probability Papers.
Figure 2.26 Plots of Data on Various Different Probability Papers.
2.5.1 Generalized Extreme Value Distribution

The maximum yearly water levels are fitted using a generalized extreme value (GEV) distribution, \((\alpha, \beta, \xi)\) with location parameter \((\alpha)\), scale parameter \((\beta)\), and shape parameter \((\xi)\). The PDF and CDF of the maximal GEV distribution for \(\xi \neq 0\) are given by (Gumbel, 2004):

\[
f(x; \alpha, \beta, \xi) = \frac{1}{\beta} \exp\left[-\left(1 + \frac{x - \alpha}{\beta} \frac{1}{\xi}\right) \left[1 + \frac{x - \alpha}{\beta} \frac{1}{\xi}\right] \right]
\]

For
\[1 + \frac{x - \alpha}{\beta} > 0, \text{ where } \beta > 0 \text{ and } \alpha, \xi \in \mathbb{R}\]

The CDF of the GEV distribution is

\[
F(x; \alpha, \beta, \xi) = \exp\left[-\left(1 + \frac{x - \alpha}{\beta} \frac{1}{\xi}\right) \right]
\]

For
\[1 + \frac{x - \alpha}{\beta} > 0, \text{ where } \beta > 0 \text{ and } \alpha, \xi \in \mathbb{R}\]

The mean and variance of the GEV distribution are given by

\[
\mu = \alpha + \beta \frac{\Gamma(1-\xi)-1}{\xi},
\]
\[
\sigma^2 = \frac{\beta^2 (g_2 - g_1^2)}{\xi^2}, \text{ where } g_k = \Gamma(1-k\xi)
\]
Figure 2.27 Histogram of Maximum Yearly Storm Surges and PDF of GEV Distribution.

Figure 2.28 CDF of Maximum Yearly Storm Surge and CDF of GEV Distribution.
Figure 2.27 is a histogram of maximum yearly storm surges and the PDF of the GEV for maximum yearly water levels. The CDF of the maximum yearly water levels is shown in Figure 2.28. Both are shown together with the observed data. Since the figures fit relatively well with GEV distribution curves, it is highly likely that the parent distribution of the maximum yearly water heights comply with GEV distribution. Extreme value theory will be now utilized to assess and prepare for future events.

Figure 2.29 shows a comparative analysis of the probability plot between logistic distribution and GEV distribution for the maximum yearly water levels. The blue circles represent observed data, 89 points passing closely along the line of GEV distribution. The green line is the logistic distribution, which does not fit as well with the observed maximum yearly water level data. The empirical data are distributed much closer to the probability plot line of the GEV distribution; the GEV distribution is clearly far more suitable for the observed distribution of maximum yearly water heights. This is the best fit for the entire curve. The data from the first point to the last point fit very well, except for two points; the first of these is not important because it is a very small value and the second is the data point representing Hurricane Sandy. It is indeed off the curve. If we try to find another curve, it is possible to find one that passes closer to the Sandy data point, but we are likely to miss the other points. Consequently, it is concluded that the best parent distribution is a GEV distribution with a mean value of 10.73 feet and a COV of 10.07%.
Figure 2.29 Probability Plot of Logistic Distribution, GEV Distribution and Empirical Data for Maximum Yearly Storm Surge.
2.6 Distributions of Maximum Storm Surges in a Period of n Years

2.6.1 Exact Distributions of Extremes

Extreme value theory is effective in assessing the risks for highly unusual events, since extremes of natural phenomena are significant in engineering (Haldar and Mahadevan, 2000). The statistics of such extremes can predict and help prepare for natural disasters such as the maximum hurricane event in the next n years. The exact distributions of extremes will be used here for this purpose.

Consider a random variable, $X$, with known probability distribution PDF and CDF denoted by $f_X(x)$ and $F_X(x)$ (Katz et al., 2002). In this research, GEV distribution is considered as the known probability distribution. $X_1, X_2, ..., X_n$ have to be independent random variables.

$$Y_n = \max(X_1, X_2, ..., X_n) \quad (2.7)$$

A sample of size $n$ will have a largest and a smallest value. These extreme values will also have their respective distributions which are related to the distribution of the random variable $X$ (Castillo et al., 2005). Denoting by $Y_n$ and $Z_n$ the random variables describing the largest and smallest value from such a sample of size $n$, their respective exact CDF and PDF are (Gumbel, 2004):
The CDF and the PDF of $Y_n$ is

$$F_{Y_n}(y) = [F_X(y)]^n$$

(2.8)

$$f_{Y_n}(y) = \frac{dF_{Y_n}(y)}{dy} = n[F_X(y)]^{n-1}f_X(y)$$

(2.9)

The CDF and the PDF of $Z_n$ is

$$F_{Z_n}(y) = 1 - [1 - F_X(y)]^n$$

(2.10)

$$f_{Z_n}(y) = \frac{dF_{Z_n}(y)}{dy} = n[1 - F_X(y)]^{n-1}f_X(y)$$

(2.11)

$F(y)$ is the CDF for one year which corresponds to the GEV distribution already established.

2.6.2 Results

In this research, we consider two cases: one, which looks at data from 1920 to 2011, excluding Hurricane Sandy; the other includes Hurricane Sandy (2012). Because we had finished this research before the arrival of Hurricane Sandy (Figure 2.30), additional research had to be conducted for the case which includes Hurricane Sandy (Figure 2.31).

Depending on whether or not Hurricane Sandy is included in the data, the parent distribution determined through goodness of fit testing will be different.
Therefore, we have two different types of parent distribution with 3 different parameters ($\alpha, \beta$ and $\xi$) for the GEV distribution. These two parent distributions are considered as the CDF for one year for exact distribution of extremes of $n$ years.

Applying exact extreme value theory and using the established GEV distribution for maximum yearly storm surge levels, the probability distributions for maximum sea water levels over a range of different multi-year periods is determined. Specifically, 10, 50, 100, 200, 500, 1,000 and 2,000 years are considered. These eight distributions are plotted in Figure 2.30 and Figure 2.31. When the number of years increases, the distribution moves to the right because we are expecting a larger maximum. The mean values of these curves are displayed in Table 2.11 along with peak heights and standard deviations for our two cases. The peak heights are a value at the maximum probability density of probability distribution for periods of Multi-year. For example, 17.38 feet is the mean value for 2,000 years with Hurricane Sandy. At this time, the peak height is 16.71 feet and 1.33 of standard deviation.
Figure 2.30 Probability Distributions for Maximum Storm Surges for Periods of Multi-Year (Excluding Hurricane Sandy).

Figure 2.31 Probability Distributions for Maximum Storm Surges for Periods of Multi-Year (Including Hurricane Sandy).
Table 2.11 Statistics for the Maximum Storm Surge at Various Multi-Year Intervals (Based on Exact Distributions of Extremes).

<table>
<thead>
<tr>
<th>Years</th>
<th>Excluding Hurricane Sandy (ft.)</th>
<th>Including Hurricane Sandy (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Heights</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>10.36</td>
<td>10.66</td>
</tr>
<tr>
<td>10</td>
<td>11.83</td>
<td>12.09</td>
</tr>
<tr>
<td>20</td>
<td>12.23</td>
<td>12.47</td>
</tr>
<tr>
<td>50</td>
<td>12.72</td>
<td>12.95</td>
</tr>
<tr>
<td>100</td>
<td>13.07</td>
<td>13.28</td>
</tr>
<tr>
<td>200</td>
<td>13.41</td>
<td>13.61</td>
</tr>
<tr>
<td>500</td>
<td>13.82</td>
<td>14.01</td>
</tr>
<tr>
<td>1000</td>
<td>14.11</td>
<td>14.29</td>
</tr>
<tr>
<td>2000</td>
<td>14.39</td>
<td>14.56</td>
</tr>
</tbody>
</table>

Table 2.12 Storm Surges of Return Periods for the Two Cases.

<table>
<thead>
<tr>
<th>Return periods</th>
<th>Excluding Hurricane Sandy (ft.)</th>
<th>Including Hurricane Sandy (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 years</td>
<td>11.76</td>
<td>12.03</td>
</tr>
<tr>
<td>20 years</td>
<td>12.15</td>
<td>12.60</td>
</tr>
<tr>
<td>50 years</td>
<td>12.68</td>
<td>13.38</td>
</tr>
<tr>
<td>100 years</td>
<td>13.03</td>
<td>13.98</td>
</tr>
<tr>
<td>200 years</td>
<td>13.37</td>
<td>14.34</td>
</tr>
<tr>
<td>Sandy (17.27 feet)</td>
<td>20 million years</td>
<td>2,545 years</td>
</tr>
</tbody>
</table>
The return period of a given event is the inverse of the probability that the event will be exceeded in any one year. This is the recurrence interval for estimating the time interval between events of certain intensity (Ang and Tang, 2007). Table 2.12 shows the storm surges for different return periods. A 100-year flood has a storm surge of 13.03 feet for the case excluding Sandy and 13.98 feet for the case including Sandy. Also, from this established distribution for n=1, we can estimate the return periods for hurricane Sandy. The case excluding hurricane Sandy has 20 million years for return period. Then, the case including hurricane Sandy has 2,545 years for return period. It is still an extremely unusual event. Therefore, Hurricane Sandy’s storm surge can be considered as a singular event, that is, a statistical outlier, based on this data set.

2.7 Comparison with Alternative Approach

These results can be compared with Lin el al.’s model-based risk assessment methodology (Lin et al., 2010). Lin el al. assessed hurricane risk using synthetic data obtained from a statistical hurricane model with the hydrodynamic model called SLOSH (Sea, Lake, and Overland surges from hurricanes) (NOAA, 2012). They developed a model-based hurricane study of storm surges. Our research, however, focuses on historical empirical data on storm surges. The SLOSH model results are compared to our research for verification and validation.
Lin el al.’s synthetic data followed the generalized Pareto distribution. This is compared with the generalized extreme value distribution of the empirical data. Figure 2.32 is a histogram of the SLOSH model simulated storm surge at the Battery from Lin el al.’s study and Figure 2.33 is a histogram of empirical data from 1920 to 2012 at the Battery with our GEV distribution. Figure 2.32 has the peak of the number of events between 7 and 10 feet and the empirical data has the peak between 10 and 12 feet. However, after these plots are compared, the return periods have come close to the Lin el al’s study.

Figure 2.32 Histogram of the SLOSH Model Simulated Storm Surges at the Battery (Courtesy of Lin at el, 2010).
Lin et al. concluded that their distribution has a 100-year flood level of 2.62 m and a 500-year flood level of 3.26 m. These values are converted to 11.9 feet and 13.99 feet with respect to the Station Datum. Figure 2.34 is Lin’s return level plot, which shows the mean return level and the 95% confidence band. This figure should be compared with the return level plot derived from our GEV distribution from empirical data in Figure 2.34.

Comparing the two sets of data, the synthetic data has 13.99 feet of storm surge at 500 years of return period and the empirical data has 13.78 feet for the
same return period. These results show that the two research approaches compare reasonable well. Table 2.13 Comparison of the Results between Synthetic Data and Empirical Data displays more return levels for the two approaches.

Table 2.13 Comparison of the Results between Synthetic Data and Empirical Data

<table>
<thead>
<tr>
<th>Return Period (Year)</th>
<th>Lin’s distribution from synthetic data</th>
<th>GEV distribution from empirical data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With Sandy</td>
<td>Without Sandy</td>
</tr>
<tr>
<td>100</td>
<td>11.97 feet</td>
<td>13.98 feet</td>
</tr>
<tr>
<td></td>
<td>13.00 feet</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>14.00 feet</td>
<td>15.44 feet</td>
</tr>
<tr>
<td></td>
<td>13.78 feet</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.34 Comparison with Return Level Plot for Extreme Storm Surge Heights for New York City (Courtesy of Lin et al.).
Chapter 3. FLOODING OF UNDERGROUND INFRASTRUCTURE

3.1 History of Flooding in New York City

Hurricane Sandy, which made landfall on Oct. 29, 2012, was the latest severe storm in the northeastern United States, devastating the power grid and suspending communications and transportation. In New York City, all flights, rail service and subway service were canceled. Hurricane Sandy brought tremendous flooding in New York City, especially in the low-lying areas of the south of Manhattan. Chairman Joseph J. Lhota of the Metropolitan Transportation Authority (MTA), said that although New York City’s subway system is 108 years old, it had never faced a disaster of this magnitude prior to Hurricane Sandy (Hetter, 2012). Seven subway tunnels under the East River flooded during the course of the storm, the Metro-North Railroad lost power in sections of its lines and the Long Island Rail Road sustained flooding (Hetter, 2012).

The subway system in New York City was completely suspended on October 28, 2012. Figure 3.1 shows which subway stations were put out of service by hurricane Sandy and the extent of service disruption in their respective lines as of October 29 (MTA, 2012). The faint lines show tunnel sections that
were out of service after Hurricane Sandy. Darker colored lines indicate regular subway routes that were operational.

Figure 3.1 Suspended Subway Service by Hurricane Sandy on Oct. 29, 2012 (MTA, 2012).
Floodwater rushed throughout Lower Manhattan, inundating some tunnels and led to continued suspension of many lines for days. An MTA spokesman said water had reached into all five subway tubes that stretch under the East River between Lower Manhattan and Brooklyn and the Steinway tube between Midtown and Queens.

The photo in Figure 3.2, released by the MTA, shows extensive flooding at the South Ferry subway station at Battery Park in lower Manhattan, caused by storm surges from hurricane Sandy. This is the station that had been reconstructed in 2009 at a cost of $530 million.

Figure 3.2 Flooding from Hurricane Sandy at the South Ferry Subway station (MTA, 2012).
There are three evacuation zones in New York City, based on the strength of the hurricane when making landfall (FEMA, 2012). These zones represent varying threat levels of coastal flooding resulting from storm surge. If residential homes, offices or schools are within the boundaries of an evacuation zone, people are asked to evacuate. Zone A, which includes all low-lying coastal areas and other areas that are vulnerable to flooding faces the highest risk of damage from a hurricane’s storm surge. Zone B may experience storm surge flooding from a strong (Category 2 or higher) hurricane and Zone C may experience flooding from a major hurricane (Category 3 or 4) (OEM, 2009).

Figure 3.3 New York City Hurricane Evacuation Zones (The New York Times, 2012).
### Table 3.1 Historic Occurrences of Flooding in New York City (Source: OEM, 2009).

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Locations</th>
<th>Max. surge at the Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 16, 1983</td>
<td>Flash Flood</td>
<td>Manhattan</td>
<td>8.60</td>
</tr>
<tr>
<td>Jun. 29, 1994</td>
<td>Flood/ Flash Flood</td>
<td>Citywide</td>
<td>8.38</td>
</tr>
<tr>
<td>Jun. 22, 1995</td>
<td>Flash Food</td>
<td>Brooklyn, Queens</td>
<td>8.18</td>
</tr>
<tr>
<td>Jul. 1, 1995</td>
<td>Flash Flood</td>
<td>Staten Island</td>
<td>8.39</td>
</tr>
<tr>
<td>Jul. 17, 1995</td>
<td>Flash Flood</td>
<td>Bronx, Manhattan, Queens</td>
<td>9.43</td>
</tr>
<tr>
<td>Oct. 21, 1995</td>
<td>Urban Flood</td>
<td>Manhattan, Queens</td>
<td>8.29</td>
</tr>
<tr>
<td>Nov. 14, 1995</td>
<td>Coastal Flood</td>
<td>Queens</td>
<td>10.18</td>
</tr>
<tr>
<td>Jan. 12, 1996</td>
<td>Urban Flood</td>
<td>Citywide</td>
<td>8.77</td>
</tr>
<tr>
<td>Jan. 27, 1996</td>
<td>Urban Flood</td>
<td>Queens</td>
<td>9.16</td>
</tr>
<tr>
<td>Apr. 16, 1996</td>
<td>Urban Flood</td>
<td>Citywide</td>
<td>10.15</td>
</tr>
<tr>
<td>Jul. 3, 1996</td>
<td>Flash Flood</td>
<td>Citywide</td>
<td>9.88</td>
</tr>
<tr>
<td>Jul. 8, 1996</td>
<td>Flash Flood</td>
<td>Queens, Staten Island</td>
<td>8.70</td>
</tr>
<tr>
<td>Jul. 13, 1996</td>
<td>Flood</td>
<td>Manhattan</td>
<td>8.49</td>
</tr>
<tr>
<td>Jul. 31, 1996</td>
<td>Flash Flood</td>
<td>Brooklyn, Queens, Staten Island</td>
<td>9.77</td>
</tr>
<tr>
<td>Sep. 8, 1996</td>
<td>Flash Flood</td>
<td>Bronx, Brooklyn, Staten Island</td>
<td>8.67</td>
</tr>
<tr>
<td>Oct. 19, 1996</td>
<td>Flood</td>
<td>Citywide</td>
<td>11.56</td>
</tr>
<tr>
<td>Jan. 10, 1997</td>
<td>Coastal Flood</td>
<td>Queens</td>
<td>10.71</td>
</tr>
<tr>
<td>Jan. 23, 1998</td>
<td>Urban Flood</td>
<td>Citywide</td>
<td>10.78</td>
</tr>
<tr>
<td>Mar. 9, 1998</td>
<td>Urban Flood</td>
<td>Citywide</td>
<td>9.26</td>
</tr>
<tr>
<td>Aug. 17, 1998</td>
<td>Flood</td>
<td>Brooklyn, Manhattan, Staten Island</td>
<td>8.59</td>
</tr>
<tr>
<td>Jan. 3, 1999</td>
<td>Urban Flood</td>
<td>Citywide</td>
<td>10.64</td>
</tr>
<tr>
<td>Aug. 26, 1999</td>
<td>Flood</td>
<td>Bronx, Manhattan, Queens</td>
<td>8.96</td>
</tr>
<tr>
<td>Sep. 16, 1999</td>
<td>Flood</td>
<td>Citywide</td>
<td>9.52</td>
</tr>
<tr>
<td>Jul. 3, 2000</td>
<td>Flash Flood</td>
<td>Brooklyn, Queens, Staten Island</td>
<td>9.59</td>
</tr>
<tr>
<td>Date</td>
<td>Type</td>
<td>Location</td>
<td>Amount</td>
</tr>
<tr>
<td>------------</td>
<td>-------------------</td>
<td>-----------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Aug. 11, 2000</td>
<td>Flash Flood</td>
<td>Bronx, Queens</td>
<td>9.13</td>
</tr>
<tr>
<td>Aug. 27, 2000</td>
<td>Flash Flood</td>
<td>Staten Island</td>
<td>9.21</td>
</tr>
<tr>
<td>Aug. 28, 2000</td>
<td>Flash Flood</td>
<td>Queens</td>
<td>9.73</td>
</tr>
<tr>
<td>Sep. 3, 2000</td>
<td>Flash Flood</td>
<td>Queens</td>
<td>8.94</td>
</tr>
<tr>
<td>Jun. 17, 2001</td>
<td>Flash Flood</td>
<td>Bronx, Brooklyn, Manhattan, Queens</td>
<td>8.43</td>
</tr>
<tr>
<td>Jun. 23, 2001</td>
<td>Urban Flood</td>
<td>Manhattan, Staten Island</td>
<td>9.54</td>
</tr>
<tr>
<td>Aug. 13, 2001</td>
<td>Flash Flood</td>
<td>Brooklyn, Manhattan, Queens</td>
<td>8.79</td>
</tr>
<tr>
<td>Jun. 26, 2002</td>
<td>Flood, Thunderstorm Flood</td>
<td>Bronx</td>
<td>8.91</td>
</tr>
<tr>
<td>Aug. 16, 2002</td>
<td>Flash Flood</td>
<td>Bronx, Manhattan, Queens</td>
<td>8.57</td>
</tr>
<tr>
<td>Sep. 2, 2002</td>
<td>Flash Flood</td>
<td>Brooklyn, Queens</td>
<td>8.84</td>
</tr>
<tr>
<td>Jul. 22, 2003</td>
<td>Flash Flood</td>
<td>Queens, Staten Island</td>
<td>8.06</td>
</tr>
<tr>
<td>Aug. 4, 2003</td>
<td>Flash Flood</td>
<td>Brooklyn, Manhattan, Queens, Staten Island</td>
<td>8.76</td>
</tr>
<tr>
<td>Aug. 17, 2003</td>
<td>Flash Flood</td>
<td>Brooklyn</td>
<td>8.46</td>
</tr>
<tr>
<td>Sep. 23, 2003</td>
<td>Flash Flood</td>
<td>Bronx, Brooklyn, Manhattan, Queens</td>
<td>9.23</td>
</tr>
<tr>
<td>Jun 17, 2004</td>
<td>Flash Flood</td>
<td>Bronx, Brooklyn, Manhattan, Queens</td>
<td>8.49</td>
</tr>
<tr>
<td>Jun. 25, 2004</td>
<td>Flash Flood</td>
<td>Queens, Staten Island</td>
<td>8.19</td>
</tr>
<tr>
<td>Jul. 2, 2004</td>
<td>Flash Flood</td>
<td>Bronx, Queens</td>
<td>9.34</td>
</tr>
<tr>
<td>Sep. 8, 2004</td>
<td>Flash Flood</td>
<td>Bronx, Brooklyn, Manhattan, Queens</td>
<td>8.84</td>
</tr>
<tr>
<td>Sep. 18, 2004</td>
<td>Flash Flood</td>
<td>Citywide</td>
<td>9.36</td>
</tr>
<tr>
<td>Sep. 28, 2004</td>
<td>Flash Flood</td>
<td>Citywide</td>
<td>9.85</td>
</tr>
<tr>
<td>Jul. 6, 2005</td>
<td>Flash Flood</td>
<td>Brooklyn</td>
<td>8.94</td>
</tr>
<tr>
<td>Oct. 24, 2005</td>
<td>Flash Flood</td>
<td>Brooklyn, Queens</td>
<td>10.44</td>
</tr>
<tr>
<td>Jun. 2, 2006</td>
<td>Flash Flood</td>
<td>Manhattan, Queens, Staten Island</td>
<td>8.07</td>
</tr>
<tr>
<td>Jul. 12, 2006</td>
<td>Flash Flood, Thunderstorm</td>
<td>Citywide</td>
<td>9.02</td>
</tr>
<tr>
<td>Jul. 21, 2006</td>
<td>Flash Flood, Thunderstorm</td>
<td>Citywide</td>
<td>8.86</td>
</tr>
<tr>
<td>Aug. 10, 2006</td>
<td>Flash Flood</td>
<td>Manhattan, Queens, Staten Island</td>
<td>9.57</td>
</tr>
<tr>
<td>Aug. 25, 2006</td>
<td>Flash Flood</td>
<td>Bronx, Queens</td>
<td>8.82</td>
</tr>
</tbody>
</table>
Historic occurrences of flooding in New York City have been documented by the New York City Office of Emergency Management. The preceding table shows how often flooding events have occurred in New York City from 1993 to 2007. There is no description after 2007 in OEM reports.
3.1.1 Lowest Critical Elevation (LCE)

Figure 3.4 Profile of the Rapid Transit Railroad: Manhattan and Bronx Lines (Interborough Rapid Transit Co., 1904).

Figure 3.4, shows an approximate profile cross-section of Manhattan’s rapid transit railroad: Manhattan and Bronx Lines (Interborough Rapid Transit Co., 1904). This is what would become eventually MTA’s number 1 subway line.
Each station has its own lowest critical elevation (LCE), with the minimum being 5 feet for the South Ferry Station (Deodatis and Jacob, 2011).

The lowest critical elevations for various tunnels in the area and at JFK Airport are listed below (Table 3.2). These indicate the elevation from where water will inundate a portion or all of a given structure if storm surge waters reach it. If the water level exceeds a critical elevation level, the structure will be overwhelmed by flooding and operation will be impeded. The lowest critical elevations are in feet and with respect to NAVD1988 as defined in Chapter 2.
Table 3.2 Lowest Critical Elevations for Certain Critical Infrastructures in New York (US Army Corps of Engineer, 1995).

<table>
<thead>
<tr>
<th></th>
<th>Critical Elevations</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NAVD88</td>
<td>Station Datum</td>
<td></td>
</tr>
<tr>
<td><strong>Brooklyn-Battery Tunnel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manhattan West Street Entrance</td>
<td>7.46 feet</td>
<td>13.53</td>
<td></td>
</tr>
<tr>
<td>Manhattan Battery Entrance</td>
<td>7.46 feet</td>
<td>13.53</td>
<td></td>
</tr>
<tr>
<td>Brooklyn Plaza at Hamilton Avenue</td>
<td>10.46 feet</td>
<td>16.53</td>
<td></td>
</tr>
<tr>
<td>Governor’s Island Blower Bldg. Floor</td>
<td>11.46 feet</td>
<td>17.53</td>
<td></td>
</tr>
<tr>
<td>Manhattan Blower Bldg. Floor</td>
<td>12.46 feet</td>
<td>18.53</td>
<td></td>
</tr>
<tr>
<td>Brooklyn Blower Bldg. Floor</td>
<td>13.46 feet</td>
<td>19.53</td>
<td></td>
</tr>
<tr>
<td><strong>Holland Tunnel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Jersey Land Vent Shaft</td>
<td>6.46 feet</td>
<td>12.53</td>
<td></td>
</tr>
<tr>
<td>New Jersey Top-of-Ramp</td>
<td>6.46 feet</td>
<td>12.53</td>
<td></td>
</tr>
<tr>
<td>New York River Vent Shaft</td>
<td>7.46 feet</td>
<td>13.53</td>
<td></td>
</tr>
<tr>
<td>New York Land Vent Shaft</td>
<td>7.46 feet</td>
<td>13.53</td>
<td></td>
</tr>
<tr>
<td>New York Top-of-Ramp</td>
<td>8.36 feet</td>
<td>14.53</td>
<td></td>
</tr>
<tr>
<td>New Jersey River Vent Shaft</td>
<td>9.46 feet</td>
<td>15.53</td>
<td></td>
</tr>
<tr>
<td><strong>Lincoln Tunnel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Jersey Vent Shaft</td>
<td>9.46 feet</td>
<td>15.53</td>
<td></td>
</tr>
<tr>
<td>New York 3rd Tube Vent Shaft</td>
<td>9.46 feet</td>
<td>15.53</td>
<td></td>
</tr>
<tr>
<td>New York River Vent Shaft</td>
<td>10.46 feet</td>
<td>16.53</td>
<td></td>
</tr>
<tr>
<td>New York Land Vent Shaft</td>
<td>18.46 feet</td>
<td>24.53</td>
<td></td>
</tr>
<tr>
<td>New York Top-of-Ramp</td>
<td>21.46 feet</td>
<td>27.53</td>
<td></td>
</tr>
<tr>
<td>New Jersey Top-of-Ramp</td>
<td>26.46 feet</td>
<td>32.53</td>
<td></td>
</tr>
<tr>
<td><strong>Airport</strong></td>
<td>Lowest Point on Runway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>John F. Kennedy International Airport</td>
<td>11.7 feet</td>
<td>17.77</td>
<td></td>
</tr>
<tr>
<td>LaGuardia Airport</td>
<td>5.66 feet</td>
<td>11.73</td>
<td></td>
</tr>
<tr>
<td>Newark International Airport</td>
<td>9.16 feet</td>
<td>15.23</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Simulation of a Flooding Event

3.2.1 Estimating Volume of Water Entering Tunnels

Figure 3.5 illustrates how water enters into the subway system. Normally, when water falls through a ventilation grate, it is pumped out. But, if the water is too much, the pumping system will be overwhelmed and tunnels can be flooded.

![Diagram of subway drainage and pumping system](image)

Figure 3.5 Typical Subway Drainage and Pumping System (MTA, New York City Transit, 2010).

There are two ways for water to enter the underground infrastructure. Vertical flow is applied to calculate the total volume of water entering the subway...
and inclined flow is used in the case of car tunnel systems. When storm surges overwhelm the subway system, large volumes of water can flow into the ventilation openings and station entrances. Severe downpours associated with hurricanes can also inundate the underground infrastructure.

Figure 3.6 Points of Entry into Car Tunnels (Deodatis and Jacob, 2011).

1) Vertical Flow through openings

Figure 3.7 Vertical Flow through Openings.
Figure 3.7 shows schematically the vertical flow through an opening. In a vertical flow, the water seeps through subway grates and stairwells with average flow velocity $V(t)$, where $g$ is the gravitational constant, and $h(t)$ is the height of water above the opening. This results in an average flow $Q(t)$ through an opening with area $A_o$. The average flow velocity $V(t)$ can be found from Torricelli’s Theorem (e.g. Lamb, 1953).

$$V(t) = \sqrt{2gh(t)}$$

$$Q(t) = A_o V(t)$$

(3.1)

2) Inclined Flow through entrance of car tunnel

![Diagram of inclined flow through tunnel]

Figure 3.8 Section of Tunnel for Calculating Incoming Flow.

Figure 3.8 shows a cross-sectional view of a tunnel entrance with the height of water $h(t)$ as function of time and tunnel width $b$. The inclined flow is obtained by combining the flow area, $A(t)$, the wetted perimeter, $P(t)$, the
hydraulic radius, \( R(t) \), the average flow velocity, \( V(t) \) and the average flow rate, \( Q(t) \) as follows (Munson, 2012):

\[
A(t) = bh(t)
\]
\[
P(t) = b + 2h(t)
\]
\[
R(t) = \frac{A(t)}{P(t)}
\] (3.2)

Figure 3.9 describes the flow through the entrance of a tunnel with slope \( S_o \). The average flow velocity (ft/s), \( V(t) \), the roughness coefficient, \( n \) and the average flow rate (ft\(^3\)/s), \( Q(t) \) are related as follows (Munson, 2012):

\[
V(t) = \frac{1.49}{n} R(t)^{2/3} S_o^{1/2}
\] (3.3)
\[
Q(t) = A(t)V(t)
\]

The volume of water at the time of peak flood \( (T_p) \) is given by:
\[ \text{VOL}_1(T_p) = \int_{T_p}^{T_f} Q_1(t) \, dt \quad (3.4) \]

and the volume of water after the peak flood at time \( T \) is given by:

\[ \text{VOL}_2(T) = \text{VOL}_1(T_p) + \int_{T_p}^{T} Q_2(t) \, dt \quad (3.5) \]

Therefore, the total volume of water entering the tunnel at the final flood event time \( (T_f) \) is given by:

\[ \text{VOL}_2(T_f) = \text{VOL}_1(T_p) + \int_{T_p}^{T_f} Q_2(t) \, dt \quad (3.6) \]

### 3.2.2 Modeling the Time History of the Storm Surge

The objective of this research is to compute how much water will get into the tunnels when a specific hurricane hits the city. In order to do this, we need to calculate not only the maximum level of a storm surge but also the evolution of a storm surge.

Figure 3.10 shows the modeling of the time history of the storm surge for a 100-year period event in New York City (Deodatis and Jacob, 2011). There are some dots from specific hurricane events provided by the US Army Corps of Engineers (US Army Corps of Engineers, 1995). Exponential curves fit quite well. The corresponding equations for a 10 feet peak water height are:
\[ h_1(t) = 0.23 \exp^{0.029t} \text{ for } 0 \leq t \leq 130 \text{ min.} \] (3.7)

\[ h_2(t) = 18,800 \exp^{-0.058t} \text{ for } 130 \text{ min} \leq t \leq \infty \]

![Graph showing the time history of storm surge height for the 100-Year Event](image)

**Figure 3.10 Time History of Storm Surge Height for the 100-Year Event**
*(Deodatis and Jacob, 2011).*

We will model the storm surge evolution with the exponential function for the increasing part, \( h_1(t) \) and another exponential function for the decreasing part, \( h_2(t) \). These equations can be applied for each different peak height that was generated based on the GEV distribution.
3.3 Calculating the Total Volume of Water Entering the Underground Infrastructure

There are three basic variables necessary for calculating the volume of water entering the system: time evolution of water height \( h(t) \), peak height of water and lowest critical elevation (LCE) of the infrastructure under consideration.

![Diagram showing the calculation of total volume of water entering the underground infrastructure.](image)

**Figure 3.11 Calculating the Total Volume of Water Entering the Underground Infrastructure**

Figure 3.11 demonstrates how to calculate the total volume of water entering the system. Each piece of the infrastructure has a different LCE level. In this example, the LCE has been assumed to be 7.5 feet for demonstration purposes, with 10 feet of peak height for the storm surge. By subtracting the LCE...
level from the overall water height, 2.5 feet is the height of water above the
critical infrastructure and the volume of the flood water entering the infrastructure
can be calculated from the shaded area. \( h'(t) \) is the time evolution of the flooding
water height with lowest critical elevation \( (H) \). The head of water above the LCE
is described as:

\[
h'_1(t) = h_1(t) - H
\]

\[
h'_2(t) = h_2(t) - H
\]

The initial time \( (T_o) \) and final time \( (T_f) \) are defined as:

\[
T_o = \ln \left( \frac{H}{0.23} \right) / 0.029 \quad \text{for} \ h'_1(t) = 0
\]

\[
T_f = -\ln \left( \frac{H}{18,800} \right) / 0.058 \quad \text{for} \ h'_2(t) = 0
\]
Chapter 4. STOCHASTIC ANALYSIS OF INFRASTRUCTURE VULNERABILITY

The methodology used in the calculation of the total volume of flooding in Chapter 3 is applied now to specific components of the infrastructure. There are two sources of uncertainty in this research. The first is the random peak height; the second is the random time history of the storm surge.

Monte Carlo Simulation is utilized to determine the volume of water entering the tunnel from all openings. For every sample run with a different peak height and a different time history, we will obtain a different total volume of water entering the tunnel. This set of different flooding volumes is used to establish exceedance curves and fragility curves.

The following flow chart (Figure 4.1) shows the simulation procedure for determining exceedance and fragility curves. After selecting values for the return period (n) and LCE (H), the first sample is run. First, a random peak height of the storm surge is generated and a time history of the evolution of the storm surge above all openings is determined. Then, we calculate the volume of water entering the tunnel from all openings. This simulation is repeated for 10,000 times (runs). Finally, exceedance curves and fragility curves are computed from the resulting 10,000 values. In addition, random walk theory is used to consider the possibility of obstruction of tunnel ventilation entrances and different probabilities of this obstruction are integrated into our calculations.
Figure 4.1 Monte Carlo Simulation Procedure for Stochastic Analysis.
4.1 Generating Random Storm Surge Peak Heights

For a given return period, the uncertainty in the peak height of the storm surge is described by the probability distributions established in Figure 2.30 (excluding Sandy) and Figure 2.31 (including Sandy). Using these distributions, sample realizations of the storm surge peak height are generated using a slice sampling algorithm (Neal, 2003).

The resulting histograms of the generated peak heights for six different return periods are displayed in Figure 4.2.

![Histograms of Generated Peak Storm Surge Heights for Six Different Return Periods (Heights from Station Datum at the Battery).](image)

Figure 4.2 Histograms of Generated Peak Storm Surge Heights for Six Different Return Periods (Heights from Station Datum at the Battery).
4.2 Generating Random Storm Surge Height Time Histories for a Given Peak Height

As noted in Chapter 3, in order to compute how much water will enter a tunnel when a specific hurricane hits the city, we need to determine not only the maximum height of the storm surge, but also the evolution of the storm surge in time. Here we will model the storm surge with an exponential function, which was proposed in Chapter 3.

First, we define the general equation for the time history of the storm surge based on the time evolution of four significant hurricanes (see Figure 2.7), which were mentioned in Chapter 2 (Hurricanes Donna, Gloria, Irene, and Sandy). These four time histories are used to introduce uncertainty into our general equation (specifically with respect to the rate of exponential increase and decay). The general equation for the time history is described as:

\[ h_1(t) = A \exp^{\alpha t} \quad \text{for} \quad 0 \leq t \leq 130 \]

\[ h_2(t) = B \exp^{-\beta t} \quad \text{for} \quad 130 \leq t \leq \infty \]

Second, the different peak storm surge heights are utilized for establishing specific time evolutions. These peak heights are already generated using the approach described in Section 4.1.

Third, \( \alpha \) and \( \beta \) in Eq.(4.1) are selected randomly according to a uniform distribution in \([C_1, C_2]\). Figure 4.3 shows the time histories of storm surge heights.
for the different time evolutions referred to as narrow, medium and wide. Specifically, $\alpha$ follows a uniform distribution in $[0.019, 0.039]$ and $\beta$ follows a uniform distribution in $[-0.068, -0.048]$. The narrow and wide time evolutions in Figure 4.3 correspond to the extremes of the two uniform distributions.

**Figure 4.3 Time Histories of Storm Surge Heights for a Given Peak Height of 10 feet**

Narrow Function

$$h_1(t) = 0.063\exp^{0.039\, t}, \quad h_2(t) = 69,050\exp^{-0.068\, t}$$

Medium Function

$$h_1(t) = 0.231\exp^{0.029\, t}, \quad h_2(t) = 18,800\exp^{-0.058\, t}$$

Wide Function

$$h_1(t) = 0.845\exp^{0.019\, t}, \quad h_2(t) = 58,406\exp^{-0.048\, t}$$
Once $\alpha$ and $\beta$ are generated for Eq. (4.1), A and B are easily determined using the generated value for the peak storm surge height $peakH$ and the time when it occurs, $t_p$:

$$A = \frac{peakH}{\exp(\alpha \cdot t_p)}$$

(4.3)

$$B = \frac{peakH}{\exp(\beta \cdot t_p)}$$

This way, 10,000 different time histories are established for the time evolution of the storm surge height.

### 4.3 Application of Proposed Methodology to #1 Subway Line in Manhattan, close to South Ferry Station

#### 4.3.1 South Ferry Station

Figure 4.5 shows the southern end of the number 1 subway line, including the South Ferry Station at Battery Park (Figure 4.4). There are several segments where flooding can occur either through station entrances or through ventilation grates. These tunnel segments start from State Street (South Ferry Station) and extend to Morris Street (Rector Street Station).
Figure 4.4 Entrance of South Ferry Station after Hurricane Sandy.

Figure 4.5 Map of the Segments of the #1 Subway Line in the Vicinity of the South Ferry Station (Google, 2012).
Table 4.1 Tunnels in the Vicinity South Ferry Station (Deodatis and Jacob, 2011).

<table>
<thead>
<tr>
<th>Intervening Streets along Route</th>
<th>LCE (H)</th>
<th>Ventilation Opening Area</th>
<th>Stairway Opening Area</th>
<th>Tunnel Segment Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>State St.</td>
<td>5 ft</td>
<td>48 ft²</td>
<td>150 ft²</td>
<td>27,450 ft³</td>
</tr>
<tr>
<td>State St. (Battery Park)</td>
<td>9 ft</td>
<td>-</td>
<td>180 ft²</td>
<td>177,300 ft³</td>
</tr>
<tr>
<td>Pearl St.</td>
<td>10 ft</td>
<td>-</td>
<td>75 ft²</td>
<td>16,200 ft³</td>
</tr>
<tr>
<td>Bridge St. - Battery Pl.</td>
<td>11 ft</td>
<td>-</td>
<td>-</td>
<td>256,500 ft³</td>
</tr>
<tr>
<td>Battery Place</td>
<td>11 ft</td>
<td>608 ft²</td>
<td>-</td>
<td>261,450 ft³</td>
</tr>
</tbody>
</table>

Total Volume of Tunnel 738,900 ft³

Table 4.1 displays the lowest critical elevations, the areas of ventilation grates and stairway opening, as well as the volume of the tunnel for each segment. The total volume of all these tunnel segments examined here is 738,900 ft³.

The volume of flooding is investigated for six different time windows: 1, 10, 20, 50, 100, and 150 years. Figure 4.6 displays simulated results for total volume of flood water entering the tunnel as a function of the peak storm surge height. Since the State Street opening is only at 5 feet of LCE, this segment of the tunnel can overflow easily.

Figure 4.6 displays simulated results for the total volume of flood water entering the tunnel as a function of the peak storm surge height. Since the State
street openings are only at 5 feet of LCE, this segment of the tunnel can overflow easily.

Figure 4.6 Total volumes of Flood Waters Entering the Tunnel Segment in the Vicinity of South Ferry Station Resulting from Simulations and Provided as a Function of Peak Storm Surge Height.
Figure 4.7 Histograms for the Total Volume in Figure 4.6 of Flood waters Plotted (10,000 Simulated Values).

Figure 4.7 plots the 10,000 simulated total volumes of flood waters shown in Figure 4.6 in histogram form. These 10,000 values are used to calculate the fragility curves.
4.4 Potential Partial Covering of Ventilation Openings by Debris

An additional level of uncertainty is considered: whether debris will be blocking the entrance of ventilation grates. Figure 4.8 shows a typical ventilation grate of the NYC subway system. As shown, it is essentially completely open. If a storm surge carries water to the grate, it may also carry a certain amount of debris partially blocking the grate and interrupting the flow of water into the tunnel. In this section, the potential of partially blocking the ventilation opening is considered via a simulation procedure.
4.4.1 Simulation Procedure

A simple random walk approach is followed here (Pearson, 1905). The simulation procedure is described in the following. First, the ventilation grate is divided into 100 equal cells. Second, a cell is set as blocked or unblocked; if a cell is blocked by debris, that cell is considered to be fully covered. Otherwise, it is completely unblocked. Third, debris arrival is assumed to follow an exponential distribution and the spatial distribution of debris is assumed to be uniform. Fourth, different probabilities of debris removal after its arrival are considered: 0%, 10%, 30% and 50%.
Figure 4.9 presents ensemble-averaged results from 10,000 simulations, for the four different probabilities of debris removal: 0%, 10%, 30% and 50%. At 130 minutes, the probability of full coverage of the ventilation opening is 70%, 60%, 33%

![Graph showing probability of full coverage over time for different debris removal probabilities.](image)

**Figure 4.9 Simulation Results of Covering Ventilation Grate Openings.**

In a real situation, after debris has fallen on the ventilation grate, it may be moved by different factors—rainfall, wind, continually flowing floodwater. This simulation considers four different probability cases: no clearing of the debris, 10%, 30% and 50% clearing. This, 130 minutes, duration after surge exceeds LCE, is calculated by a time-history storm surge function. When the probability of
debris removal is 0%, the probability of complete coverage of the ventilation opening is 76%. However, after 50% removal of debris, the probability decreases to 38%. This simulation is computed using the theory of random walk, which we have discussed above.

Table 4.2 Probability of Completely Covering Ventilation Grate

<table>
<thead>
<tr>
<th>Probability of debris removal (P)</th>
<th>Probability of completely covering ventilation opening at 130 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 %</td>
<td>76 %</td>
</tr>
<tr>
<td>10 %</td>
<td>68 %</td>
</tr>
<tr>
<td>30 %</td>
<td>53 %</td>
</tr>
<tr>
<td>50 %</td>
<td>38 %</td>
</tr>
</tbody>
</table>

Figure 4.10 Probability Graphs of Completely Covering Ventilation Grate.
Now, we plot exceedance curves of flooding for South Ferry Station in various time windows including 1, 10, 20, 50, 100, 150 years are plotted. In a given time window, the aggregate normalized loss is lower in the range of large exceedance probability levels but higher in the range of small exceedance probability levels. As we will see in Figure 4.11, when structures experience more exposure time with the same exceedance probability, there is likely to be more aggregate normalized loss.

Figure 4.16 shows the simulation results for exceedance curves. The yellow line represents a return period of 1 year, blue line represents 10 years, pink line represents 100 years. When water enters a tunnel, the probability of flooding is 20% for a return period of 10 years, 38% for 20 years, 85% for 100 years. The vertical orange line is the total volume of South Ferry Station tunnel.

The difference in the exceedance probabilities increases with the length of the time window and the number of simulations. This is obvious when the 20-year and 50-year scenarios are compared to each other, as in Figure 4.11. A large separation between the exceedance probabilities 0.03 and 0.9 is observed. The graph shapes of loss exceedance curves in longer time windows with larger number of simulations are much smoother.

However, these probabilities decrease when calculations of debris removal are applied. Figure 4.12 shows the adjustments that inclusion of debris removal calculations make to the exceedance curves. Return periods are represented by lines of the same color as in Figure 4.16, and additional lines of corresponding
colors have been added to represent different debris removal scenarios. When water enters the tunnel through a grate that has been obstructed by debris, because less water enters the tunnel, the probability of flooding will decrease. In 100 years, when the probability of debris removal is 0%, the exceedance probability is 85%, but when the probability is 50%, the exceedance probability is decreased to 72%.

Therefore, South Ferry Station is a very vulnerable structure, prone to easy flood. As a result, it has been flooded several times since was renovated. Much of the damage to the subway system is concentrated in its underground tunnels. After Hurricane Sandy, South Ferry Stations was devastated; was full of water.

![Figure 4.11 Exceedance Probability Curves for Different Return Periods of n without Debris Removal.](image)

Figure 4.11 Exceedance Probability Curves for Different Return Periods of n without Debris Removal.
Figure 4.12 Exceedance Probability Curves for Different Return Periods of n with Debris Removal (0, 30, and 50%).

4.5 Fragility Curves

Fragility curves predict the probability of reaching or exceeding different damage states as a function of the intensity of the hazard. Our purpose is to set forth the basis for developing fragility curves that can be used in various ways as part of a vulnerability analysis methodology for flooding of the underground infrastructure (subway tunnels) in New York City. In this research, we examine subway tunnels in the New York City. To develop a set of fragility curves for various damage states (slight, moderate, major (extensive) and collapse
(complete) for a specific structure, the following pieces of data are needed: (1) Lowest Critical Elevation Level; (2) Definition of damage states for flooding; and (3) Random realizations of the evolution of the storm surge height above the lowest critical elevation.

The likelihood function is expressed as (Shinozuka at al., 2003)

\[
L = \prod_{i=1}^{N} \left[ F_k(a_i) \right]^{x_i} \cdot \left[ 1 - F_k(a_i) \right]^{1-x_i}
\]  

(4.5)

where, \( F_k(\cdot) \) = fragility curve for a given level of damage

\( a_i \) = peak height of storm surge

\( x_i = 1 \) or 0 depending on whether or not the structure sustains the specific state of damage under \( a_i \)

When the state of damage is reached under \( a_i \), \( x_i = 1 \) and otherwise, \( x_i = 0 \)

\( N \) = total number of simulated cases

\( F(a) \) takes the following analytical form (Shinozuka at al., 2003):

\[
F_k(a) = \Phi \left[ \frac{\ln \left( \frac{a}{c_k} \right)}{\zeta_k} \right]
\]  

(4.6)

when \( a \) represents the peak height of storm surge; and \( \Phi[\cdot] \) is the standardized normal distribution function. The two parameters \( c_k \) and \( \zeta_k \) in this equation are computed by maximizing \( \ln L \) and consequently:
\[
\frac{d \ln L}{d c_k} = \frac{d \ln L}{d \xi_k} = 0, \quad k = 1, 2, ..., N_{\text{state}}
\]  

where, \(N_{\text{state}}\) = total number of damage levels considered

This computation is performed by implementing a straightforward optimization algorithm. In this research, the states of damage for flooding of subway tunnels are considered as: total (100% flooding), major (75% flooding), moderate (50% flooding), minor (25% flooding). Consequently, a set of 4 fragility curves is established for each case.

Fragility curves show that up to a certain level of storm surge, the probability of flooding rests at 0, but once a threshold is reached, the exceedance probability rises quickly toward a probability of 1: complete flooding. It can be seen in Figure 4.13 that the Exceedance probability for damage levels for the peak surge height according to the total volumes of flooding. Computing the fragility curves, these processes are simulated in 10,000 iterations. Each figure has different return periods and four damage levels. These damage levels are divided by the vulnerability of the structure, namely the capacity of the total tunnel volume.
Figure 4.13 Exceedance Probability for Damage Level when Return Periods is 1-Year.
Figure 4.14 Exceedance Probability for Damage Level when Return Periods is 10-Year.
Figure 4.15 Exceedance Probability for Damage Level when Return Periods is 50-Year.
Finally, in Figure 4.17 we compute all of the fragility curves. This is the set of fragility curves for the South Ferry Station at Battery Park. Fragility curves show that up to a certain level of storm surge, the probability of flooding rests at 0, but once a threshold is reached, the exceedance probability rises quickly toward a probability of 1: complete flooding.

There are 4 graphs—showing minor, moderate, serious, and complete damage—for different return periods $n$: 1 year, 10 years, 50 years and 100 years. Complete damage means the probability flooding of the tunnel volume is over 100%, collapse damage and moderate damage are when the probability of flooding of the tunnel volume is over 50%.
Figure 4.17 Fragility Curves for Different Return Periods.
Chapter 5. CONCLUSIONS

Hurricanes are among the most catastrophic types of natural hazards, with the potential to cause serious loss of life and property. Storm surge hazards from the New York Harbor arise from tropical cyclones—hurricanes, tropical storms, tropical depressions—during the summer and fall, and from nor’easter storms during winter and early spring (NYS ClimAID, 2012). Consequently, analyzing sea water level time histories and estimating the resulting losses are key in the planning of mitigation measures. This research studies long term trends in sea water levels in New York City in order to estimate their probability distributions.

The methodology of hurricane analysis using Monte Carlo simulation has been developed to predict probabilistic events and the risk of flooding subject to exact distribution based on GEV distribution in a given time window. Contrary to previous research, which has been based mostly on theoretical models, the main focus of this dissertation is the empirical data available for water levels in New York City over the last century.

GEV distribution was used as the parent distribution to determine applying exact extreme value theory, the parent GEV distribution was used to determine the probability distributions for maximum sea water heights over a range of different multi-year periods including 5, 10, 50, and 100 years. We established probability distributions for maximum annual storm surge levels based on real data in New York City. Using these distributions we could determine exceedance
curves and fragility curves related to flooding of subway tunnels in New York City. Fragility curves and loss exceedance curves were calculated to assess the reliability of the underground infrastructure. Using the established probability distributions for sea water levels, the vulnerabilities of different parts of the underground infrastructure in New York City were studied. The models and methodologies developed in this dissertation can be used to predict and calculate vulnerabilities in the infrastructure and to reduce the damage and loss to infrastructure in the event of future hurricanes that may affect New York City.

The stochastic analysis of water levels using Monte Carlo simulation was developed through simplified examples. This methodology can be applied to generate a reliability assessment for several infrastructures subjected to hurricane loading and storm surges. The concept of fragility curves can be used to express the vulnerabilities of different parts of the infrastructure.

An additional element and a crucial factor in estimating potential future losses and planning mitigation actions will be expected rises in overall sea level. Future empirical data as well as ongoing estimations of sea level rise will need to be included in analysis of possible future damage from hurricanes. From FEMA’s 100-year flood in coastal zone, there are 3 scenarios—current sea level with a 100-year coastal flood, 2-foot rise in sea level, 4-foot rise in sea level. Adding these scenarios in this research, the simulation will make more extreme results.

The results of this and future studies can be used for evaluation of mitigation measures using a cost-benefit analysis. Natural disasters such as
earthquakes, cyclone, hurricanes, and so on, are unpredictable events that can cause much damage in a short time. There have been many cases of natural disasters in history and these disasters cause massive destruction in society. We cannot stop natural disasters, but we can reduce their damage and loss to prepare to deal with random crises. This research is useful to predicting future events and preventing tremendous damage from destruction.
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