URBAN COASTAL FLOOD MITIGATION STRATEGIES FOR THE CITY OF HOBOKEN & JERSEY CITY, NEW JERSEY

By

Eleni Athanasopoulou

A dissertation submitted to the

Graduate School- New Brunswick

Rutgers, The State University of New Jersey

In partial fulfillment of requirements

For the degree of

Doctor of Philosophy

Graduate Program in Civil and Environmental Engineering

Written under the direction of

Dr. Qizhong Guo

And approved by

____

____

____

____

New Jersey, New Brunswick

January 2017

ABSTRACT OF THE DISSERTATION

URBAN COASTAL FLOOD MITIGATION STRATEGIES FOR THE

CITY OF HOBOKEN & JERSEY CITY, NEW JERSEY

by ELENI ATHANASOPOULOU

Dissertation Director:

Dr. Qizhong Guo

Coastal cities are undeniably vulnerable to climate change. Coastal storms combining with sea level rise have increased the risk of flooding and storm surge damage in coastal communities.

The communities of the City of Hoboken and Jersey City are low-lying areas along the Hudson River waterfront and the Newark Bay/Hackensack River with little or no relief. Flooding in these areas is a result of intense precipitation and runoff, tides and/or storm surges, or a combination of all of them. During Super-storm Sandy these communities experienced severe flooding and flood-related damage as a result of the storm surge.

Following the damage that was created on these communities by flooding from Sandy, this research was initiated in order to develop comprehensive strategies to make Hoboken and Jersey City more resilient to flooding. Commonly used flood measures like storage, surge barrier, conveyance, diversion, pumping, rainfall interception, etc. are examined, and the research is focused on their different combination to address different levels of flood risk at different scales.

Apart from the commonly used measures and their combination and placement, this research is expanded to evaluate a new approach in drainage management in densely populated areas. The main concept of a new flood measures for low-lying areas, namely, “Rainwater Driven Pump” (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014), is investigated. Initial evaluations indicate their good potential in terms of availability of rainwater energy from the building tops and ground surfaces while estimating energy losses along the flow pathways.

Acknowledgements

This dissertation thesis would not have been possible without the support and encouragement of many people who generously contributed their time and knowledge.

First, I wish to extend the most sincere gratitude to my thesis director Dr. Qizhong Guo. His honest insight and extensive knowledge were invaluable during the course of this thesis.

To professors Monica Mazurek, Steven Medlar and Robert Miskewitz for serving on my dissertation thesis committee and providing valuable comments and suggestions. Special thanks are also extended to Dr. Robert Miskewitz for his help with the study funded by NJDEP, 2013 in order to develop comprehensive strategies to make New Jersey and its coastal areas more resilient to flooding.

To the professors and instructors from the Department of Civil and Environmental Engineering and from the Department of Environmental Sciences for sharing their knowledge and for encouraging my intellectual growth.

To the staff of the Department of Civil and Environmental Engineering who were always willing to help and answer my questions.

Finally, my utmost gratitude goes to my family and friends, who with their love and caring have supported me throughout this process.

Table of Contents

Abstract of the dissertation .... **ii**

Acknowledgements .... **iv**

Chapter 1 Introduction **1**

Chapter 2 Storm Surge and Stormwater Threats in Hoboken and Jersey City **10**

2.1 Background 10

2.2 Storm Surge Threat 12

2.3 Stormwater Threat 20

2.3.1 City of Hoboken *21*

2.3.2 Jersey City *27*

Chapter 3 Approach to Developing Flood Mitigation Strategy and Threats **32**

3.1 Framework 32

Chapter 4 Regional Flood Mitigation Measures **37**

Chapter 5 Flood Mitigation Measures at Hoboken **42**

5.1 Coastal Flood Mitigation Measures 42

5.2 Flood Mitigation Measures for Rainfall and MHHW 46

5.2.1 Measure 1: Surface Storage *46*

5.2.2 Measure 2: Separation *49*

5.2.3 Measure 3: Green Infrastructure for Runoff Reduction *51*

Chapter 6 Flood Mitigation Measures in Jersey City **52**

6.1 Flood Mitigation Measures for Rainfall and MHHW 52

6.1.1 Measure 1: Green Infrastructure / Surface Storage *52*

6.1.2 Measure 2: Surface Storage at Morris Marina ... *61*

6.1.3 Measure 3: Separation ... *66*

6.1.4 Measure 4: Green Infrastructure for Runoff Reduction ... *66*

6.1.5 Block and Lot Scale Storm water Flood Mitigation Measures ... *66*

Chapter 7 Alternative Flood Mitigation Measures ... 69

7.1 Rainwater Power and its Utilization for Draining Flood Water from Low-lying Areas ... 69

7.1.1 Background ... *69*

7.1.2 Main concept of alternative flood mitigation measure: "Green Pumps" ... *72*

7.1.3 Study Area ... *77*

7.1.4 Theoretical Background ... *78*

7.1.5 Source Data ... *80*

7.1.6 Methodology ... *81*

7.1.7 Results ... *83*

7.1.8 Future Work ... *90*

7.2 Projects Currently Proposed and Comparison ... 91

7.2.1 City of Hoboken ... *91*

7.2.1 Jersey City ... *97*

Chapter 8 Conclusions ... 103

List of Figures

Figure 1.1 Different Aspects of Changes in Climate System. Source: (Melillo, Richmond, & Yole, 2014) __1

Figure 1.2 Rate of Change in Total Annual Precipitation in Different Parts of the United States since The Early 20th Century. Source: (EPA, 2016) __3

Figure 1.3 Extreme One-Day Precipitation Events in The Contiguous 48 States, 1910-2015. Source: (EPA, 2016) __4

Figure 1.4 Observed Trends in Hurricane Power Dissipation. Source: (Kossin , Knapp, Vimont, Murnane, & Harper, 2007) __5

Figure 2.1 Regional map of Jersey City & Hoboken, NJ. Source: (NJGIN, 2015) __10

Figure 2.2 Map of Regional Digital Elevation Model of Jersey City & Hoboken, NJ. Source: (NJGIN, 2015) __11

Figure 2.3 10-Year Storm Map, Jersey City & Hoboken, NJ. Source: (FEMA Map Service Center) __14

Figure 2.4 50-Year Storm Map, Jersey City & Hoboken, NJ. Source: (FEMA Map Service Center) __15

Figure 2.5 100-Year Storm Map, Jersey City & Hoboken, NJ. Source: (FEMA Map Service Center) __16

Figure 2.6 10-Year Storm, at North End of Hoboken, NJ. Source: (FEMA Map Service Center) __17

Figure 2.7 50-Year Storm, Hoboken, NJ. Source: (FEMA Map Service Center) __17

Figure 2.8 100-Year Storm, Hoboken, NJ. Source: (FEMA Map Service Center) __18

Figure 2.9 10- Year Storm Jersey City, NJ. Source: (FEMA Map Service Center) __18

Figure 2.10 50-Year Storm, Jersey City, NJ. Source: (FEMA Map Service Center) __19

Figure 2.11 100-Year Storm Jersey City, NJ. Source: (FEMA Map Service Center) __19

Figure 2.12 Flap Gate at Morris Marina, Jersey City, NJ __21

Figure 2.13 Flood Prone Areas in Hoboken along Hudson River Waterfront under 3 feet Level Rise Scenario. Source: (NJ Flood Mapper, 2013) __22

Figure 2.14 Map of Drainage Basins & CSO Outfalls, Hoboken, NJ. Source: (NHSA, 2002) __23

Figure 2.15 Sub-Basins of Drainage Basin H1. Source: (NHSA, 2002) __25

Figure 2.16 Flood Prone Areas in Jersey City along Hudson River Waterfront under 3 feet Level Rise Scenario. Source: (NJ Flood Mapper, 2013) __27

Figure 2.17 Flood Prone Areas in Jersey City along Newark Bay/Hackensack River Waterfront Under 3 feet Level Rise Scenario. Source: (NJ Flood Mapper, 2013) ____ *28*

Figure 2.18 Storm Water Basin, Jersey City, NJ. Source: (Malcolm Pirnie, INC., 2008) ____ *31*

Figure 3.1 Framework for Flood Risk Reduction Strategy Development. Source: (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014) ____ *34*

Figure 3.2 Flood Risk Reduction Measures. Source: (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014) ____ *35*

Figure 4.1 Flood Mitigation Measures Map, Jersey City & Hoboken, NJ. Source: (NJGIN, 2015) ____ *37*

Figure 4.2 Floodwall Schematic Showing Bulkhead. ____ *38*

Figure 4.3 Floodwall Schematic Showing Bulkhead and Extensions ____ *39*

Figure 5.1 Flood Mitigation Measures Map, Hoboken, NJ. Source: (NJGIN, 2015) ____ *43*

Figure 5.2 Conventional Concrete Floodwall Source: (Flood Break , 2016) ____ *44*

Figure 5.3 Automatic Roadway Floodgate. Source: (Flood Break , 2016) ____ *45*

Figure 5.4 Location of Long Slip, Hoboken, NJ. Source: (NJGIN, 2015)) ____ *47*

Figure 5.5 Drainage Area H1, Hoboken, NJ. Source: (NJGIN, 2015) ____ *48*

Figure 5.6 Northwest Drainage Area, Hoboken, NJ. Source: (NJGIN, 2015) ____ *50*

Figure 6.1 Direction of Existing Sewer System at Route 78, in Jersey City. Source: (NJGIN, 2015). ____ *54*

Figure 6.2 Drainage Area 1 Affected by the Green Belt under Route 78. Source: (NJGIN, 2015). ____ *56*

Figure 6.3 Green Open Spaces under Route 78, Jersey City, NJ (Gooogle Maps, 2016) ____ *57*

Figure 6.4 Land Use of Open Spaces around Route 78. Source: (NJGIN, 2015) ____ *60*

Figure 6.5 Morris Marina Area, Jersey City, NJ Source: (NJGIN, 2015) ____ *63*

Figure 6.6 Drainage Area 2 Located along the Morris Marina. Source: (NJGIN, 2015) ____ *64*

Figure 6.7 Recommended Area for Retention Basin for Drainage Area 2. Source: (NJGIN, 2015) ____ *65*

Figure 6.8 Flooded Intersections at Route 440, Jersey City, NJ. ____ *68*

Figure 7.1 Abandoned Portion of The Blue Island Avenue Tunnel. Source: (Gage, Yurik, & Martin , 2016) ____ *70*

Figure 7.2 Cross Section of Blue and Green Roof. Source: (NYC DEP, 2016) ____ *71*

Figure 7.3 System Illustration of Rainwater Driven Pump Application. (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014). ____ *73*

Figure 7.4 Conceptual Sketch of Rainwater Driven Pump. Source: (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014). ____ *74*

Figure 7.5 Conceptual Sketch of Rainwater Flow Driven Venturi Pump. (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014). ____ *75*

Figure 7.6 System Illustration of Rainwater Flow Driven Venturi Pump Application. (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014). ____ *76*

Figure 7.7 Aspect of DEM of H1 Drainage Area. Source: (NJGIN, 2015) ____ *82*

Figure 7.8 Existing Sewer System in Hoboken, NJ, (green line is the longest sewer pipe line connecting the building farther away with the existing pump station) Source: (NJGIN, 2015). ____ *84*

Figure 7.9 Remaining Hydraulic Head for Different Rainfall Events for Drainage System Designed for One-hour Peak 25-Year storm. ____ *87*

Figure 7.10 Remaining Power from Buildings & Power Needed to Pump from Low-Lying Areas for Different Rainfall Events for Drainage System Designed for One-hour Peak 25-Year storm. ____ *87*

Figure 7.11 Remaining Hydraulic Head for Different Rainfall Events for Drainage System Designed for One-hour Peak 10-Year storm. ____ *89*

Figure 7.12 Remaining Power for Different Rainfall Events for Drainage System Designed for One-hour Peak 10-Year storm. ____ *89*

Figure 7.13 Flood Prevention Approach for Hoboken, NJ Source: (OMA, 2014) ____ *92*

Figure 7.14 Alternative 3: Draft Idea of Resist Alignment, which Provides Storm Surge Risk Reduction Benefits Using Public Right–Of-Way. Source: (Rebuilt by Design , 2016) ____ *93*

Figure 7.15 Project Site Plan H-5 WWPS. Source: (NHSA, 2015) ____ *95*

Figure 7.16 Construction Site of the H-5 WWPS in Hoboken. Source: (The New York Times, 2016) ____ *95*

Figure 7.17 Conceptual Flood Adaptation Strategies for the City of Jersey City. Source: (Orton, et al., 2015) ____ *97*

List of Tables

Table 2.1 Water Elevations Accordingly to Level of Threats, along The Coastline of Hudson River Study Area 13

Table 2.2 Areas of Existing Storm Water Basins Jersey City, NJ 30

Table 3.1 Flood Mitigation Functions and Associated Measures 36

Table 4.1 Regional Flood Measure, Bulkhead and Steel Flood Wall along Hudson River 39

Table 4.2 Regional Flood Measure, Bulkhead and Steel Flood Wall along Newark Bay 40

Table 4.3 Regional Flood Measure, Canal Gates 41

Table 5.1 Flood Barriers for Hoboken Only 45

Table 5.2 Surface Storage in the Long Slip 46

Table 5.3. Calculations of Runoff from H1 Drainage Basin 48

Table 5.4 Calculations of Runoff from Northwest Drainage Basin 50

Table 6.1 Calculations of Runoff from Drainage Basin 1 55

Table 6.2 Division of Total Area around Route 78 According to Land Use 59

Table 6.3 Available Storage around Route 78 61

Table 6.4 Surface Storage at Morris Marina 62

Table 6.5 Calculations of Runoff from Drainage Basin 2 63

Table 7.1 Characteristics of The Drainage System Designed for One-hour Peak, 25-Year Storm. 84

Table 7.2 Characteristics of The Drainage System Designed for One-hour Peak, 10-Year Storm. 85

Table 7.3 Head Losses for Different Rainfall Frequencies Data for the Drainage System Designed for One-hour Peak 25-Year Storm. 86

Table 7.4 Head Losses for Different Rainfall Frequencies Data for the Drainage System Designed for One-hour Peak 10-Year Storm. 88

Table 7.5 Anticipated Past Sandy Planning Assistance Grant Activities. 98

Chapter 1 Introduction

The climate is changing rapidly. The impacts of climate change have been observed in many ways in the environment (Melillo, Richmond, & Yole, 2014). These climate-related changes include: sea level rise, more frequent and intense precipitation events, melting of the glaciers and increase frequency droughts are some of the phenomena observed over the last decades, (Melillo, Richmond, & Yole, 2014). Figure 1.1 from "The Climate Change Impacts in the Unites States: The Third National Climate Assessment" summarizes which different aspects from the climate system are changing.

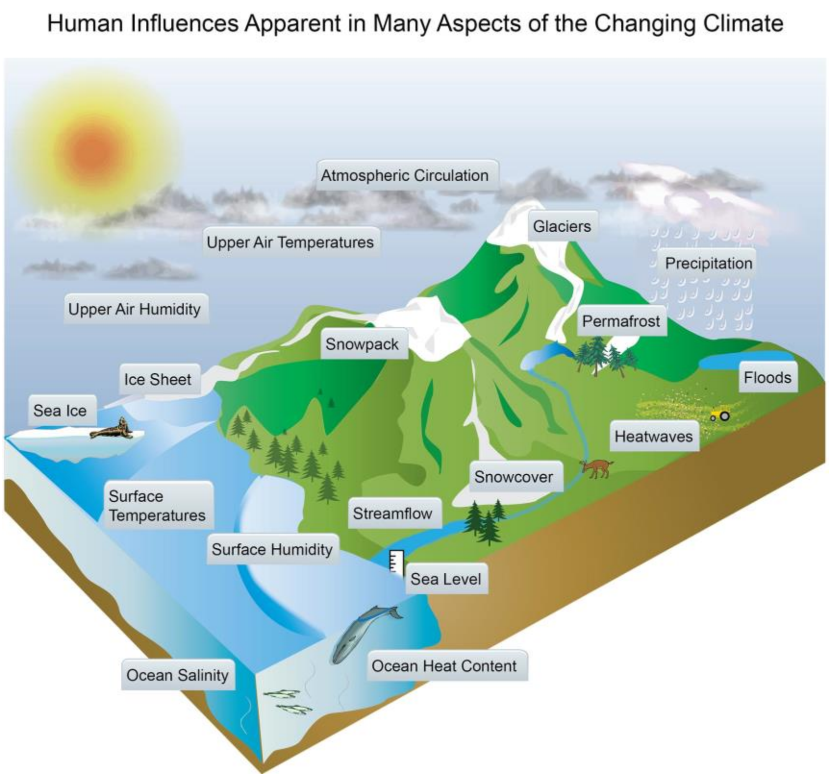


Figure 1.1 Different Aspects of Changes in Climate System. Source: (Melillo, Richmond, & Yole, 2014)

.

While all the above aspects have shown different patterns of changes, this research will only address the climate changes in precipitation, hurricanes, sea level rise and increasing flood risk in many parts in U.S.

Precipitation patterns have sifted (Melillo, Richmond, & Yole, 2014). Some areas are projected to have biggest periods of droughts while other areas more rainfall events, (Melillo, Richmond, & Yole, 2014). Especially precipitation at Northeast, Midwest and southern Great Plaines has increased an average of 8.5%, (Peterson, 2013). The following map shows the annual precipitation rate of change from 1901 to 2015 according to National Oceanic Atmospheric Administration. The data are shown in climate divisions as defined by NOAA, (NOAA, 2016). In the contiguous 48 states the precipitation rate has increased at a rate of 0.17 inches per decade, (EPA, 2016)

.

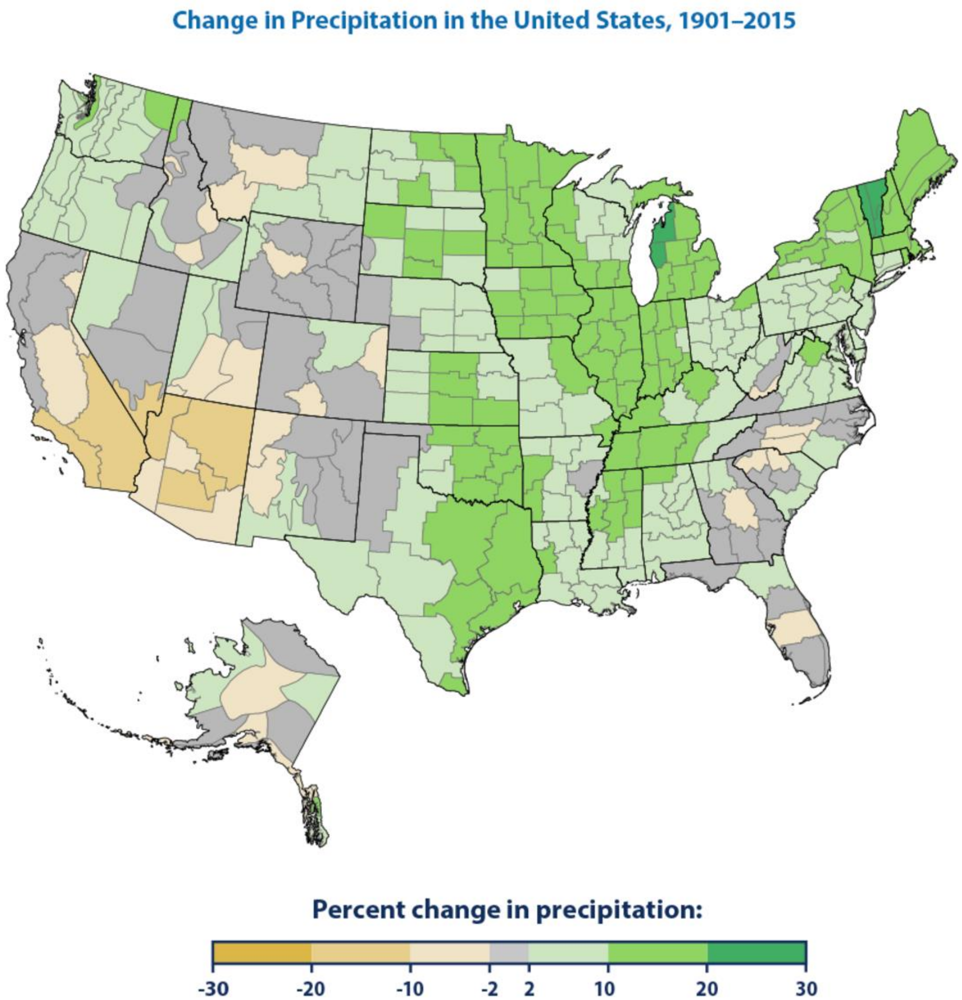


Figure 1.2 Rate of Change in Total Annual Precipitation in Different Parts of the United States since The Early 20th Century. Source: (EPA, 2016)

Over the last decades, the frequency of high intensity rainfall events has increased nationally. The Contiguous 48 States are showing an increasing trend of extreme one-day precipitation events, (EPA, 2016). Figure 1.3 shows the percentage of the land area where the total annual precipitation has occurred from extreme one-day precipitation events, (EPA, 2016).

.

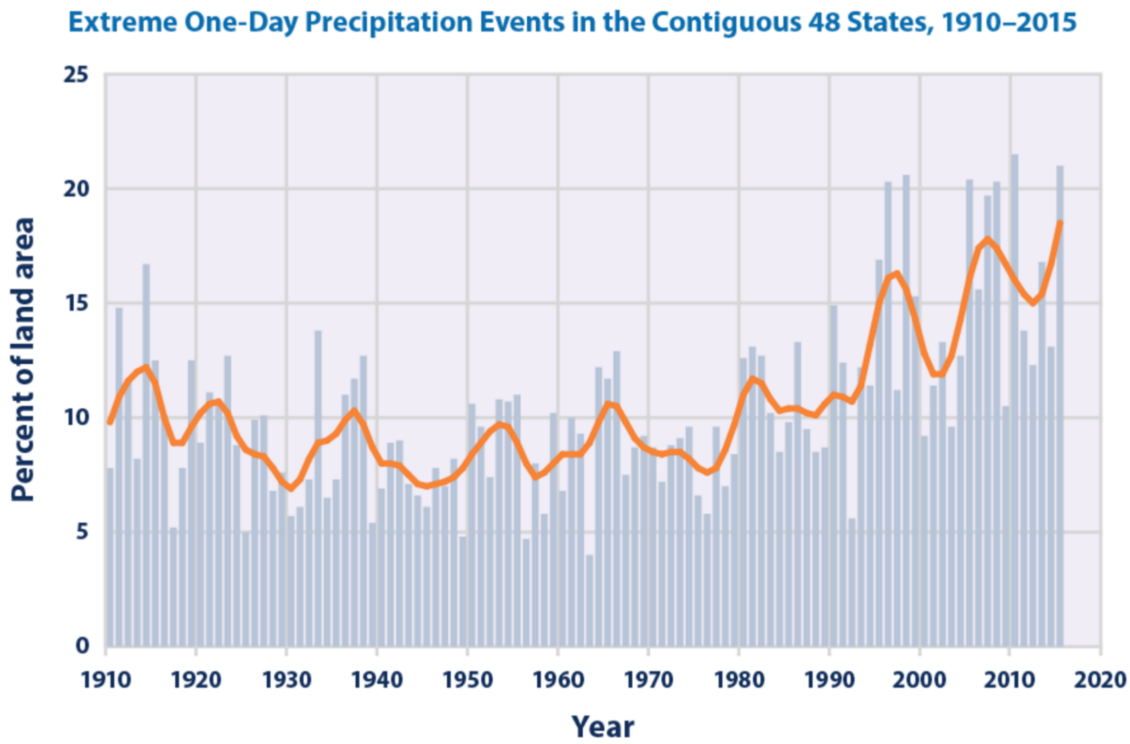


Figure 1.3 Extreme One-Day Precipitation Events in The Contiguous 48 States, 1910-2015. Source: (EPA, 2016)

It has been also, observed that the total numbers of days during a year that the precipitation exceeds 2 - 4 inches have been increased since 1900. (Karl, Knight, Easterling, & Quayle, 1996).

Changes have been also observed in some types of extreme weather events like Hurricanes. Since the early 1980s an increase has been observed in the intensity, frequency and duration in the Atlantic hurricane activity (Melillo, Richmond, & Yole, 2014). Kossin et al. (2007) Figure 1.4 shows recent variation of the Power Dissipation Index (PDI) in the Eastern North Pacific and in the North Atlantic Oceans.

.

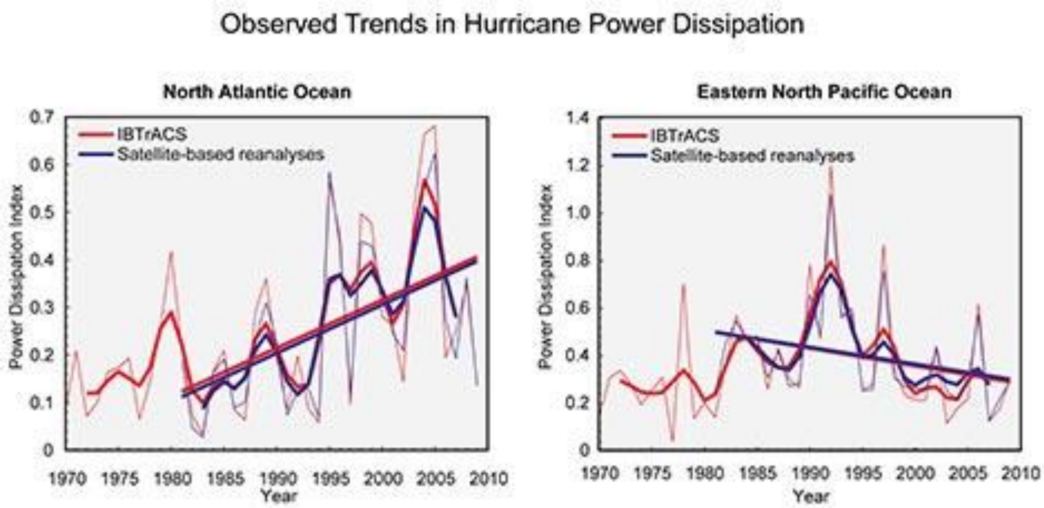


Figure 1.4 Observed Trends in Hurricane Power Dissipation. Source: (Kossin , Knapp, Vimont, Murnane, & Harper, 2007)

One can observe that there is an upward trend in PDI in North Atlantic while there is a downward trend in Eastern North Pacific Ocean. These graphs were created by historical data and satellite images, (Kossin , Knapp, Vimont, Murnane, & Harper, 2007).

While this is still ongoing research, many model-based studies have been made in order to project the Atlantic Hurricane activity with respect to climate change due to anthropogenic factors, [(Knutson, et al., 2013), (Murakami, et al., 2012) and (Pielke, Gratz, Landsea, Collins, Saunders, & R., 2008)]. Knutson et al. (2013) is using a dynamical downscaling approach in order to investigate the response of tropical cyclones and hurricanes in the Atlantic basin for different climate change scenarios. According to their study a decrease is projected in the overall frequency of tropical storms and hurricanes while there will be an increase in the frequency of the most intense simulated hurricanes. Another study from H. Murakami et al. (2012) projects an increase of +290% storm days in category 5.

.

Hurricanes with high intensity, while they are considered rare they bear great importance. Pielke et al. (2008) concluded that hurricanes of category 4 and 5 partitioned to almost half of the U.S. hurricane damage, making landfall between the years 1900 to 2005.

At the end of October 2012 the most destructive, costly and deadliest Hurricane of the Atlantic Hurricane Season was recorded. Sandy made landfall on October 29th, 2012 near Brigantine on the coastline of New Jersey, almost a year after Hurricane Irene (National Hurricane Center, 2013). In New Jersey, New York and Connecticut, storm surges and inundation reached record levels for the area, (National Hurricane Center, 2013). The highest storm surge measured in New Jersey at Sandy Hook in the Gateway National Recreation Area was 8.57 ft above normal tide levels, (National Hurricane Center, 2013). The aftermath of Hurricane Sandy was thousands of houses washed away from their foundation, entire communities inundated under water and debris, and approximately 8.5 million people without power (National Oceanic and Atmospheric Administration, 2013). On the contrary Hurricane Irene produced intensive rainfall that resulted in major flooding. Many record-breaking crests on rivers were recorded. Along the New Jersey shore the storm surge reached 3-5ft, which caused moderate to severe flooding. (National Hurricane Center, 2011)

Apart from changes in precipitation and extremes weather events, like hurricanes, changes have also been observed in the mean sea level. According to Intergovernmental Panel on Climate Change (IPCC) the global sea level rise rate was 0.067 +/-0.02 inches/year for the 20th Century, (Bindoff, et al., 2007). Sea level rises throughout the Northeast. Mean sea level rises at a range from 0.073 inches/year at Portland, Maine to

.

0.23 inches/year at the Chesapeake Bay Bridge-Tunnel, Virginia for the Northeast Region, (NOAA, 2013).

The risk of flooding has increased in many parts of the United States. There are many different flood types. Urban flash flooding due to heavy precipitation, coastal flooding due to storm surge and sea level rise, and riverine flooding due to heavy precipitation are some of the most common. Coastal storms combined with sea level rise have increased the risk of flooding and damage in coastal communities. The Atlantic and Gulf coasts have experienced damage and similar phenomena are expected in the future. Urban communities and coastal infrastructure like ports, roads, airports and energy facilities are under high risk of flooding. Floods in highly urbanized areas have also increased because of human-caused changes in the watershed. The effect of impervious surfaces on runoff in urban areas, often exacerbate flood phenomena. A characteristic example of intensive flooding are the urbanized areas located at Hudson River in New Jersey.

The communities of Hoboken and Jersey City (Hudson River Study Area) are located in the low elevation sections along the Hudson River waterfront, the Newark Bay / Hackensack River waterfront in Jersey City and the western half of Hoboken. These communities experienced severe flooding and flood related damage as a result of the storm surge and backup runoff from Hurricane Sandy.

Following the damage that was created on these communities by flooding from Hurricane Sandy, Rutgers University’s Department of Civil and Environmental Engineering was funded, (NJDEP, 2013), to develop comprehensive strategies to make New Jersey and its coastal areas more resilient to flooding.

.

The purpose of this dissertation research is to determine the flood vulnerability of the communities along the Hudson River waterway and to develop strategies measure to mitigate these vulnerabilities. The research was initiated with the NJDEP-sponsored study.

In the absence of an acceptable framework for a coastal flood risk reduction strategy development and following the damage that was created from Sandy, this research was initiated in order to develop comprehensive strategies to make New Jersey coastlines more resilient to flooding. The strategy development framework includes different combinations of different flood measures that address different levels of flood risk at different scales. Especially includes measures in regional, municipal and block and lot scale level that address coastal and rainwater flooding.

Apart from the commonly used flood measures like storage, surge barrier, conveyance, diversion, pumping, rainfall interception etc. this dissertation aims to evaluate the main concept of a newly proposed flood measure for low-lying areas, "Rainwater Driven Pump" (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014).

This measure represents a new approach in drainage management in densely populated areas. The concept behind is that rainwater from roofs or high ground elevations will be used as source of a renewable source of power, in order to change the conventional way of pumping rainwater and sewer to the treatment plant. Some other forms of renewable power that have been developed the last couple of years include wind, surge/wave, and river flow.

Chapter 2 states a detailed description of the storm surge and stormwater threats affecting Jersey City and the City of Hoboken. Chapter 3 then, describes a state of the art

.

framework for coastal flood risk reduction strategy development. Chapter 4, 5 and 6 present in detail the flood measures proposed in order to make Hoboken and Jersey City more resilient in regional, municipal and block and lot scale addressing both storm surge and rainwater drainage problems. Then, Chapter 7 describes and analyzes the alternative measure of “Rainwater Pump”. Also in the same chapter alternative flood mitigation strategies are discussed in this research. Finally Chapter 8 discusses the strategies recommended.

.

Chapter 2 Storm Surge and Stormwater Threats in Hoboken and Jersey City

2.1 Background

Jersey City and Hoboken are extremely low-lying cities with little or no relief. Flooding in these areas is a result of intense precipitation and runoff, tides and/or storm surges, or a combination of all of them.

Figure 2.1 Regional map of Jersey City & Hoboken, NJ. Source: (NJGIN, 2015)

.

Several locations in Jersey City and Hoboken experience chronic flooding during precipitation events. These locations are typically in the low elevation sections along the Hudson River waterfront, the Newark Bay / Hackensack River waterfront in Jersey City and the western half of Hoboken. These areas are characterized by little or no slope and elevations less than 10 feet above sea level. Hurricane Sandy also demonstrated that these areas are susceptible to coastal inundation. Floodwater traveled into these areas either directly from waterfront or, in the case of the western areas of Hoboken via low-lying areas on the northern (Weehawken) and southern (Jersey City) borders.

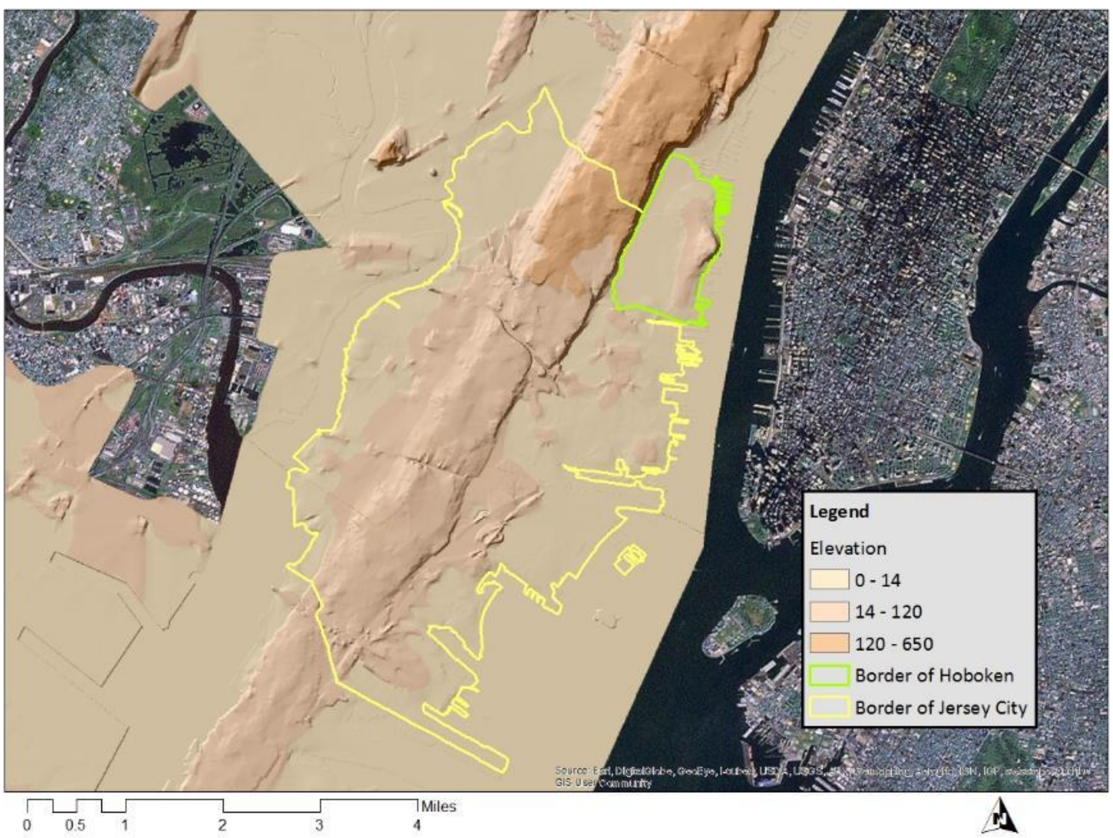


Figure 2.2 Map of Regional Digital Elevation Model of Jersey City & Hoboken, NJ. Source: (NJGIN, 2015)

.

In this study, the flood remedies that are proposed take into account both the scale of the remedy itself, as well as the event (precipitation/surge). The scales discussed are: 1.) Regional: measures discussed will address the whole area of study for major flood events (>10 year storm surge) and 2) Municipal: these measures include the use of new infrastructure or upgrade to existing infrastructure to protect areas from flooding that occurs on yearly scale. 3) Block and lot scale measures: In this scale flood protection strategies will address projects to be completed on individual properties and provide protection to small areas. These are the easiest and potentially most effective strategies. This is due to the fact that while larger scale projects will provide protection for extreme losses during huge events such as Hurricane Sandy, a storm of that magnitude may not occur for another hundred years, while it is a given fact that small scale flooding will occur and impact society in this area regularly.

2.2 Storm Surge Threat

This section describes the estimated water levels that are associated with conditions of future coastal inundation events (FEMA Map Service Center). The sea level rise is included in this analysis as well, and the best estimates of future sea level rise by Miller et al. (2013) are used. In order to determine the required height of the flood protection measures, it is necessary to determine the design water level. Total water levels above 0 feet NAVD88 include storm surge, astronomical higher high tide, (MHHW) and sea level rise. During Sandy, the NOS tide gauge at the Battery recorded storm tide values 9.0 feet above Mean Higher High Water (MHHW) (National Hurricane Center, 2013).

.

Table 2.1 Water Elevations Accordingly to Level of Threats, along The Coastline of Hudson River Study Area

Level of Threat	**Water Elevations (NAVD88)**
10 - Year Storm	8.5 feet
50 - Year Storm	11.3 feet
100 – Year Storm	12.3 feet
100 – Year Storm + 2050 SLR	13.6 feet
100 – Year Storm + 2100 SLR	15.4 feet
2050 Sea Level Rise	1.3 feet
2100 Sea Level Rise	3.1 feet

The following flood maps (Figure 2.3 to Figure 2.11) are constructed using the data obtained from the FEMA Map Service Center and show the flood prone areas in the cities of Hoboken and Jersey City under different case scenarios of coastal storms.

.

10 - Year Coastal Storm

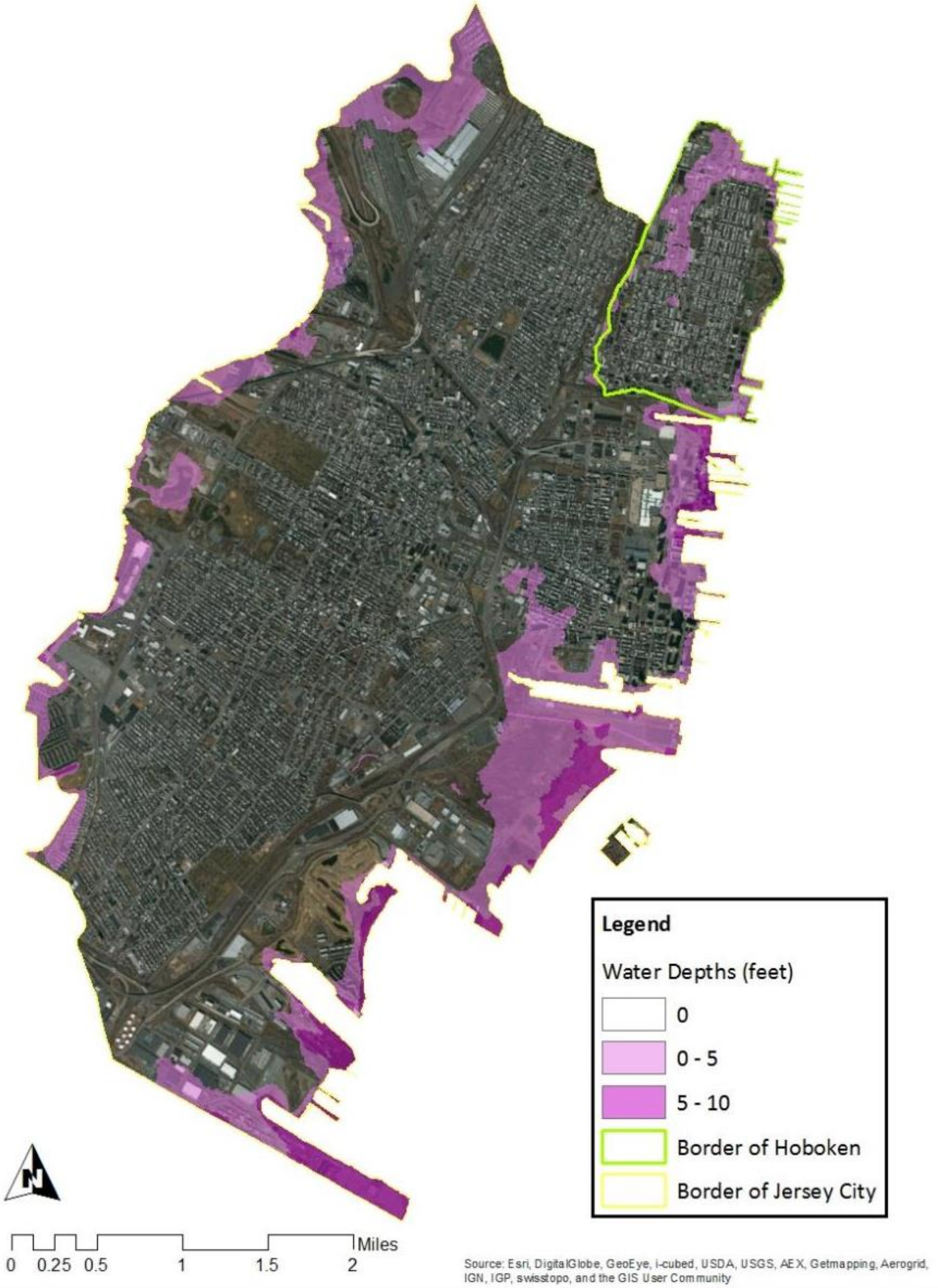


Figure 2.3 10-Year Storm Map, Jersey City & Hoboken, NJ. Source: (FEMA Map Service Center)

.

50 - Year Coastal Storm

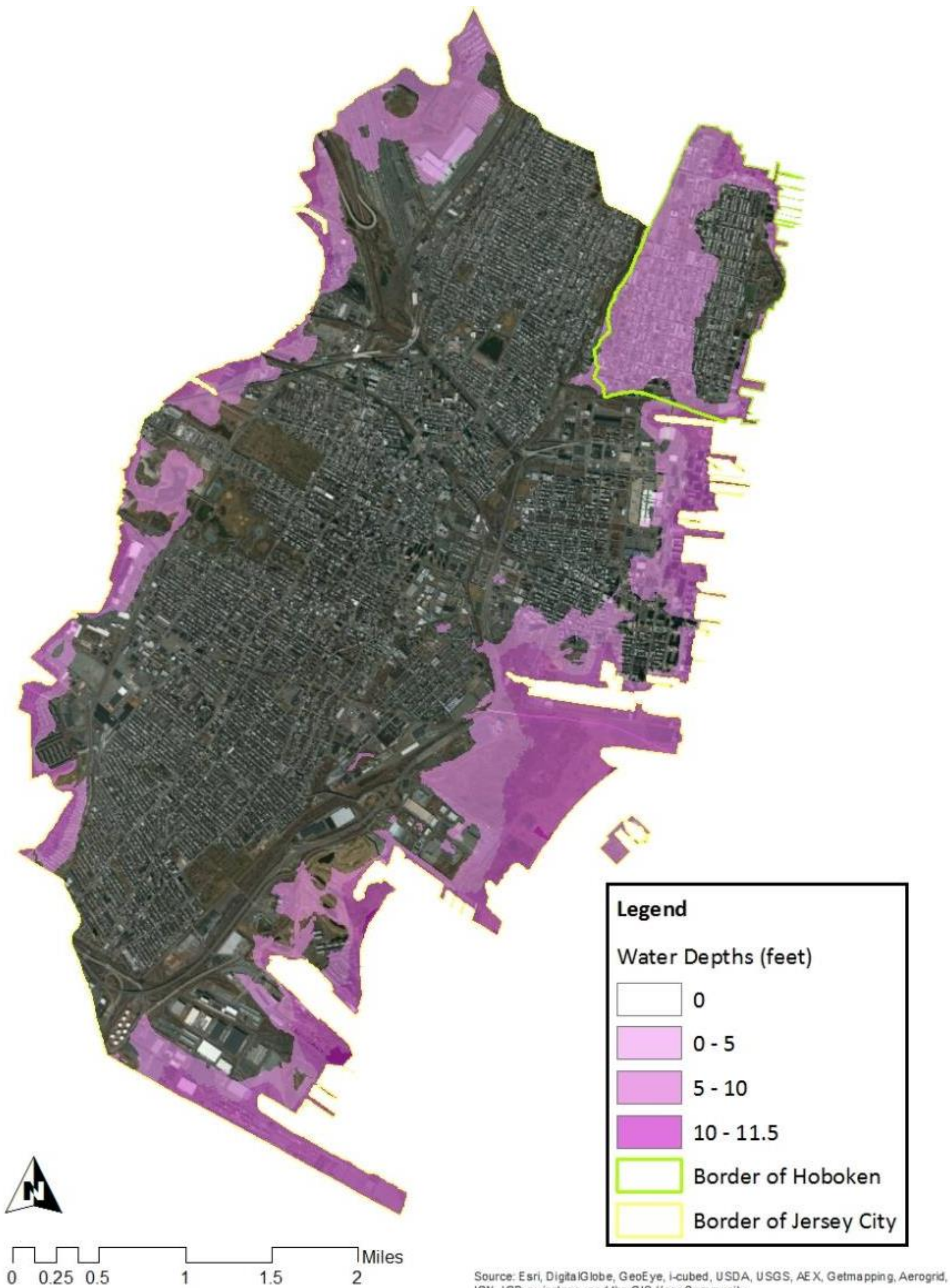


Figure 2.4 50-Year Storm Map, Jersey City & Hoboken, NJ. Source: (FEMA Map Service Center)

100-Year Coastal Storm

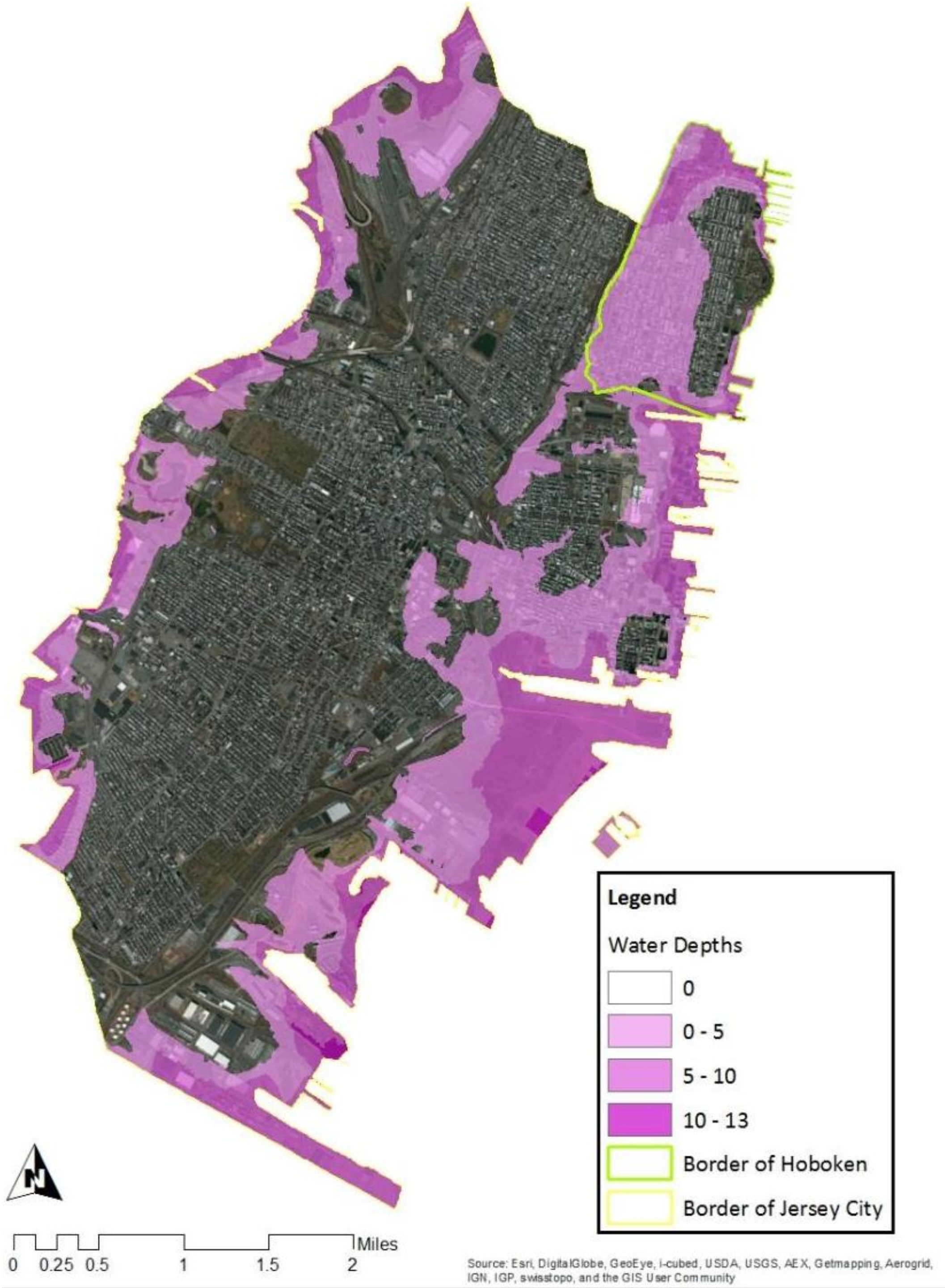


Figure 2.5 100-Year Storm Map, Jersey City & Hoboken, NJ. Source: (FEMA Map Service Center)

.

According to the FEMA FIRM map (FEMA Map Service Center, National Flood Hazard Layer Database) Hoboken experienced flooding for all storm surges with return periods of 10, 50, 100-years.

10-Year Coastal Storm: Water enters from the northern boundary of the City where Columbus Park is, and reaches south to 7th street. In some locations water depths reach up to 2 feet around Jefferson St (Figure 2.6).

Figure 2.6 10-Year Storm, at North End of Hoboken, NJ. Source: (FEMA Map Service Center)

50-Year Coastal Storm: Water floods from the northern and southern boundaries of the City. Most of the western area of Hoboken has floodwater depth reaching up to 3.5 feet (Figure 2.7).

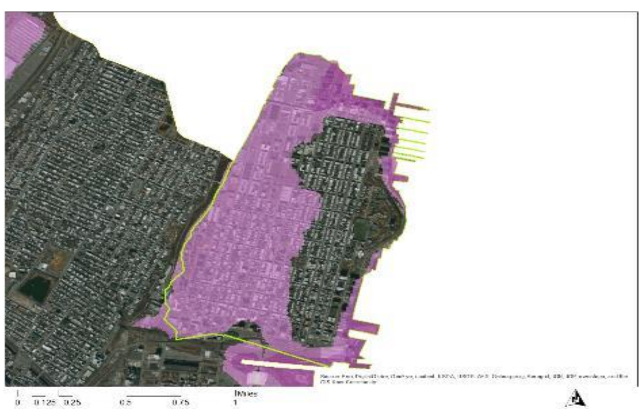


Figure 2.7 50-Year Storm, Hoboken, NJ. Source: (FEMA Map Service Center)

.

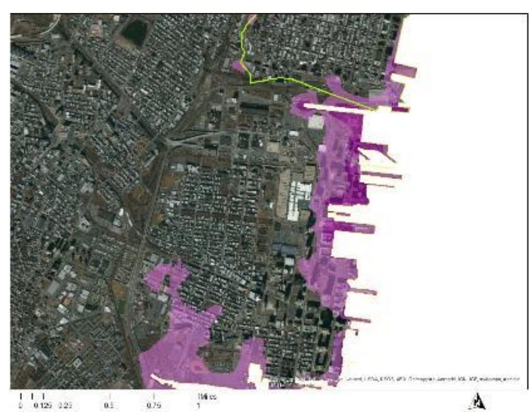
100-Year Coastal Storm: In most parts of the western areas of Hoboken water depth reaches almost 6 feet (Figure 2.8).

Figure 2.8 100-Year Storm, Hoboken, NJ. Source: (FEMA Map Service Center)

According to the FIRM map Jersey City floods for 10, 50 and 100- year as well:

10- Year Coastal Storm: Storm water floods the southern part of downtown of Jersey City up to 2nd Street where water depth reaches almost 5 feet.

10-Year Storm, at South Downtown Jersey City, NJ.



10-Year Storm, at North Jersey City, NJ.

Figure 2.9 10- Year Storm Jersey City, NJ. Source: (FEMA Map Service Center)

.

50- Year Coastal Storm: Water at Grant Street reaches depths up to 3.5 feet (Figure 2.10).

Figure 2.10 50-Year Storm, Jersey City, NJ. Source: (FEMA Map Service Center)

100-Year Coastal Storm: Floodwater reaches depths up to 2 feet under the elevated Route 78 at south while water elevations around Morris Marina reach 5 to 7 ft NAVD88 (Figure 2.11).

100-Year Storm, at Route 78, Jersey City, NJ

100-Year Storm, Downtown Jersey City, NJ,

Figure 2.11 100-Year Storm Jersey City, NJ. Source: (FEMA Map Service Center)

2.3 Stormwater Threat

Most of the frequent floods that Hoboken and Jersey City have to face are due to the backpressure that restricts flow out of the combined sewers. During periods of heavy rainfall, sanitary wastewater and storm water can overflow the conveyance system and discharge directly to surface water bodies. Each CSO outfall is protected from coastal surge via a flap gate. The condition of some of these gates is unknown. If the gates are non-functional, the CSOs can provide a conduit directly into the basements and streets. If the gates are completely functional, the storm surge (assuming it doesn't occur over land) will be blocked from entering the City, however backwater effects will cause the gates to not open and drain the system thus backing untreated sewage up into basements and streets. Walsh and Miskewitz (2011) indicate that large increases in downstream elevation will impact flap gate function and may result in upland flooding even though backflow through the gate is blocked. In addition to storm surges, sea level rise will result in higher downstream water elevations, which may exacerbate the impact of storm surges.

Proper operation and regular maintenance programs for the sewer systems with CSOs should be taken into consideration. Plans should begin with a review of the sewer system, which identifies and locates all CSO and storm water points. Key monitoring or observation points should be selected to best reflect conditions in the entire sewer system. One minimum control is proper functionality of the flap gates (Figure 2.12). Tide gate failure can often be attributed to debris becoming lodged in the gate or corrosion of the gate or deterioration of the gate gaskets (Van Abs, McClean, Tsoulou, Gao, & Evans, 2014).

.

Figure 2.12 Flap Gate at Morris Marina, Jersey City, NJ

2.3.1 City of Hoboken

Federal Emergency Management Administration (FEMA) designates the flood prone areas on the western side of Hoboken as High Flood Risk Zones (Spinello, 2013).

.

It is also apparent from Figure 2.13 that a three-foot rise in sea level above MHHW would result in catastrophic flooding in this area.

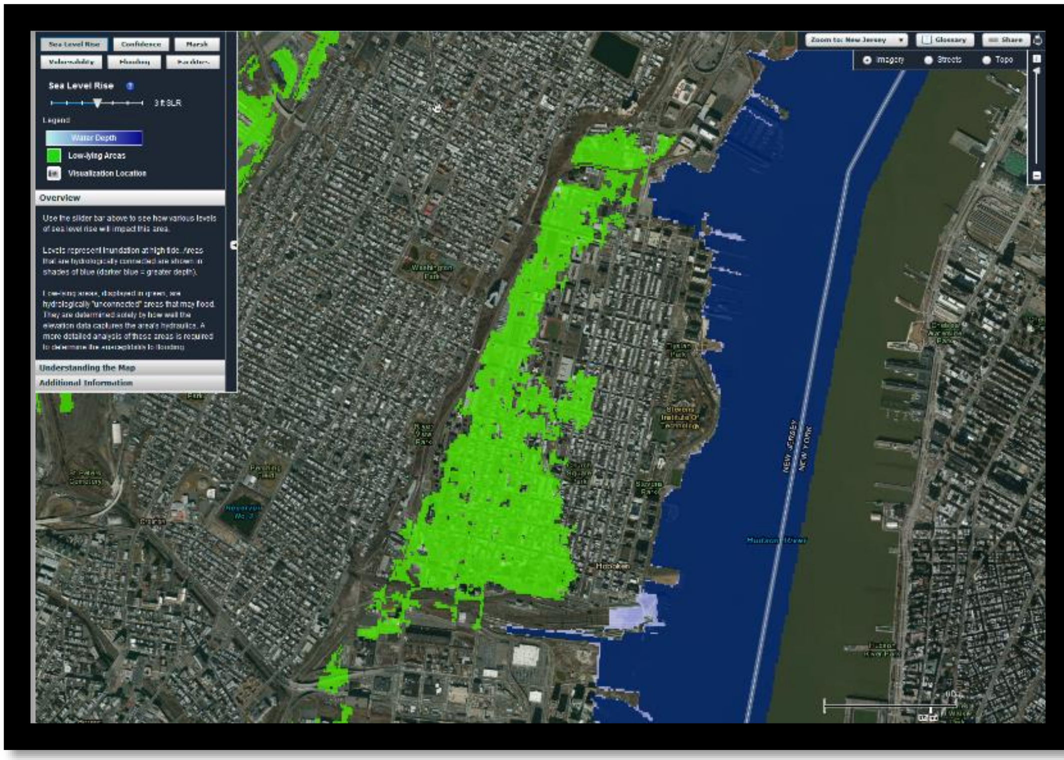


Figure 2.13 Flood Prone Areas in Hoboken along Hudson River Waterfront under 3 feet Level Rise Scenario. Source: (NJ Flood Mapper, 2013)

Among all New Jersey cities, Hoboken ranks at the top for the largest population exposed to flood risk (Climate Central, 2012). 53% of the City's population of 50,000 residents lives at locations with elevations less than 5 feet above the local high tide elevation. Besides housing, much of the City's vital infrastructure is also at significant risk because it also lies below the 5-foot mark. 100% of Hoboken's fire stations, hospitals, libraries, community centers, rail and ferry stations, sewage plants, and major hazardous waste sites are all located below five feet. 57% of its houses of worship, 57% of roads, and 50% of its schools are also below five feet (Climate Central, 2012)

.

The Hoboken drainage system is a combined storm water and sanitary sewer system. It drains to the Adams Street Waste Water Treatment Plant that is operated by North Hudson Sewage Authority. It features 8 CSO outfalls located along the Hudson River Waterfront and a wet-weather pump station located in the southeast corner of the City, on 99 Observer Hwy. Flap gates to restrict back flow from the Hudson River into the sewer system protect CSO outfalls. Figure 2.14 shows the drainage areas of Hoboken.

Figure 2.14 Map of Drainage Basins & CSO Outfalls, Hoboken, NJ. Source: (NHSA, 2002)

Identification of flood impacts resulting from precipitation events were conducted via two analyses by the North Hudson Sewage Authority, (NHSA, 2002), (NHSA, 2013)]. The modeling analysis of frequent flooding on the southwestern side of the town, which was completed in 2002, shows that flooding would be expected to occur during 3-

.

month, 1-year, 2-year, and 5-year storms. Based on the model results the following areas and sub-basins flood:

- During a 0.25-year storm, the area between Marshall Street and Jackson Street and Newark Street and 2nd Street, which corresponds to the most low-lying area in the H1 drainage basin and sub-basin H1-4 (Figure 2.15), experiences significant flooding with flooding depths in some locations reaching up to 1.5 feet.
- 0.25-, 1-, 2- and 5-year storms flood the sub-basins H1-4, H1-5, H1-6 and H1-7 (Figure 2.15).

Installation of two different capacities pumps was suggested in the NHSA 2002 report. One 38 MGD to drain the H1-4 basin and sized to carry peak flows for up to the 5-Year storm capacity and the other 56 MGD sized to carry peak flows up to the 5-Year storm capacity to drain the H1-4 and H1-5 sub basins (Figure 2.15).

In 2011, the H1 wet weather pump station located at the southeast corner of the city at 99 Observer Hwy was constructed to help relieve the flooding problems in the low-lying southwest part of the city (the H1 area). The station has a pump design capacity of 50 MGD. The pump station has two pumps each capable to pumping 50 MGD with only one expects to operate at one time. Also for this project two 36-inch mains were installed under the Observer Hwy in order to carry the flow to the pump station. The cost of the pump station was $17,605,500.

.

Figure 2.15 Sub-Basins of Drainage Basin H1. Source: (NHSA, 2002)

Another Hoboken Flood Analysis study for NHSA (NHSA, 2013) installed a sewer monitoring system throughout the Hoboken collection system in order to:

.

- Determine the benefits of the H1 Wet Weather Pump Station (H1WWPS) citywide.
- Quantify the extend of the remaining flooding
- Determine flood remediation options.

During the 2013 analysis period for NHSA flooding occurred four times. The flooding occurred under rain events with storm designation of:

- 1-year New Jersey Design Storm and a duration of 12 hours,
- 1-year New Jersey Design Storm and a duration of 1-hr,
- Almost 1-year New Jersey Design Storm, and
- 4-year New Jersey Design Storm and duration of 12-hr.

The 24-hr design storm rainfall depth for 1-year return period for Hudson County is 2.7 inches

Over the four events the peak flood volumes were calculated either for the H1 basin or the northern drainage areas. The resulting peak flood volume ranges were:

- H1 Basin: 1.0 MG to 4.2 MG. The additional required pumping capacity identified is from 25 MGD to 100 MGD
- Northern drainage area: 0.1 MG to 4.3 MG. The additional required pumping capacity identified is from 1 MGD to 100 MGD

The 2013 NHSA study recommended 2.7 MG of storage or 65MGD of pumping capacity (split between the H1 area and the H5 area to the north) is added in order to prevent flooding in all but the largest observed storm event.

.

2.3.2 Jersey City

Using the NJ Flood Mapper Software, low-lying areas have been identified along the Hudson River waterfront in Jersey City (Figure 2.16). Water levels are shown, as they would appear during highest tides excluding the one's driven by wind. In the following , the low-lying areas for a sea level rise of 3 feet from MHHW are displayed in green, the coastal water displayed from light blue to dark blue represent the change of inundation depth.

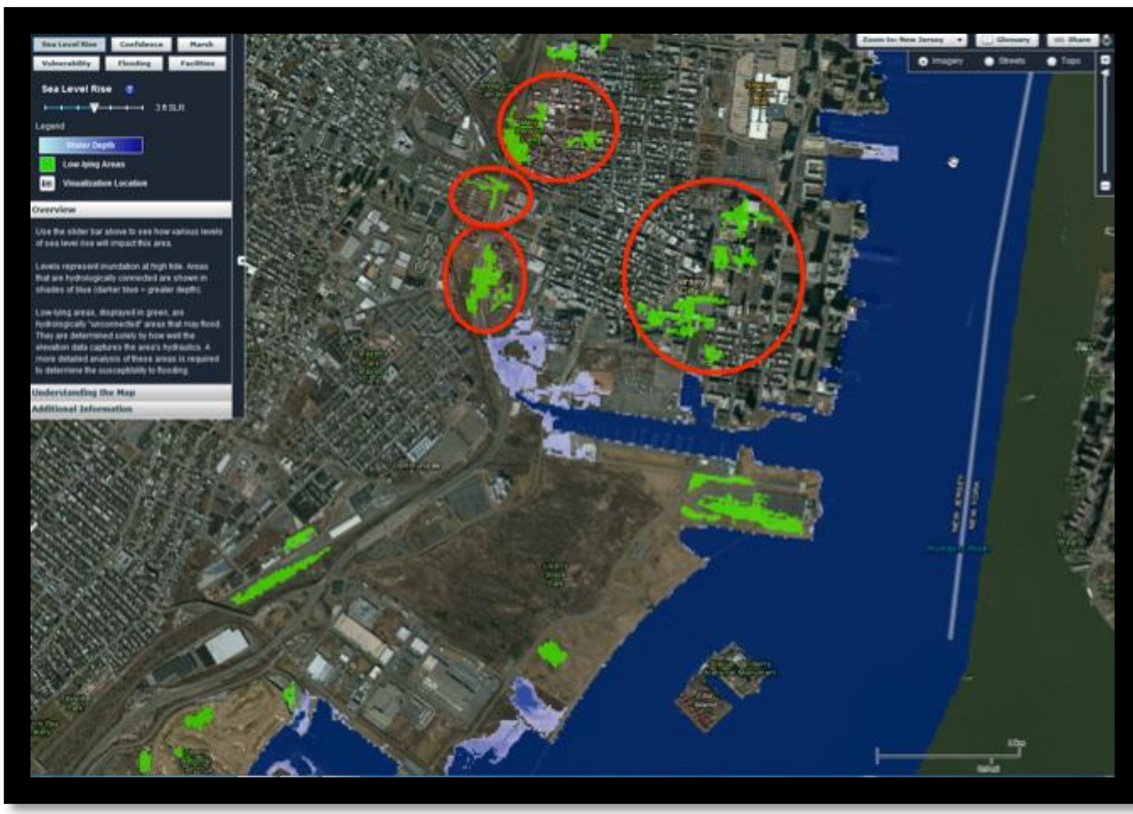


Figure 2.16 Flood Prone Areas in Jersey City along Hudson River Waterfront under 3 feet Level Rise Scenario. Source: (NJ Flood Mapper, 2013)

The areas identified as prone to flooding are investigated further to determine the impact of Hurricanes Sandy and Irene. The red circles drawn on Figure 2.16 are specific

.

areas, identified by the Jersey City Municipal Utilities Authority (JCMUA) as chronic flood areas. These areas will be addressed with flood mitigation strategies. Flood impacts along the Newark Bay/Hackensack River waterfront are also investigated (Figure 2.17).

Figure 2.17 Flood Prone Areas in Jersey City along Newark Bay/Hackensack River Waterfront Under 3 feet Level Rise Scenario. Source: (NJ Flood Mapper, 2013)

The Jersey City sewer system is a combined system that collects both sanitary and storm flows and conveys it by force main (72 inch) to Passaic Valley Sewerage Commissioner's (PVSC) plant in Newark. Approximately 50 MGD of wastewater is conveyed under standard conditions (dry) across the City, under Newark Bay to the PVSC plant in Newark. When the system is charged with storm water excess flow is directed to the Hudson River/NY Harbor through 21 CSOs. These CSOs discharge to the

.

tidal Hudson River, Newark Bay and the Hackensack River. Any interruption of service will result in backing up of sewage and either CSO discharge or backup regardless of conditions. The pumps required to transfer the water are by necessity at low elevation and energy intensive. These pumps must have backups as well as backup power including generators during power outages.

Jersey City has installed four pumps that will help alleviate flooding in some parts of Downtown. The last one was installed on December 2013. Each of the four pumps can discharge approximately 1,400 gallons per minute, or 80 million gallons daily. These four pumps are located on Pine Street in Bergen-Lafayette, Mina Drive in Country Village and 18th Street in Downtown and last one at the foot of Essex Street. JCMUA officials commented that the downtown area of Jersey City had not experienced any flooding since the installation of the four pumps. This measure was completed in order to prevent flooding and keep dry the Downtown area from sewer water backing up during heavy rain.

Officials also comment that Jersey City should eventually move forward to the separation of the sewer system. More options are available to handle the storage and disposal of storm water than there are for sewage. Jersey City also has some storm water basins used to manage the runoff in order to prevent flooding and improve the water quality in adjacent rivers. The following Figure 2.18 gives the exact locations of these basins. Table 2.2 gives the area of each storm water basin.

.

Table 2.2 Areas of Existing Storm Water Basins Jersey City, NJ

Storm Water Basins	**Total Area (acres)**
Carol Ave	2.23
Pershing Field	6.76
Communipaw Ave	0.87

.

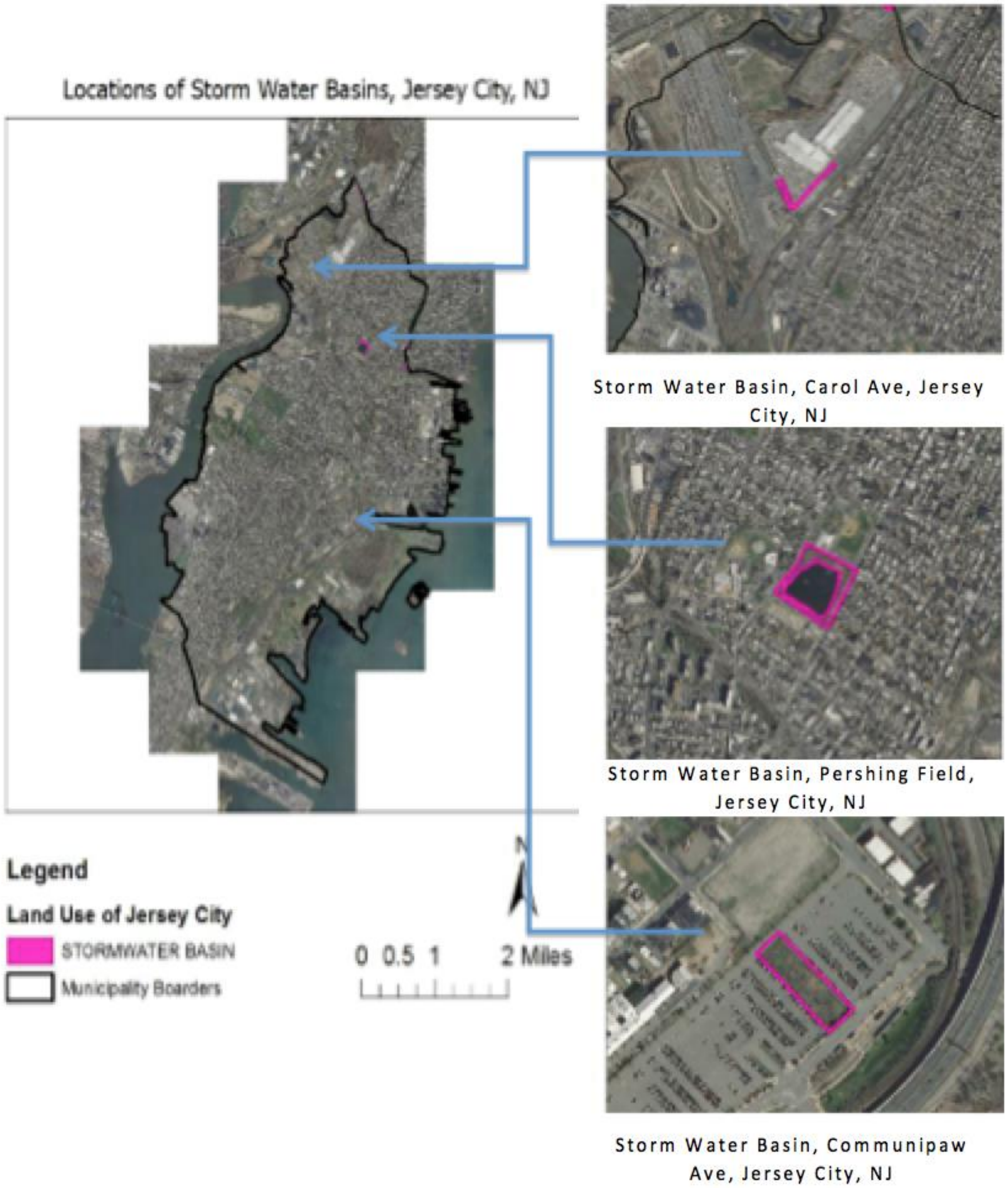


Figure 2.18 Storm Water Basin, Jersey City, NJ. Source: (Malcolm Pirnie, INC., 2008)

The project team consulted with JCMUA officials to determine locations that experience chronic flooding resulting from rainfall and high tides. These locations were identified along with predicted flood areas using Flood Mapper (Figure 2.16 and Figure 2.17).

.

Chapter 3 Approach to Developing Flood Mitigation Strategy and Threats

3.1 Framework

The Rutgers University Flood Mitigation Study Team, headed by Principal Investigator, Dr. Qizhong (George) Guo developed a framework to facilitate the assessment of flood risk to communities and to facilitate the selection of flood mitigation measures for these communities Figure 3.1.

The Rutgers University Flood Mitigation Study Team also developed a menu of flood risk-reduction functions and their associated measures. Figure 3.2 is a schematic showing the application of various flood mitigation measures and Table 3.1 provides a listing of each function and its associated measures.

The strategy development framework includes the consideration of (a) all three sources of the threat (the flood water), namely, local rainwater, upstream riverine flow, and downstream coastal water; (b) various levels (recurrence intervals) of the threat and their future changes; (c) types and extents of the exposure/vulnerability including various types of land use and infrastructure; (d) regional, municipal, and neighborhood/block/lot scales of solutions; (e) types of possible flood mitigation measures, (f) functions of possible flood mitigation measures, and (g) costs, benefits, environmental impacts, waterfront accessibility and synergy of the proposed solutions. The types of the measures considered include: maintenance/repair vs. new construction, mobile/adaptable vs. fixed, green/nature-based vs. grey, non-structural (policy, regulation, etc.) vs. structural, micro-grid vs. large-grid powered, innovative vs. conventional, preventative vs. protective,

.

retroactive vs. anticipatory, and short-term vs. long-term. The functions of the measures considered include: (1) rainfall interception, (2) storage, (3) conveyance, (4) upstream flow reduction, (5) diversion, (6) deceleration, (7) tide barrier, (8) pumping, (9) surge barrier, (10) mobile barrier, (11) elevation, and (12) avoidance. Implementation of the flood mitigation measures will help the communities achieve resilience.

.

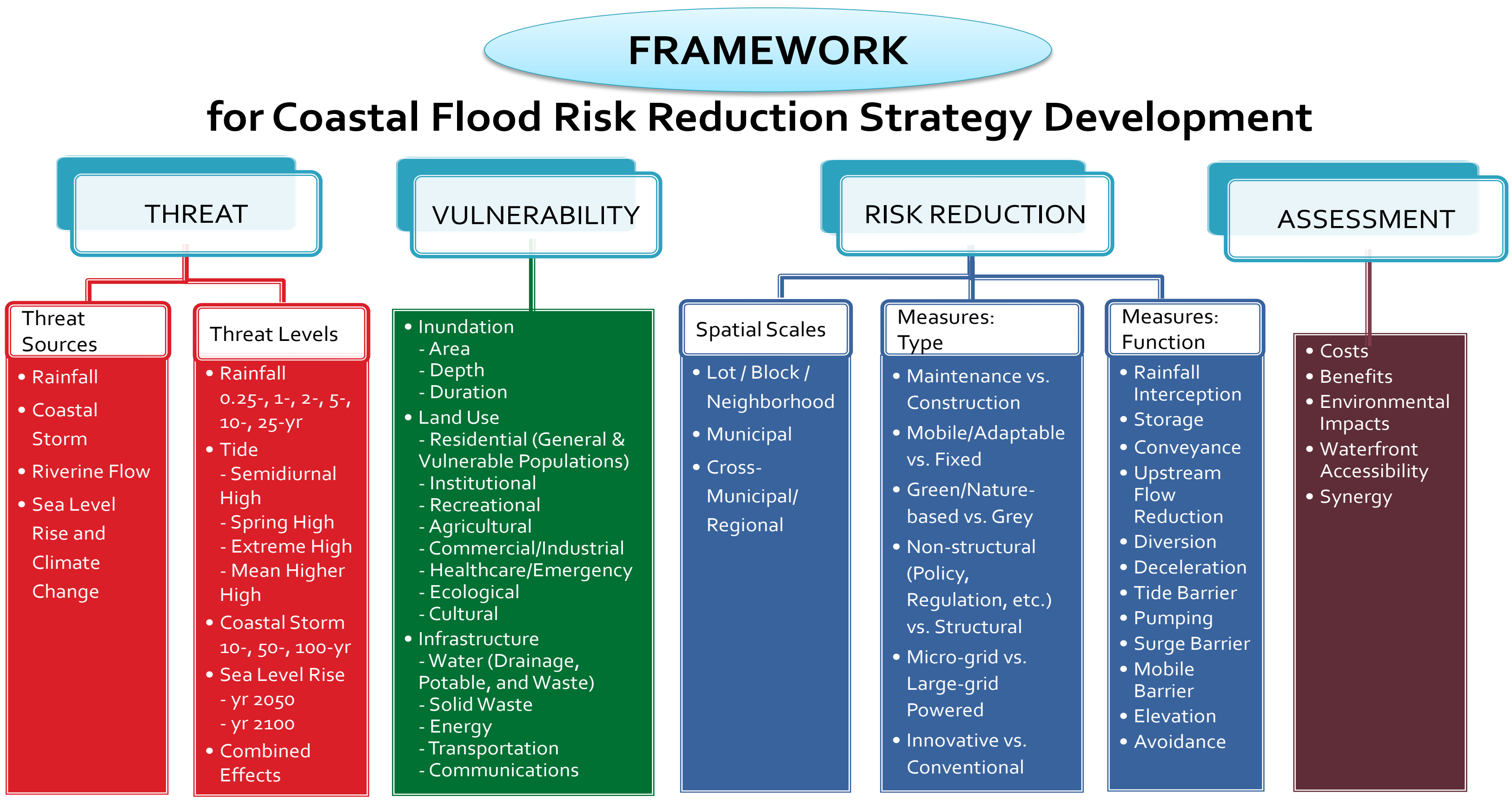


Figure 3.1 Framework for Flood Risk Reduction Strategy Development. Source: (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014)

.

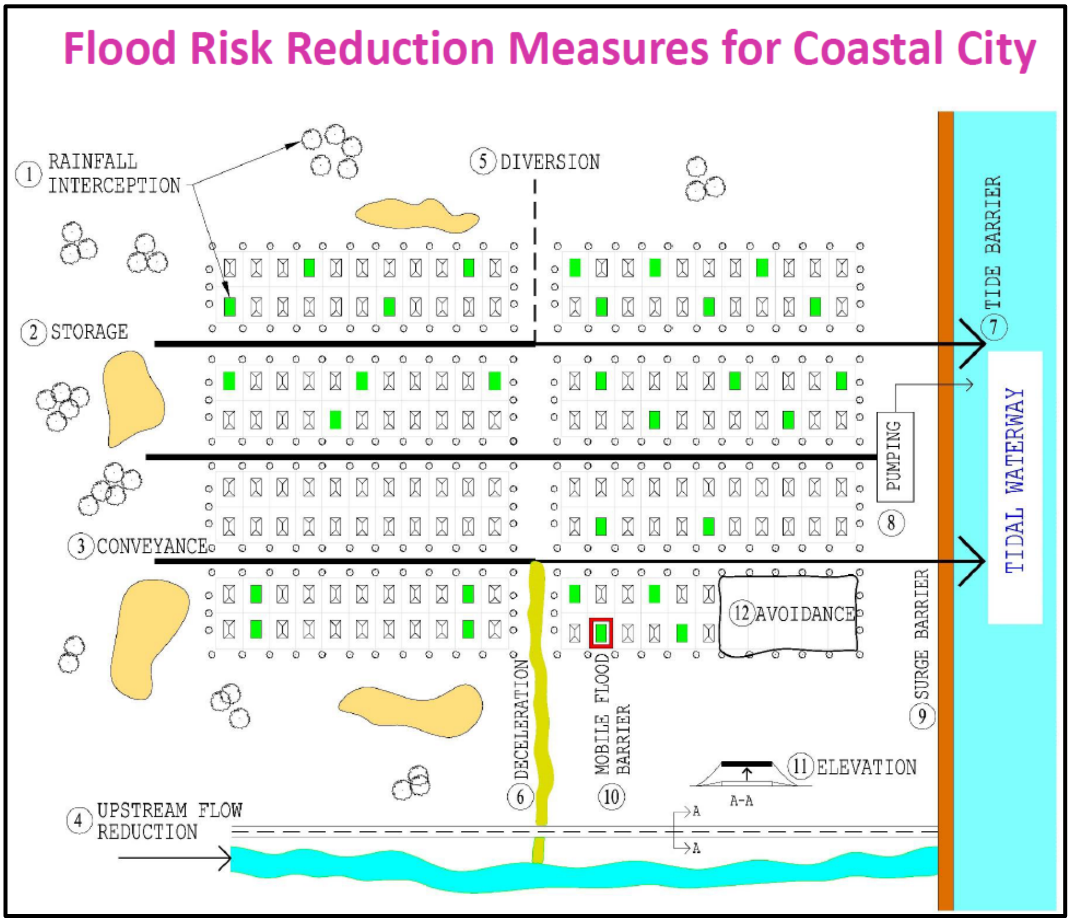


Figure 3.2 Flood Risk Reduction Measures. Source: (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014)

.

Table 3.1 Flood Mitigation Functions and Associated Measures

FUNCTIONS AND MEASURES

RAINFALL INTERCEPTION	**STORAGE**	**CONVEYANCE**	**UPSTREAM FLOW REDUCTION**	**DIVERSION**	**FLOW DECELERATION**	**TIDE BARRIER**	**PUMPING**	**SURGE BARRIER**	**MOBILE FLOOD BARRIER**	**ELEVATION**	**AVOIDANCE**
INCREASE VEGETATION	RETENTION	SEWERS	DAM	NEW SEWER	SWALE	FLAP GATE	PUMPING STATION	NEW LEVEE	MUSCLE WALLS	ELEVATE	BUYOUT
GREEN ROOF	DETENTION	DREDGING			ARTIFICIAL WETLANDS	SLUICE GATE	EMERGENCY POWER	SEAWALL	FLOOD GATE	ELEVATED ROAD	
VEGETATIVE SWALES	TEMPORARY	COMBINED SEWER CONVERSION				HEADWALL	WIND PUMP	TEMPORARY SEAWALL			
POROUS PAVING	EXPANSION	CULVERT SIZE					RAIN PUMP	ELEVATING LEVEE			
RAIN GARDEN	CONSTRUCTED WETLANDS						WAVE PUMP	NEW DUNES			
PLANTER BOX	LAKE EXPANSION						CURRENT PUMP	BEACH NOURISHMENT			
								ARTIFICIAL WETLANDS			
								SHEETING BULKHEAD			
								CONCRETE BULKHEAD			
								REPAIR LEVEE			
								VEGETATE LEVEE			
								BREAKWATER			
								IN-WATER BARRIER			
								RESTORE WETLANDS			
								LIVING SHORELINE			
								FLOATING BARRIER			
								EXTENDABLE FLOOD PANEL			
								CAUSEWAY WITH OPERABLE FLOOD GATE			

Chapter 4 Regional Flood Mitigation Measures

Based on the pattern of flooding in the Hudson River Study area, two regional flood measures are proposed that could be implemented to mitigate coastal storm inundation. The measures that are suggested change according to the flood level of threat they are intended to protect against. The measures are summarized in Figure 4.1, Table 4.1 and Table 4.2.

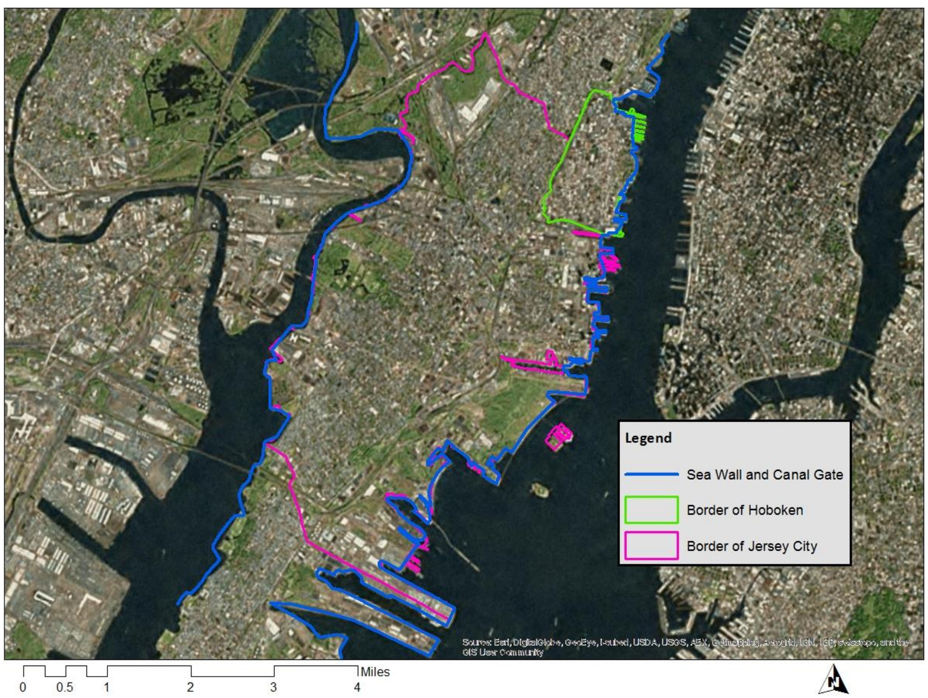


Figure 4.1 Flood Mitigation Measures Map, Jersey City & Hoboken, NJ. Source: (NJGIN, 2015)

4.1.1.1 Measure 1: Sea Walls

The range of required crest elevation for the barrier is 9 to 16 feet based upon the combination of tides, sea level rise, and storm surge. However, if wave overtopping is

.

taken into account an additional 2 to 3 feet should be added to the design. The resulting barrier should have a crest elevation between 12 to 19 feet. The ground elevation along the water edge is from 2 to 3 feet. The height of the barrier/seawall should be the difference between the desired crest elevation and the ground elevation. A total length of 13 miles of seawall for the side of Hudson River and 11 miles for the Newark Bay is required to protect the area.

In this study a flood barrier is considered that includes a sheet pile bulkhead and cap base with top height 4 feet above grade and then four vertical extensions each 4 feet high combining to create a 20 feet tall barrier.

The 4-feet high (above ground) bulkhead base and cap plus the deep piling and anchoring underground (Figure 4.2) are estimated at $4000 per foot. The 4-feet high extensions (Figure 4.3) are estimated at $400 per foot**. Please note that the cost of maintenance has not been examined.** Detailed cost analysis is presented in the report submitted to NJDEP. (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

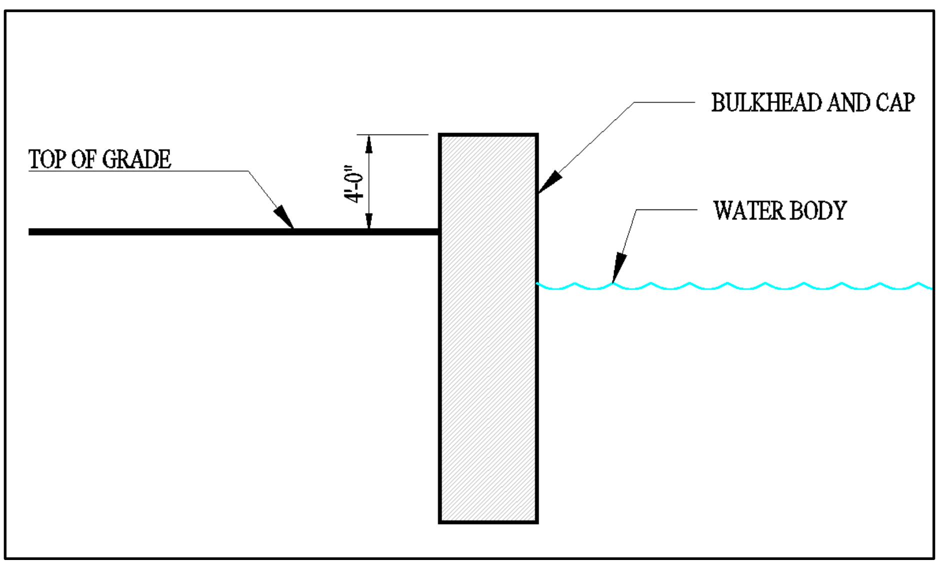


Figure 4.2 Floodwall Schematic Showing Bulkhead.

.

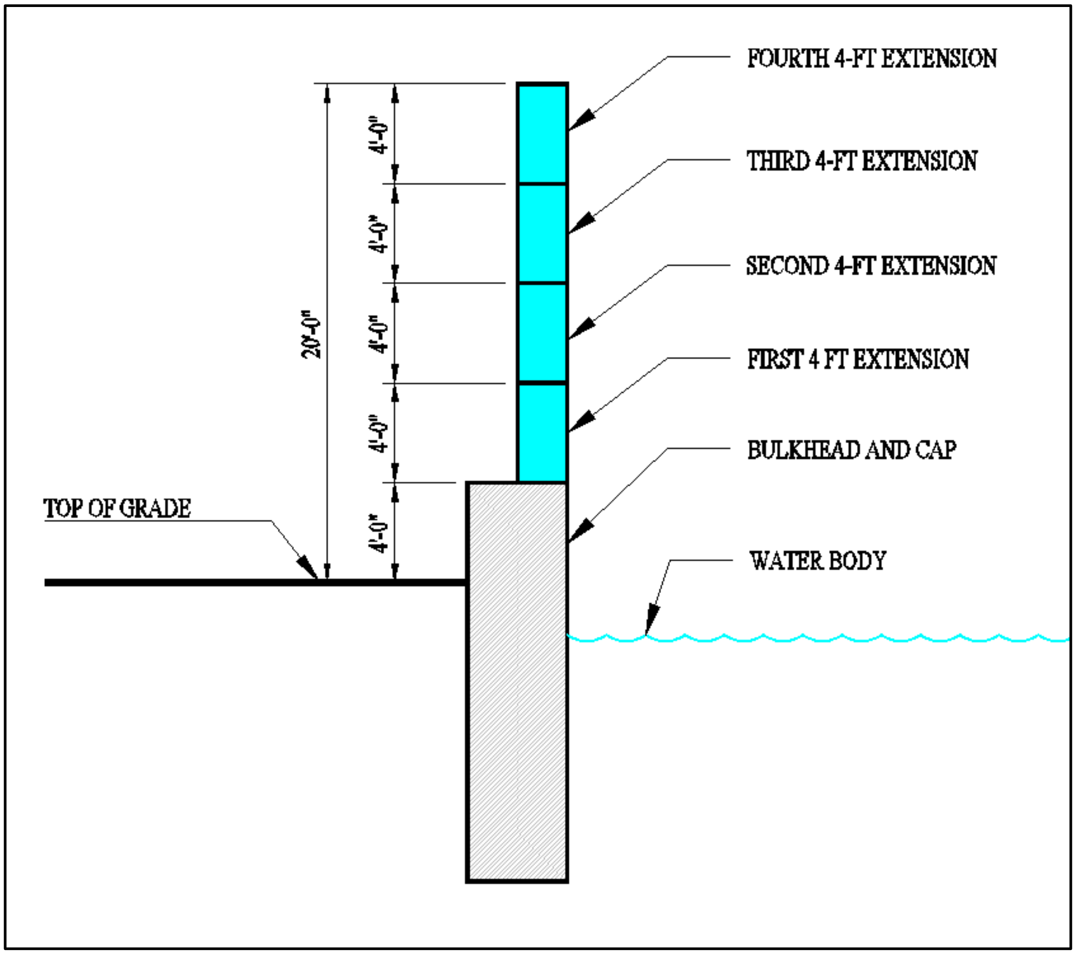


Figure 4.3 Floodwall Schematic Showing Bulkhead and Extensions

Table 4.1 Regional Flood Measure, Bulkhead and Steel Flood Wall along Hudson River

Protection Level	Wall Height
10 - Year Storm	12 feet
50 - Year Storm	16 feet
100 - Year Storm	16 feet
100 – Year Storm + 2050 SLR	16 feet
100 – Year Storm + 2100 SLR	20 feet

.

Table 4.2 Regional Flood Measure, Bulkhead and Steel Flood Wall along Newark Bay

Protection Level	Wall Height
10 - Year Storm	12 feet
50 - Year Storm	16 feet
100 - Year Storm	16 feet
100 – Year Storm + 2050 SLR	16 feet
100 – Year Storm + 2100 SLR	20 feet

The length of the floodwall along the Hudson River and the Newark Bay, can be shortened by taking advantage of some existing structures and/or high ground/landscape. Also, using alternative protective options such as elevating and/or barricading the individual buildings could shorten it.

Other floodwall options are available, potentially cheaper. However, all the options, structural stability and waterfront accessibility, among other factors, should be considered before their actual implementation.

Also note the floodwall's directly running across wetlands should be avoided as much as possible. It should be set back inland letting the wetlands survive and if the space allows, migrate upland as the sea level rises. The wetlands will provide the ecological values as well as the damping effects on the onshore waves and surge.

Further note that the lengths of the floodwalls and the associated costs are for those within the borders of Hoboken and Jersey City only. The regional floodwalls will need to be extended beyond the municipal boundaries.

.

4.1.1.2 Measure 2: Gates at Open Tidal Canals

In the study area, there are two open canals, the Long Slip in Hoboken and the Morris Marina in Jersey City. Both of these canals represent an entrance for storm surge from the Hudson River. Low elevations provide a conduit through which floodwaters enter the city (approximately 5 to 6 feet for Long Slip at the side of Hoboken, and 4 to 5 feet Morris Marina NAVD88).

Table 4.3 summarizes the dimensions of the gates required for 100-year storm surge at 2100 SLR scenario. To determine the required height of the barriers, the water elevations and bathymetry were considered. For the 100-year storm surge with high tide and SLR 2100 the crest elevation is suggested to be 19 feet. Also this measure should be implemented in connection with the measure of the sea walls.

Table 4.3 Regional Flood Measure, Canal Gates

Long Slip	**Length**	**Height**
100 – Year Storm + 2100 SLR	100 feet	24 feet

Morris Marina	**Length**	**Height**
100 – Year Storm + 2100 SLR	200 feet	24 feet

In order to preserve the Morris Marina as a recreational boating resource a sliding gate or other moveable structure should be implemented. Detailed cost analysis of the tidal gates is presented in the report submitted to NJDEP. (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

.

Chapter 5 Flood Mitigation Measures at Hoboken

5.1 Coastal Flood Mitigation Measures

Hoboken can protect itself from the coastal flooding by using flood barriers within its municipal border. Hoboken is exposed to tidal surge at Weehawken to the north and the New Jersey Transit rail yards to the south. During Hurricane Sandy water from north and south inundated Hoboken. The municipality of Hoboken can take advantage of the existing concrete walls of the elevated road at 14 Street with a length of 1,368 feet as well as the existing elevated railroad above from Long Slip with a length of 2,752 feet. Water elevations at the western part of Hoboken reach from 2 to 10 feet. Flood barriers to cover 3,281 feet of length at north along 14 Street and 2,636 feet along the railroads of NJ Transit Terminal, above Long Slip are recommended.

The following map Figure 5.1 shows the location of the measures suggested for the coastal storm flood threat for Hoboken.

.

Figure 5.1 Flood Mitigation Measures Map, Hoboken, NJ. Source: (NJGIN, 2015)

In this study a combination of different types of flood barriers are examined: 1) fixed floodwalls and 2) movable floodgates.

Fixed floodwall is a primary artificial vertical barrier designed to contain the waters of a waterway, which may rise to unusual levels during extreme or seasonal weather events. A fixed floodwall (Figure 5.2), of 5 feet height and 12 feet wide, costs $11,000. In this study fixed floodwalls are recommended for the flood barrier along the eastern part along the railroads of NJ Transit Terminal.

.

Figure 5.2 Conventional Concrete Floodwall Source: (Flood Break , 2016)

Movable flood mitigation systems like roadway gates are designed for continuous traffic service and heavy use on local roads and highways. They are hidden underground to allow uninterrupted vehicle traffic until deployed by water. A hinged roadway gate (Figure 5.3) cost $15,000 for a panel of 5 feet height and 12 feet width. Detailed cost analysis of the flood barriers is presented in the report submitted to NJDEP. (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

The heights of flood barriers and roadway gates chosen above (4 to 5 feet) will protect the City of Hoboken from an approximately 10-year storm surge.

.

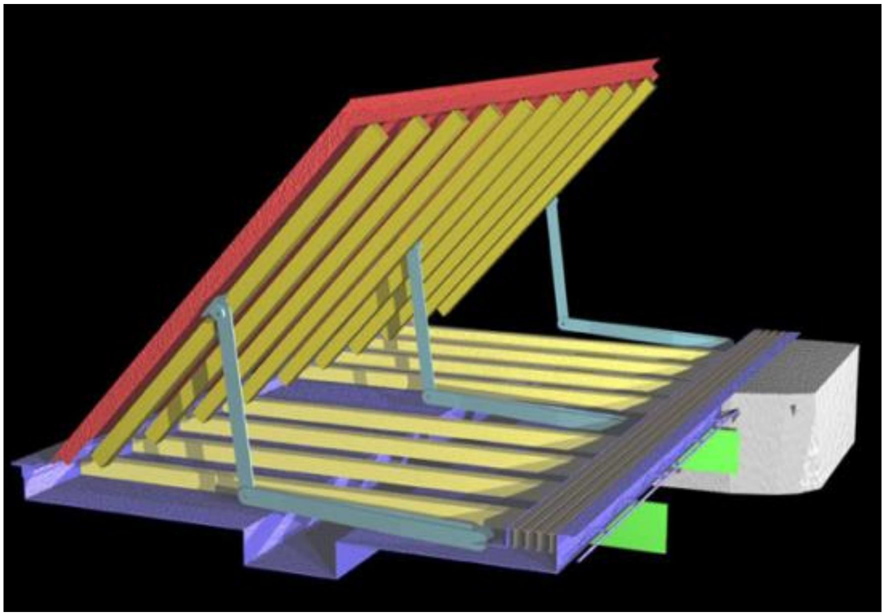


Figure 5.3 Automatic Roadway Floodgate. Source: (Flood Break , 2016)

Table 5.1 Flood Barriers for Hoboken Only

Measure	Dimensions
Roadway Floodgate	612 feet length and 5 feet height
Conventional Concrete Floodwall	5,305 feet length and 5 feet height

.

5.2 Flood Mitigation Measures for Rainfall and MHHW

5.2.1 Measure 1: Surface Storage

It was mentioned earlier in the report that by implementing a gate at the entrance of Long Slip water from storm surge events cannot enter Hoboken. Long Slip (Figure 5.4) is located at the south part of Hoboken alongside to the rail station and it was one of the major channels through which water from Hurricane Sandy entered the City. It is proposed to install a mobile gate that would remain open during rainfall events, when coastal inundation doesn't take place, in order for storm water to drain into Hudson River. However, this channel could also be used to receive and store storm water. The gate could be closed during low tide and through pumping the water level could be maintained or lowered before any storm event. The following Table 5.2 gives hypothetical storage volumes assuming mean depths of 3 feet, 5 feet, 10 feet, 15 feet or 20 feet for each column.

Table 5.2 Surface Storage in the Long Slip

Total Area ft^2	**Volume with 3 feet depth (ft^3)**	**Volume with 5 feet depth (ft^3)**	**Volume with 10 feet depth (ft^3)**	**Volume with 15 feet depth (ft^3)**	**Volume with 20 feet depth (ft^3)**
168,164	504,492	840,820	1,681,640	2,522,460	3,363,280
	Volume with 3 feet depth (MG)	**Volume with 5 feet depth (MG)**	**Volume with 10 feet depth (MG)**	**Volume with 15 feet depth (MG)**	**Volume with 20 feet depth (MG)**
	3.77	6.29	12.57	18.87	25.15

.

Figure 5.4 Location of Long Slip, Hoboken, NJ. Source: (NJGIN, 2015))

The amount of water that could be drained into this canal is calculated from the adjacent drainage area H1 (Figure 5.5). Table 5.3 indicates the amount of water that drains from H1 for different types of rainfall events. The area of H1 is 10,331,970 ft^2; the total length of pipes contained in this drainage area is 47,694ft and the curve number is 92.6.

.

Table 5.3. Calculations of Runoff from H1 Drainage Basin

Rainfall Event	Design Storm Rainfall Depth (inches)	Runoff Depth from Storm (inches)	Runoff Volume (ft^3)	Runoff Volume (MG)
1-year	2.7	1.9	1,664,675	12.45
2- year	3.3	2.5	2,156,194	16.12
5-year	4.2	3.4	2,904,962	21.73
10-year	5.0	4.2	3,577,476	26.76
25-year	6.2	5.3	4,593,305	34.36

Figure 5.5 Drainage Area H1, Hoboken, NJ. Source: (NJGIN, 2015)

For the level of threat of 5-year rainfall event a runoff of 21.73 MG from the drainage area of H1 is created. It was shown before in the Table 5.2 that Long Slip could have a surface storage volume of 25.15 MG with depth of 20 feet. So this entire volume of runoff from H1 could be stored in Long Slip.

.

A pump station should be installed at Long Slip in order to lower the water elevation at Long Slip priori a rainfall event. A pump station with a capacity of 7 MGD will allow the drainage of a volume of 21 MG in three days (to leave room for the subsequent storm as well as for the treatment).

Flap gates should be used at the Long Slip and along the Hudson River when conveying storm water. A new 3 feet diameter flap gate is recommended at the end of Long Slip.

5.2.2 Measure 2: Separation

For the areas in Hoboken where chronic flooding appear, it is suggested to separate the sewer system from CSO pipes to storm ones in order to convey storm water directly to Hudson River or Long Slip without treatment. The areas proposed for separation are: the H-1 basin and the basin at the northwestern part of the City.

The following map (Figure 5.6) shows the drainage area investigated in this project for the northwest part of Hoboken. The area of this drainage basin is 7,012,538 ft^2 with the curve number of 91.4. The runoff volumes were calculated and the results are presented in Table 5.4.

.

Table 5.4 Calculations of Runoff from Northwest Drainage Basin

Rainfall Event	Design Storm Rainfall Depth (inch)	Runoff Depth from Storm (inch)	Runoff Volume (ft^3)	Runoff Volume (MG)
1-year	2.7	1.8	1,066,706	7.98
2- year	3.3	2.4	1,394,936	10.43
5-year	4.2	3.3	1,897,417	14.19
10-year	5.0	4.0	2,350,188	17.58
25-year	6.2	5.2	3,035,564	22.71

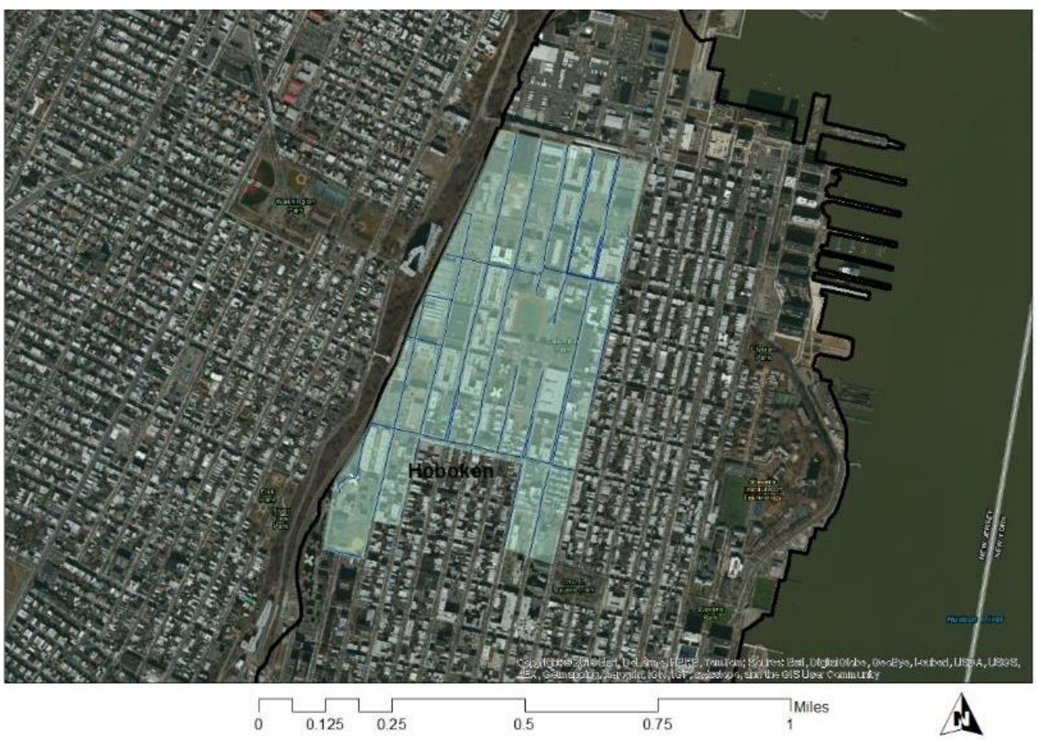


Figure 5.6 Northwest Drainage Area, Hoboken, NJ. Source: (NJGIN, 2015)

The conversion of the combined sewer system for the whole drainage areas H1 and northwestern have been investigated. A length of 47,694ft sewer pipes is suggested to convert from combined sewer pipes to storm ones for basin H-1 (southwest part of the city) and a length of 33,921ft at the northwestern part of the City.

Another arrangement investigated was the separation of the combined sewer system of less length. It is suggested to separate the system of main streets that experience the worst flooding. A length of 32,968ft sewer pipes for H-1 drainage area and a length of 24,258ft for the northwestern area have been calculated.

A pump with capacity of 84 MGD is suggested at the northeastern part of the city in order to pump 14 MG (the runoff volume from the 5-year storm) in 4 hours in order to help relieve the flooding problem.

5.2.3 Measure 3: Green Infrastructure for Runoff Reduction

The area of Hoboken is highly impervious without many parks or open spaces. Green infrastructures like porous pavements, swales, green gardens, and green roofs, can be implemented. It is proposed that the storm water inputs to the drainage system should be reduced for this study area. For further detail and cost analysis of the green infrastructure address to the report submitted to NJDEP (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

.

Chapter 6 Flood Mitigation Measures in Jersey City

6.1 Flood Mitigation Measures for Rainfall and MHHW

6.1.1 Measure 1: Green Infrastructure / Surface Storage

Development of a green belt under the NJ Turnpike elevated roadway, Route 78 will result not only the alteration of the drainage characteristics of the area but will enhance the City's aesthetics. This green belt will be a showcase for green infrastructure capable of receiving and infiltrating storm water through vegetated BMPs like rain gardens and swales while serving as a recreational area. This area under Route 78 would be ideal for the installation of green infrastructure since there are no structures beneath the roadway except local roads, and open spaces.

The entire area could be used as green space (development of wetlands, wooded areas, grassed drainage waterways etc.). This could be used to relieve some of the stress put upon the combined sewer system by receiving and holding storm water, thus reducing the occurrence of CSOs and redirecting flow through a naturalized waterway to the Hudson River bypassing the sewer system entirely. The green belt will stretch 1.5 miles to Morris Canal.

This interconnection of urban green space systems will enhance the City's outward appearance, help shape urban form and improve quality of life. The implementation of a bike route or a jogging path starting from the north, at the borders with Hoboken, and ending at Liberty Park will give the residents and visitors the opportunity to escape in a green oasis. A greenway connecting all of these areas would

.

encourage people to walk and bicycle for recreation as well as transportation. This path will have the potential to connect schools, neighborhoods, parks, light rail stations and bus stops. Opportunities and constraints were determined based on GIS and Google mapping. The focus on the data collection, as far as it concerns the proximity to schools and other community features, proximity to transit and connectivity to existing and planned facilities, was based on the area within a quarter mile of the Route 78. A quarter mile is the distance that is most likely to be considered walk able by the greatest number of pedestrians

This green belt would connect:

- 11 schools
    - 2 preschool, 5 elementary schools, 1 middle school, 3 high schools
- 5 recreation centers
- 6 health centers
- 8 worship centers
- 2 libraries
- 1 science center
- 3 light trail stations
- 1 transit station
- 18 bus stations

The drainage system currently route waters from west to east down gradient towards the Hudson River (Figure 6.1).

.

Figure 6.1 Direction of Existing Sewer System at Route 78, in Jersey City. Source: (NJGIN, 2015).

After examination of the contours and the existing sewer system around the area of Route 78 it was discovered that a drainage area starting from north at Beacon Ave. extending to west to Summit Ave. and east to Monmouth St. and ending to Audrey Zapp Dr. could relieve stress being put upon the CSO system. Figure 6.2 shows the drainage area affected by the implementation of a green route under Route 78. The area of this

.

drainage basin is 814.15 acres and has a curve number of 91.8. The calculated runoff quantities are shown in Table 6.1.

Table 6.1 Calculations of Runoff from Drainage Basin 1

Rainfall Event	Design Storm Rainfall Depth (inch)	Runoff Depth from Storm (inch)	Runoff Volume (ft^3)	Runoff Volume (MG)
1-year	2.7	1.9	5,503,346	41.17
2- year	3.3	2.4	7,173,050	53.66
5-year	4.2	3.3	9,772,600	73.10
10-year	5.0	4.1	12,020,863	89.92
25-year	6.2	5.4	15,956,129	119.4

.

Figure 6.2 Drainage Area 1 Affected by the Green Belt under Route 78. Source: (NJGIN, 2015).

Some of the largest areas under Route 78 are green open spaces with no recreational development. The following Figures depict the existing conditions of open spaces under Route 78. Areas of the route 78 between 9th and 8th St. show green open spaces with fences not allowing trespassing. Other areas such as the area beneath Route 78 along Columbus Drive are used as a parking lot (Figure 6.3).

.

Route 78, Jersey City. Source: Google Maps.

Area under Route 78 and 9th St. Source: Google Maps.

Area under Route 78 and 8th St. Source: Google Maps.

Area under Route 78 and Columbus Dr. Source: Google Maps.

Figure 6.3 Green Open Spaces under Route 78, Jersey City, NJ (Gooogle Maps, 2016)

.

By implementing a green belt for a length of 1.5 miles and taking advantage not only of the area under Route 78, but the adjacent open areas as well, the system will operate both as a recreational area and a storm water management basin. It will not only benefit the community in terms of flood reduction and storm water management, but also will improve the air quality and increase property values (European Union, 2010). According, to the land use map of Jersey City there are approximately 132 acres of adjacent areas of Route 78 that could be part of the green belt as storm water basins or wetlands. Locations for potential detention basins/mitigation wetlands or implementation of green infrastructure were identified based on land use/land cover types including forest, deciduous brush, recreational and built up area. A total of 59 areas are ideal for green implementation around Route 78 (Figure 6.4). Also Table 6.2 gives the area of open spaces divided accordingly to its land use.

Table 6.2 Division of Total Area around Route 78 According to Land Use

Land Use	Total Area (acres)
Forest/ Deciduous Brush	55.5
Old Field	4.71
Other Urban & Built up Area	72.1

Apart from rain gardens at this area of open space retention basins should be implemented.

.

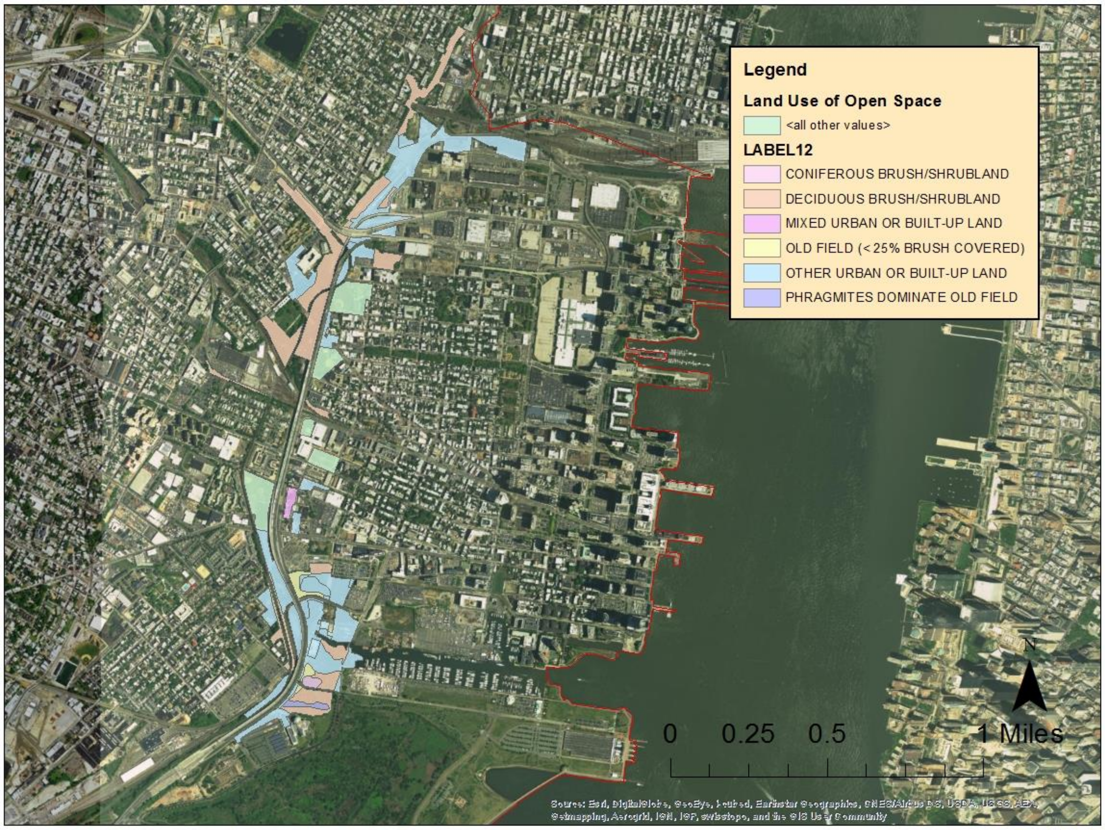


Figure 6.4 Land Use of Open Spaces around Route 78. Source: (NJGIN, 2015)

After investigating all the areas around Route 78 different scenarios of implementing rain gardens and retention basins are proposed. A rain garden can store up to 1ft of rainwater while retention basins can hold up to 6ft. The following table shows how much runoff can be stored. Three different scenarios were examined.

- 1st Scenario: Retention basins at urban or other built-up area and rain gardens at old-field and at forest/deciduous brush area.
- 2nd Scenario: Retention basins at half of the urban or other built-up area and rain gardens at old-field and at forest/deciduous brush area.
- 3rd Scenario: Only rain gardens at old-field and at forest/deciduous brush area.

.

Table 6.3 Available Storage around Route 78

Land Use	Total Area (acres)	Scenario 1 Stored Runoff (ft^3)	Scenario 2 Stored Runoff (ft^3)	Scenario 3 Stored Runoff (ft^3)
Forest/ Deciduous Brush	55.5	2,486,079	2,486,079	2,486,079
Old Field	4.71	138,520	138,520	138,520
Other Urban & Built up Area	72.1	18,838,935	9,419,467	0
Total	**132**	**21,463,535 or 160MG**	**12,044,067 or 90MG**	**2,624,599 or 19MG**

From the above Table 6.3 one can notice that if the whole available area is used then a runoff of 25-year return period can be stored in the adjacent areas of Route 78. Also if even just half of the urban & built up area is used then approximately 12,000,000 ft^3 can be stored, which corresponds to a 10-year storm event. Urban/built up area is characterized an area that hasn't been developed yet.

6.1.2 Measure 2: Surface Storage at Morris Marina

It was discussed in the report at the level of threat of coastal storms section that by implementing a gate at the entrance of Morris Marina, water from storm surge events cannot inundate Jersey City. Morris Marina is located south of the downtown (Figure 6.5) and it was one of the major channels through water from Sandy's storm surge entered the City. A mobile gate similar to the one proposed for the Long Slip should be used to allow

.

draining of the upland. The depth of the Morris Marina it ranges for 13ft to 15ft, and reaches a limitation of navigation at 6-8ft. The marina has 520-wet slips and is also home of emergency vessels, police vessels, fire vessels and commercial tenants like Statue Cruises. During Superstorm Sandy all the boats were evacuated. According to officials at Liberty Landing Marina during good weather conditions 300-400 boats are traveling daily, during fair weather 100-150 and during bad weather 10-15. The following Table 6.4 gives hypothetical storage volumes assuming mean depths of 3 feet and 5 feet for each column. The additional surface storage volume for Morris Marina was calculated according to the limitation of the water depth that can be drained based on its functionality of recreational boating.

Table 6.4 Surface Storage at Morris Marina

Total Area ft^2	**Volume with 3 feet depth (ft^3)**	**Volume with 5 feet depth (ft^3)**
1,857,312	5,571,936	9,286,560
	Volume with 3 feet depth (MG)	**Volume with 5 feet depth (MG)**
	41.68	69.46

.

Figure 6.5 Morris Marina Area, Jersey City, NJ Source: (NJGIN, 2015)

The amount of water that could be drained to this canal is originated from the adjacent drainage areas (Figure 6.6 and Figure 6.2). Table 6.5 shows the amount of water that can be drained from drainage area 2 for 5 different types of rainfall events. The drainage basin 2 has an area of 3,285,618ft^2 with a curve number of 92.8.

Table 6.5 Calculations of Runoff from Drainage Basin 2

Rainfall Event	Design Storm Rainfall Depth (inch)	Runoff Depth from Storm (inches)	Runoff Volume (ft^3)	Runoff Volume (MG)
1-year	2.7	1.9	534,137	3.99
2-year	3.3	2.5	690,771	5.17
5-year	4.2	3.4	929,293	6.95
10-year	5.0	4.2	1,143,184	8.55
25-year	6.2	5.5	1,510,779	11.3

.

Figure 6.6 Drainage Area 2 Located along the Morris Marina. Source: (NJGIN, 2015)

Retention basin can be also used in order to store storm water from the drainage area 2. The location of the basin is shown in the following figure. The total area is 4.81 acres and it can be stored approximately 1,258,458 ft^3 or 9.41MG. That represents a runoff from the adjacent drainage area of 10-year. So even if just half of the area is used it will alleviate a 2-year storm.

.

Figure 6.7 Recommended Area for Retention Basin for Drainage Area 2. Source: (NJGIN, 2015)

A pump is recommended at Morris Marina in order to convey storm water to Hudson River. For the level of threat of 1-year and 2-year rainfall the volume of water that is needed to be stored in the surface area of Morris Marina, redirected from drainage areas 1 and 2, is approximately 45MG to 58MG without taking in consideration the any rain gardens and retention basins at drainage area 1 and 2. It was shown earlier in Table 6.5 that the volume of the surface storage at Morris Marina for 5 feet depth can support 70 MG of storage. So a pump of 27 MGD is recommended in order to lower the water elevation in Morris Marina in three days, priori any storm event, to leave room for the subsequent storm as well as for the treatment. Flap gates should be used at the Morris Marina and along the Hudson River when conveying storm water in the case of high tides. A new one is recommended at the end of the Morris Marina. Detailed cost analysis is presented in the report submitted to NJDEP. (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

.

6.1.3 Measure 3: Separation

In Jersey City there are areas which experience chronic flooding. In order to address this flooding, the separation of a dedicated storm sewer system from a part of the combined sewer system is suggested. The areas, which are proposed for separation, consist of the Figure 6.2 and Figure 6.6). So a total length of 180,638 sewer pipes has been calculated for separation. Detailed cost analysis is presented in the report submitted to NJDEP. (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

6.1.4 Measure 4: Green Infrastructure for Runoff Reduction

The feasibility of implementing green infrastructure to absorb a portion of the surface water runoff has been assessed for the area of Jersey City. A more detailed analysis is presented in the report submitted to NJDEP, (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014).

6.1.5 Block and Lot Scale Storm water Flood Mitigation Measures

6.1.5.1 Block and Lot Scale Stormwater Flood Mitigation Measures at Jersey City

The flood mitigation strategies on this scale are primarily engineering practices that will make sure that existing storm water infrastructure is functioning and enhance its effectiveness by reducing the stress upon it.

The raising of some parts of Route 440 was investigated in the area of Jersey City. Small scale flooding in this area often occurs in low-lying intersections or roadways. These areas could be raised and infiltration galleries installed beneath them to provide temporary storage.

.

At 2011 Hurricane Irene left a big part of Route 440 flooded and impassable and caused major traffic and transit delays. The intersections identified to be constantly flooded are:

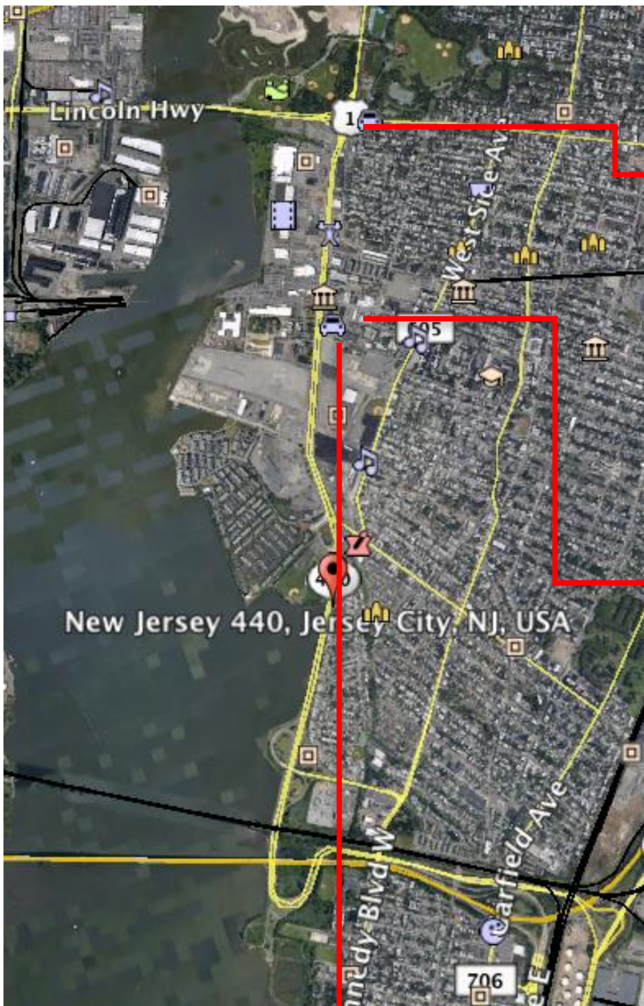
- Intersection of Route 440 and Communipaw Avenue.
- Intersection of Route 440 and Pollock Avenue.
- Intersection 440 and Culver Avenue.

These three intersections have elevations from 9 to 10 feet (NAVD 88). The elevation of a road costs $1.6 million dollars per mile per foot elevation. Detailed cost analysis is presented in the report submitted to NJDEP. (Guo, Miskewitz, Athanasopoulou, & Gharyeh, 2014). Their length consists the part of Route 440, which experiences frequent flooding.

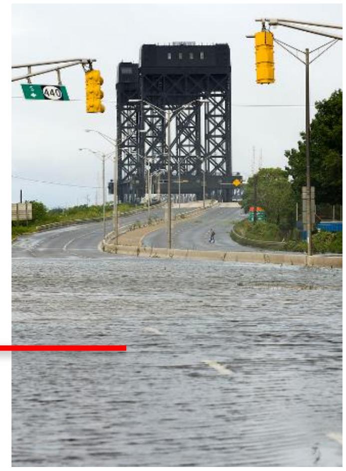
In this report it was also investigated the elevation of the appropriate length of Route 440 only at the above three intersections for the same 5 different elevations. The total length of the three intersections was calculated as 287 feet.

The space beneath the elevated roads or intersections could potentially be used to store excess runoff.

.



Route 440, Jersey City. Source: Google Maps.



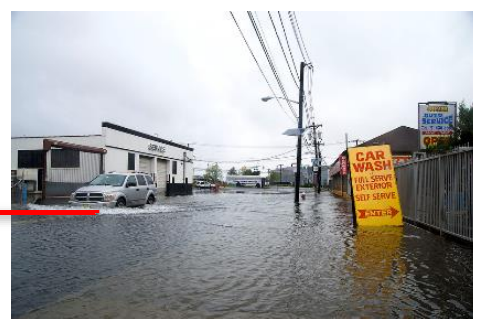
Intersection Route 440 & Communipaw Avenue.

Source: http://reenarose.com/blog/?p=4236.

Intersection Route 440 & Pollock Avenue.

Source: http://www.nj.com/hudson/index.ssf/

2011/08/you_dont_see_this_every_day_je.html



Intersection Route 440 & Culver Avenue.

Source: http://reenarose.com/blog/?p=4236

Figure 6.8 Flooded Intersections at Route 440, Jersey City, NJ.

.

Chapter 7 Alternative Flood Mitigation Measures

7.1 Rainwater Power and its Utilization for Draining Flood Water from Low-lying Areas

7.1.1 Background

Intensive research has been conducted over the last decades for renewable forms of energy. Most of the cases though, address the feasibility of renewable energy as a source of pumping clean water in developing countries by using either solar or wind energy, { (Reznicek E.P., 2014) (Granich & Elmore, 2010) (Mustafa S. G., 2011) (Cloutier & Rowley, 2011) (La Rotta & Pinilla, 2006)}.

Researchers of ocean energy are focusing more on different types of energy converts. More than 1000 wave converts have been patented all over around the world, including Japan, Europe and North America (Drew, Plummer, & Sahinkaya, 2009).

However, little research has been done for rainwater energy. Most of the studies focus on how the energy of rain can be used to provide energy savings to water pumping systems. In many developing countries and countries that face big periods of droughts like Jordan, harvesting rainwater from rooftop areas will help alleviate the water shortages. According to Chiu et al. an economic feasibility study to obtain the most cost effective water tank size to the hilly community of Taipei City was conducted. In July 2016 it was published in the Water Environment Federation journal a study about creating a rainwater collection system. The Metropolitan Water Reclamation District (MWRD) and the Chicago Department of Water Management (CDWM) are collaborating in order to conduct a feasibility study investigating if the can use an recently abandoned

.

water tunnel as a collection system of rooftop rainwater. The following Figure 7.1 shows the abandoned portion of the Blue Island Avenue Tunnel.

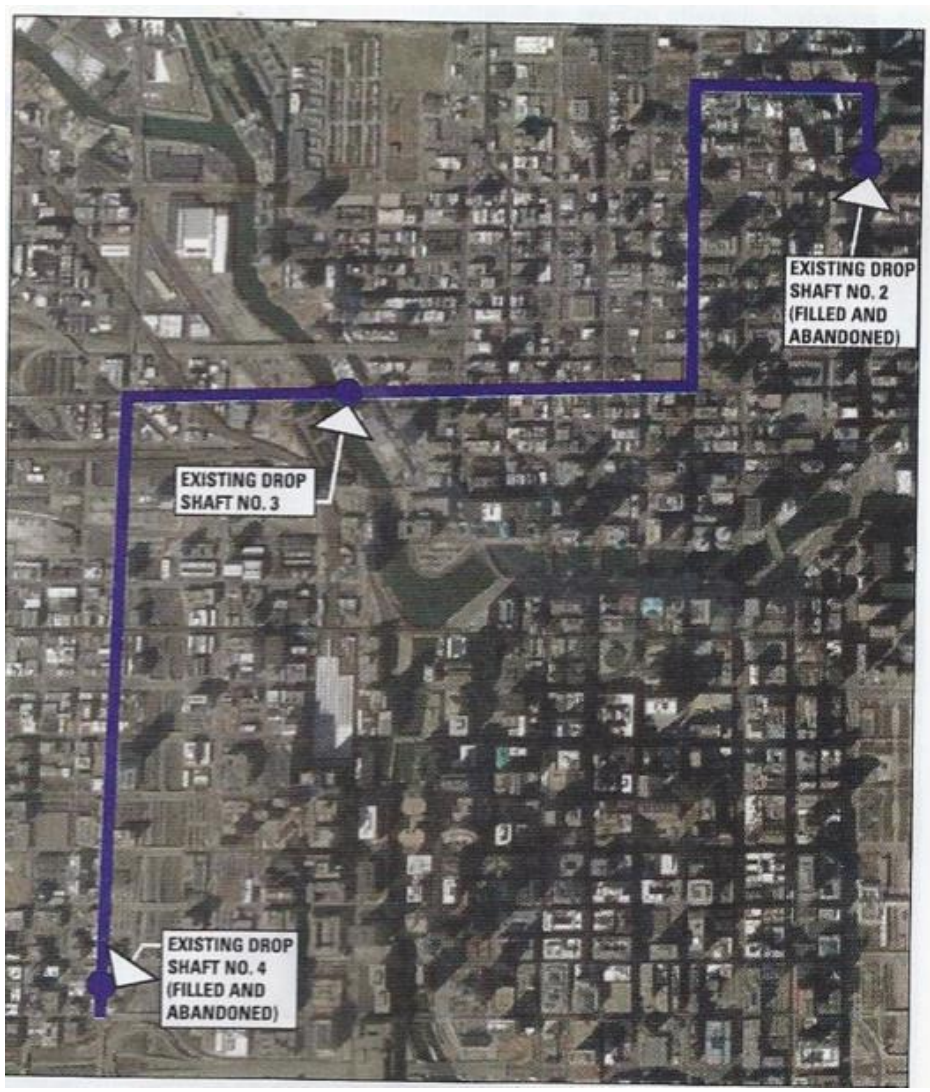


Figure 7.1 Abandoned Portion of The Blue Island Avenue Tunnel. Source: (Gage, Yurik, & Martin , 2016)

Rainfall from rooftops will be collected from buildings connected to the tunnel. There are six shafts connected to the tunnel some of them are functional and other were filled and abandoned. The potential storage volume is 6 MG.

.

NYC DEP is currently investigating two alternatives ways to reduce runoff from the rooftops. The configurations of Blue and Green roofs are investigated. In the Green roof configuration there is the vegetative layer over a specific designed soil layer and a drainage layer, which function as an absorbing and retaining system. This arrangement has become popular over the last years. As far as it concerns the Blue Roof concept, there is not a vegetative layer but weirs at the roof drain inlets, which control the runoff.

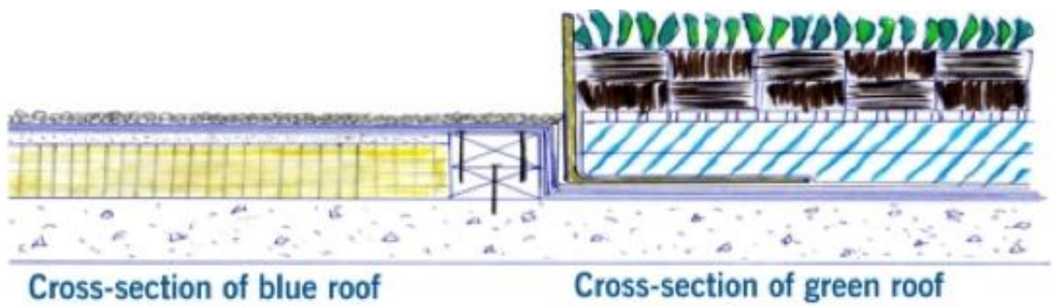


Figure 7.2 Cross Section of Blue and Green Roof. Source: (NYC DEP, 2016)

This triggered the second part of this proposed research, and answer the question "Is there enough power generated from rainwater and can this power be used in order to change the traditional way of flood mitigating rainwater flow?" To support our idea of rainwater driven pumps, calculations are made in order to identify the availability of power generated by rain. Hoboken is chosen as our area of interest since it is a densely urbanized area with high ground elevations from Palisades and high buildings. Estimations are made for power generated from ground elevations and buildings. But first, the main concept of flood mitigation measures should be introduced in detail. The following section describes the idea behind the "Green Pumps".

.

7.1.2 Main concept of alternative flood mitigation measure: "Green Pumps"

It has been identified that the main cause of flooding in developed low-lying coastal areas with combined sewer systems is the back up of storm water. These areas are vulnerable to flooding especially if a large storm rainfall is merged with elevated tidal conditions. During these events relief from combined sewers outfalls is restricted and insufficient drainage takes place. As a result untreated sewage is backing up and released into streets and basements of buildings. Engineers, over the years have been considering different measures as to mitigate these vulnerabilities. Some of the measures are pumping, conveyance, storage, rainfall interception etc. Nevertheless, innovative or different combinations of measures should be considered. A report prepared by Rutgers University for Barnegat Bay points out one of them. This measure while not new as an idea is taking in advantage the height of buildings and the higher ground elevations.

There are many forms of renewable energy that can be taken into consideration. Rainwater, wave/surge/tide, solar, river/ water bodies' flow, and wind are some energy resources.

Using stored rainwater at higher elevations, potential power can be generated in order to pump water of flooded areas that are lower in elevation than the receiving waters. By storing water in surface water tanks in higher elevations and roof collection tanks protects the downstream areas from flooding. Then by connecting these collection tanks with separate force mains from the sewer system, the water would be directly disposed to nearby water bodies without any treatment.

The following figure shows the system placement according to the topographic conditions.

.

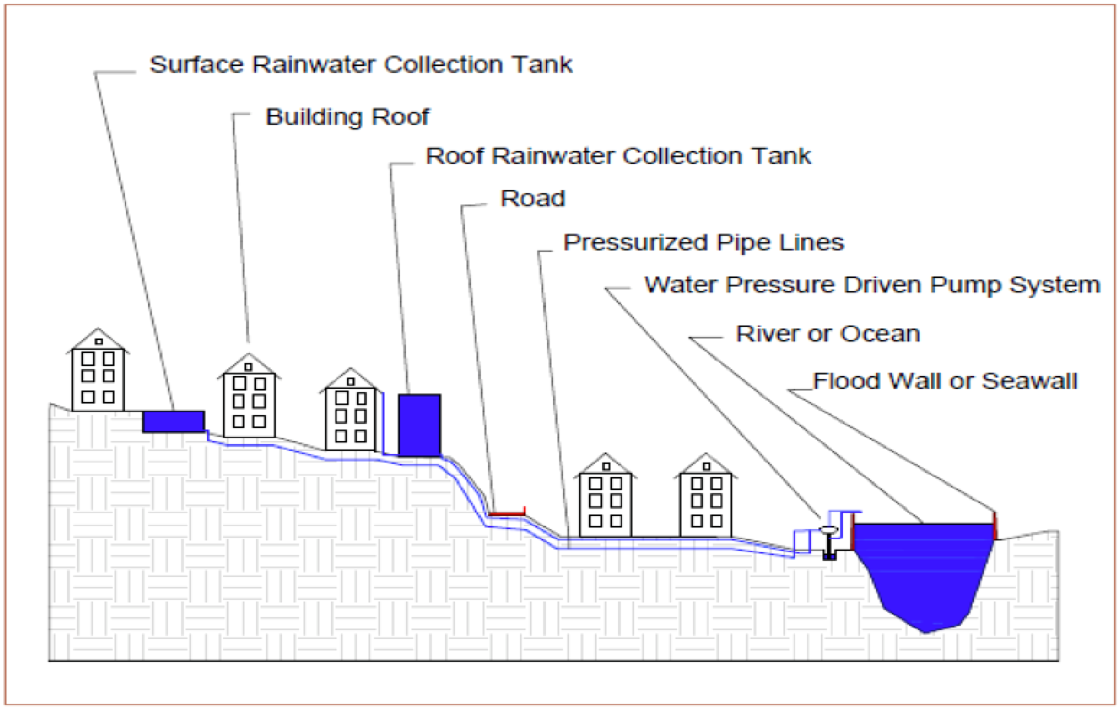


Figure 7.3 System Illustration of Rainwater Driven Pump Application. (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014).

In the same manner as it was described previously, water collected from roofs and higher grounds will be used as a green power to pump flood water that will be accumulated at the developed, low lying, and adjacent to the water body areas.

A conceptual sketch of the rainwater driven pump is illustrated in Figure 7.4. The pump has a turbine at the top and a pump at the bottom; they are connected in a common shaft. So water flowing with higher energy from higher grounds will flow through and drive the turbine, which, in its turn, will pump the water from the flooded areas and through the outlets to the nearby waterways.

.

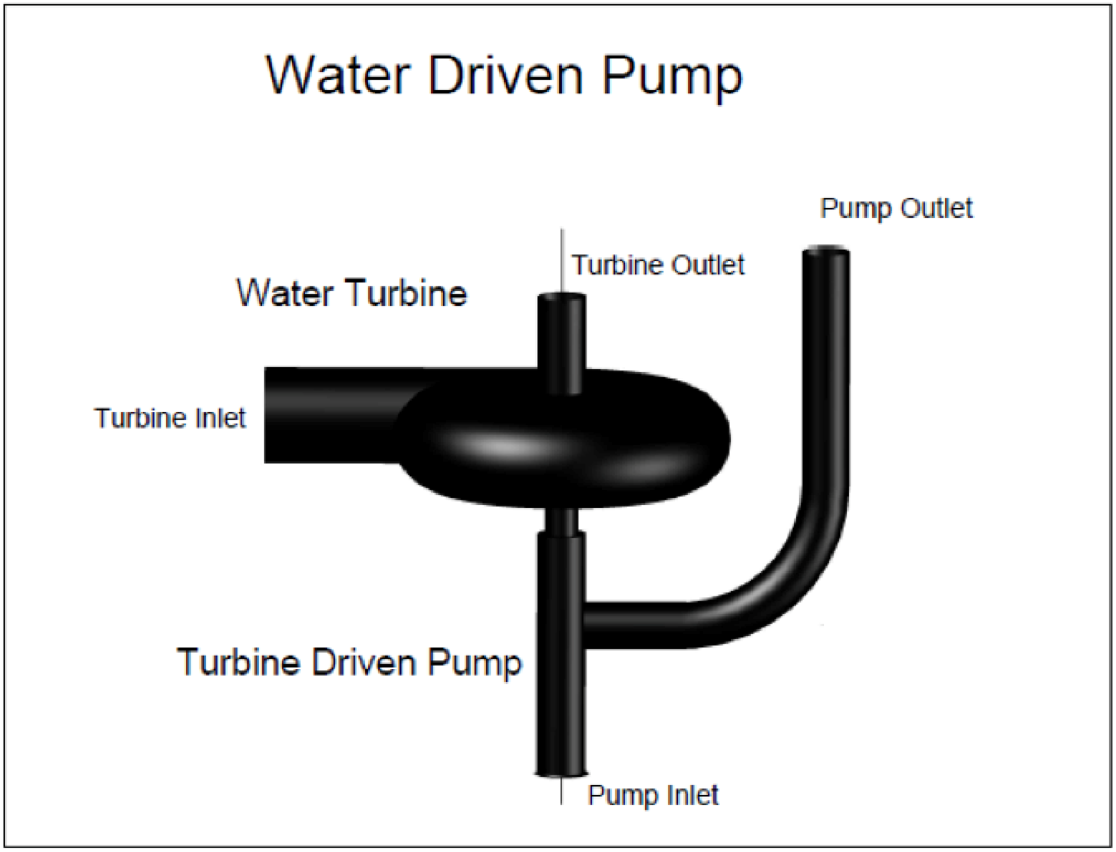


Figure 7.4 Conceptual Sketch of Rainwater Driven Pump. Source: (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014).

Another type of rainwater driven pump is a venturi pump. In this concept, water will flow through a venturi driven pump. A venturi is a pipe with varied diameter sequence. In the 18th century Giovanni Venturi discovered that the velocity rises while the pressure drops when the fluid passes through a constriction in a pipe. By taking advantage of this well-used type of a pipe, water can be pumped out from flooded areas. This pump operates on the concept that when water with high energy passes through the throat, the pressure will drop forming a vacuum, and the velocity will increase. This vacuum has the ability to pull stationary flooded water through the inlet of the pump and

.

discharge it to a nearby water body. A schematic view of this pump and its location is illustrated in the following two figures.

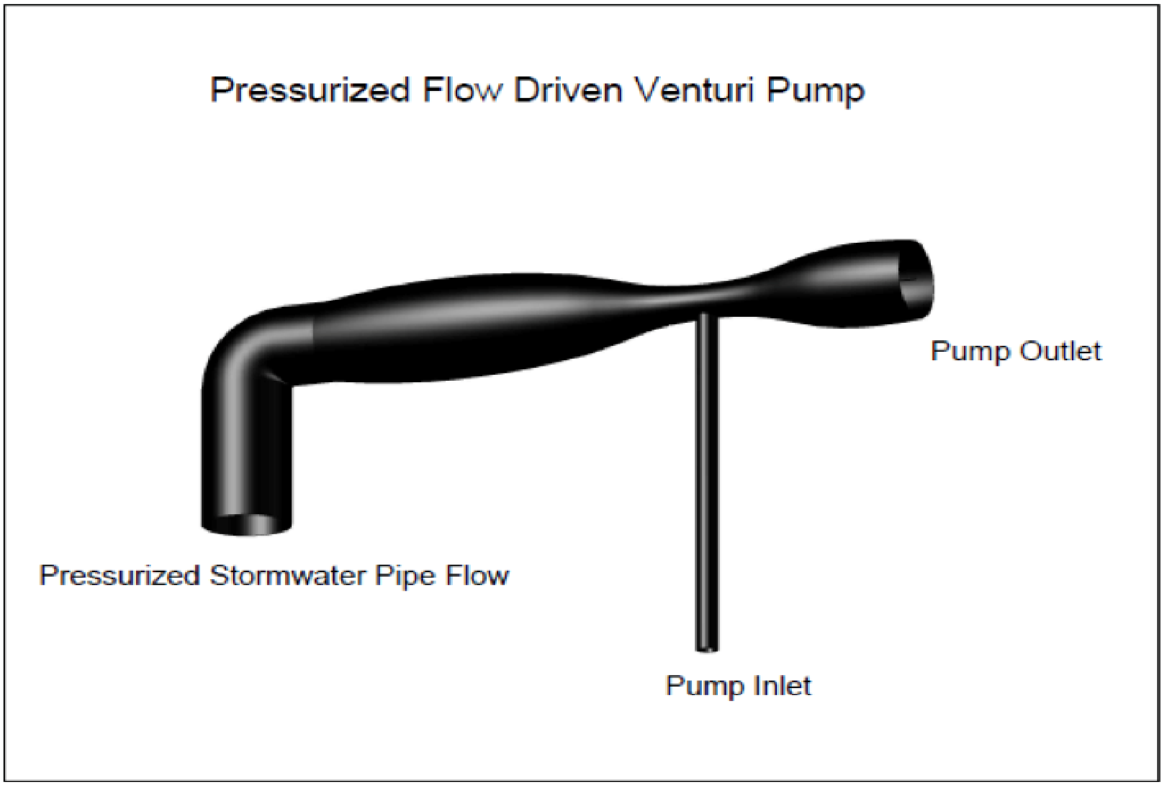


Figure 7.5 Conceptual Sketch of Rainwater Flow Driven Venturi Pump. (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014).

.

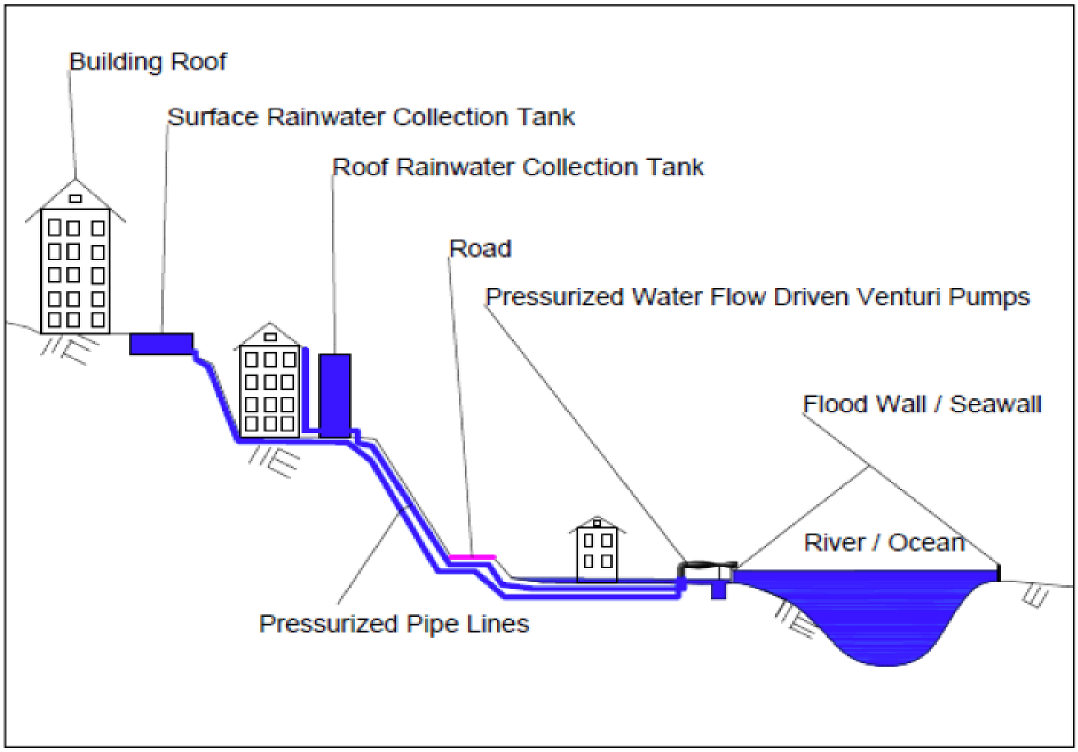


Figure 7.6 System Illustration of Rainwater Flow Driven Venturi Pump Application. (Guo Q. , Li, Kennish, Psuty, Lathrop, & Trimble, 2014).

In order to take advantage of the power produced by the elevation difference and to reduce construction cost the use of pressurized pipes inserted in the existing sewer system is proposed. Pressurized pipes have the ability to transfer water into small diameter pipes that follow the surface topography. So even in low-lying areas pressure sewers are a mean of moving storm water without depending on gravity and keeping a part, if not total, of the original power.

These technological approaches introduce a new way of thinking by using renewable power to pump rainwater from flooded areas. Depending on the characteristics of each area, more than one of the technologies can be combined. Also by combing these technologies with flood defense infrastructure like floodwalls or seawalls depending on the location, they will create an effective strategy against flood mitigation. Further

.

research like lab verification and lap test of the above technologies would be the next step.

This innovative thinking will not only protect human lives and properties from flooding, but it will protect the environment by using renewable power resources. There has been an increased research and development of comprehensive energy plans over the last decades. The lower environmental impact rather than the use of conventional energy technologies has triggered a new way of thinking. The reliance on fossil fuels has been shifting. The worldwide concern of climate change and its results like the melting of glaciers and eventually the sea level rise have increased the interest in different types of energy. It is also reasonable to introduce this thinking applied in the flood mitigation strategies.

7.1.3 Study Area

In order to answer the question how much power is generated by rainwater in an urban environment a study area has to be chosen. For this purpose, a highly urbanized coastal city with low elevations is considered ideal. In this study, the area combines four characteristics, such as:

- Ranks at the top for the largest population exposed to flood risk. (Climate Central, 2012).
- Several locations are characterized by little or no slope, and their elevations are lower than 10 feet above sea level, and along the western part of the city, the geologic formation of high elevations is located.
- The drainage system is a combined storm and sewer system. So even with a small rainfall event many of the low-lying areas get flooded. The system backs up since

.

the pump station does not have the appropriate capacity to pump the excessive water, nor can the CSO be discharged if the elevation downstream is higher than the flap gates.

- Existing pump station of 50 MGD and 350 HP in order to compare and contrast with the proposed green rainwater pumps.

7.1.4 Theoretical Background

7.1.4.1 Power Equation

In order to calculate the power that rainwater generates when it falls on different elevations, the equation of the ideal hydraulic power is used:

$$\boldsymbol{P = \gamma * Q * \frac{\Delta H}{550}}$$ *Equation 4.1*

Where P = power [hp]

γ = specific weight of water [lb/ft^3]

Q = volumetric flow rate [ft^3/sec]

ΔH = differential head [ft]

The volumetric flow rate for rainfall intensity is used from the following equation:

$$\boldsymbol{Q = \int i \; dA}$$ *Equation 4.2*

Where i = rainfall intensity [ft/sec]

dA = surface integral [ft^2]

By substituting equation 4.2 into 4.1 the following equation is formed:

$$\boldsymbol{P = \int \gamma * i * dA * \Delta H}$$ *Equation 4.3*

.

By intergrading the above equation for different areas with differential heads, it is possible to calculate the power generated from only ground elevations, or only building elevations, or a combination of both.

7.1.4.2 Head Losses in a Pipe

In hydraulic engineering practice, it is necessary to estimate the head loss along a pipeline. Loss of head is incurred by fluid mixing, which occurs at fittings such as bends, valves, or caused by frictional resistance at the pipe wall. In short pipelines with numerous fittings, the major part of the head loss will happen because of the local mixing near fittings. For long pipes, on the other hand, skin friction at the pipe wall will dominate.

Early experiments on flow of water indicated the head loss varies with velocity. Darcy-Weisbach proposed the following equation:

$$\boldsymbol{h_L = f * \frac{L}{D} * \left(\frac{u^2}{2g}\right)} \qquad \text{Equation 4.4}$$

Where f = friction factor and depends on the pipe roughness & Re.

If the Re number is less than 2100, the flow is laminar.

If the Re is over 3000, the flow is turbulent.

Between 2100 and 3000, there is a transitional type of flow.

L = length of the pipe [ft]

D = diameter of the pipe [ft]

u = velocity [ft^2/sec]

g = gravitational acceleration [ft/sec^2]

Re = u*D/ν, where ν kinematic viscosity.

.

To determine the peak runoff from a drainage basin, the rational method is used. The equation of the runoff is the following.

$$\boldsymbol{Q = c * i * A} \qquad \textit{Equation 4.5}$$

Where c = runoff coefficient, varied by surface type.

i = rainfall intensity [ft/sec]

A = surface area [ft^2]

In order to size a pipe, the time of concentration should be calculated. In this part of the study the time of concentration will be considered an hour as it is used by NHSA. Further research should be conducted to have more precise time of concentration.

In order to size the horizontal pipes, the equation of Manning was used, considering that these pipes run full.

$$\boldsymbol{Q = \frac{1.49}{n} * A * R^{\frac{2}{3}} * \sqrt{S}} \qquad \textit{Equation 4.6}$$

Where n = Manning's coefficient, varied by surface type. Here it is set equal to 0.015.

A = surface area [ft^2]

R = hydraulic radius of pipe, [ft]

S = slope of pressure gradient

7.1.5 Source Data

The focus of this study is a sub drainage area, which is approximately 285 acres. This sub drainage area called H1, is the first area that gets flooded even with a small rainfall event. The geologic formation with the high elevations is extended over the west

.

part of the H1. According to the sewer map, a part of the area of the geologic formation is draining to the sewer system of H1.

In order to investigate the power generated by rainfall water, acquisition of data is required. LiDAR data, shape files, and blueprints have been collected from NJDEP & the Bureau of GIS (OIRM/BGIS), NHSA, the Hudson County Division of Planning, CH2M Company and the New Jersey Geographic Information Network (NJGIN).

7.1.6 Methodology

The first step in this study in order to calculate the power generated from the ground elevations and the height of the building, is to manipulate the LiDAR data and shape files. Different software packages are used for this purpose.

In order to visualize/manipulate the digital elevation model (DEM) of bare terrain, the ArcGIS software is used. After obtaining the raster file from NJGIN, the digital elevation is added to that model. In ArcMAP, the tools of "raster analysis" are used in order to manipulate the DEM. First, the tool of "calculate statistics" to recalculate the statistics of the DEM and remove any points that create noise is used. Then other tools like "slope", "aspect" and "hillshade", are applied to analyze the DEM. The following figure shows the DEM with aspect. The aspect tool shows the direction of the steepest downhill slope of a terrain dataset.

.

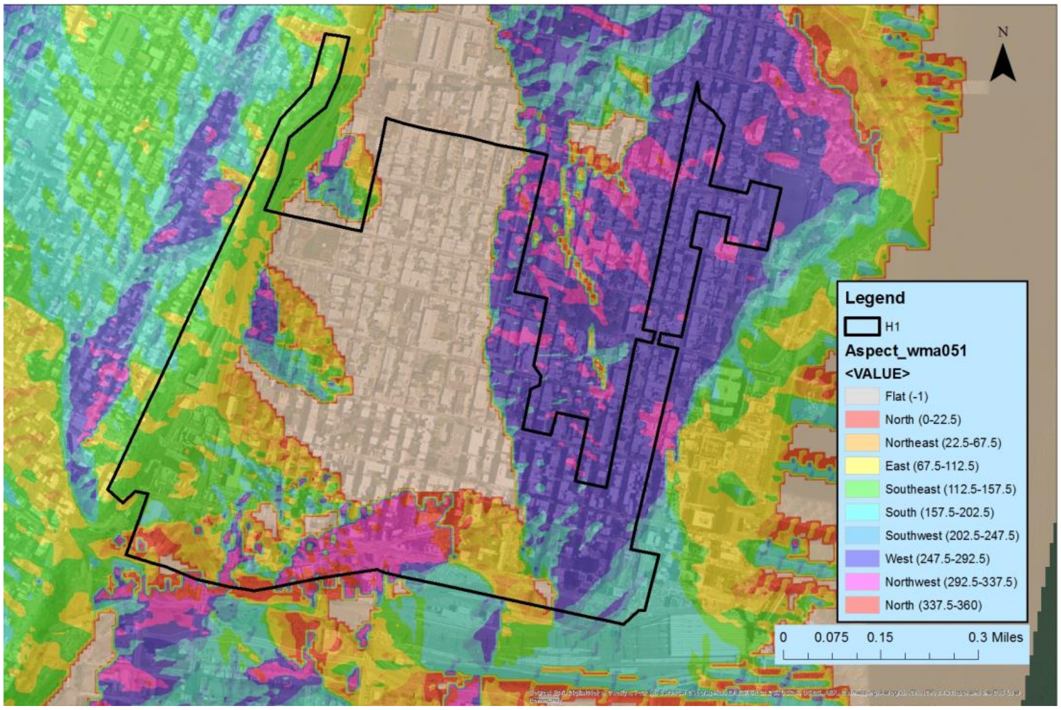


Figure 7.7 Aspect of DEM of H1 Drainage Area. Source: (NJGIN, 2015)

In ArcGIS it is possible to use different tools in order to extract elevation using point/polyline shape files. The 3-D analyst tool and the function of "add surface information" are used now in order to assign z-values to ground points and polygons such as city parcels. "Add surface information" tool allows assigning 3 different outputs of z-values: z-min, z-mean and z-max. In this research, the z-mean values are extracted from each polygon. Each shape file and raster file are projected in the NAVD_1988_2011_State Plane New Jersey FIPS 2900 ft US.

LAS format files that are acquired from BGIS are used to form the 3-D, digital elevation model of H1 and the height of the buildings. The LAS files contain the LiDAR data, the so-called tiles, which show the 3D-point cloud of Hoboken and consequently, the area under study. In this study, the Quick Terrain Modeler that is a 3D point cloud and terrain visualization are used (Applied Imagery , 2015). The LiDAR data is being used in order to identify the elevations (including terrain elevations) of the buildings that are located in H1 area. By exporting the LAS files to ASCII, it is possible to extract the elevations of each building from the ArcMAP. The shape file of the buildings provided by the Hudson Division Planning contains the footprint area of each building which is another component used in the equation of the power.

All the important data have been acquired in order to calculate the power generated by different rainfall events in the area H1. In the following section the results are presented.

7.1.7 Results

7.1.7.1 Generated Power & Head Losses

In this study, the generated power is calculated by the equation 4.3. Different rainfall frequencies are used. The frequencies are chosen in response to the design storm of H1 area. The drainage system was designed to withstand 6-months with 1-hour duration storm, according to the report prepared by Emnet. Furthermore, rainfall events that provoke flooding to the area as well as some extreme events are examined.

Head losses were calculated along the longest sewer pipeline for the building that is located the farthest from the pump station. A new separate system that will follow the existing longest sewer line was designed (green line in Figure 7.8). The accumulated peak flow rate from the whole area of study was used in order to design the separate drainage system. The rainfall events of one-hour peak of 25-year storm and one-hour peak of 10-year storm were used for the calculation of the peak flow rates. By calculating the peak flow rates and keeping the velocity constant at 6ft/sec for the two rainfall events

.

of interest it was possible to design two different drainage systems. The characteristics of each system are given in Table 7.1 and Table 7.2.

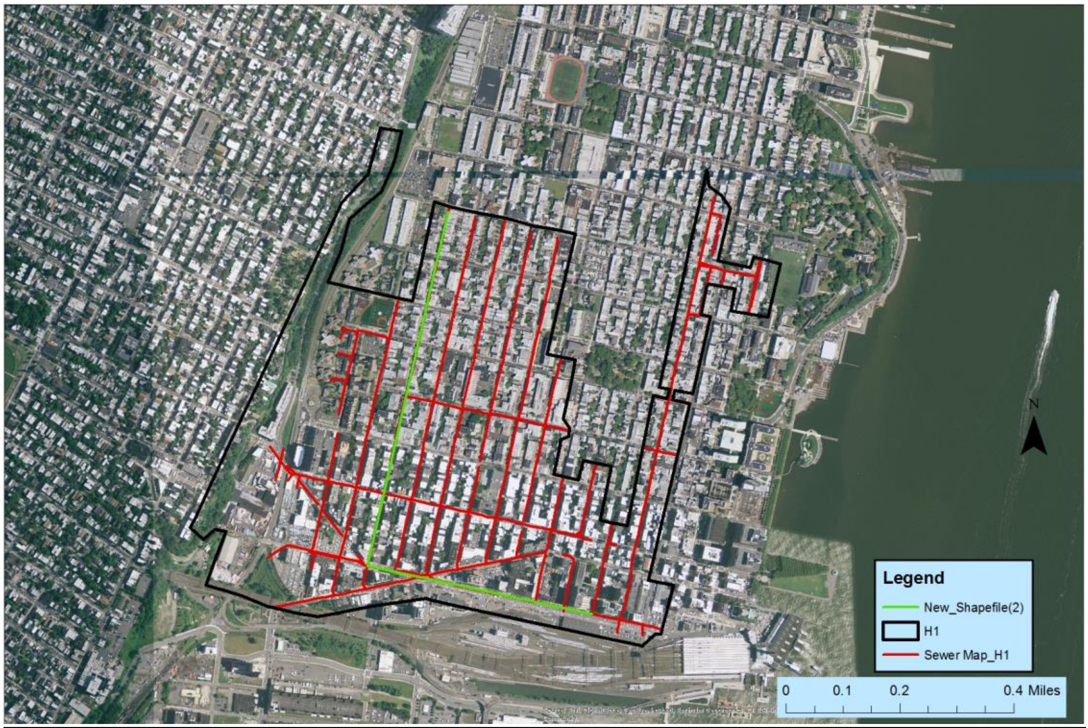


Figure 7.8 Existing Sewer System in Hoboken, NJ, (green line is the longest sewer pipe line connecting the building farther away with the existing pump station) Source: (NJGIN, 2015).

Table 7.1 Characteristics of The Drainage System Designed for One-hour Peak, 25-Year Storm.

One Hour Peak of 25-year Storm	
hl, Assuming velocity kept constant at 6ft/sec for Q peak [ft]	19.24
Minimum pipe radius for velocity kept constant at 6 ft/sec [ft]	0.43
Maximum pipe radius for velocity kept constant at 6 ft/sec [ft]	3.28
Re for the minimum pipe radius	515,583
e/d for the minimum pipe radius	5.72 E-5
Re for the maximum pipe radius	3,930,352
e/d for the maximum pipe radius	7.51 E-7

.

Table 7.2 Characteristics of The Drainage System Designed for One-hour Peak, 10-Year Storm.

One Hour Peak of 10-year Storm	
hl, Assuming velocity kept constant at 6ft/sec for Q peak [ft]	21.84
Minimum pipe radius for velocity kept constant at 6 ft/sec [ft]	0.39
Maximum pipe radius for velocity kept constant at 6 ft/sec [ft]	2.94
Re for the minimum pipe radius	463,572
e/d for the minimum pipe radius	6.47 E-6
Re for the maximum pipe radius	3,533,863
e/d for the maximum pipe radius	8.5 E-7

For each designed system, the head losses, the average remaining head, and the average remaining power for an average height building at the beginning of the sewer system were calculated. In these calculations, the average elevation of the farthest away building was considered being approximately 54 ft. The elevation of the buildings in the area of interest ranges from 15-167 ft. Also the Mean High High Water (MHHW) elevation and the actual inside the pump station elevation was taken into consideration (2.28 ft and -1.32 ft respectively from NAVD88).

In this study, also, the amount of power needed in order to pump from the low-lying areas to the MHHW elevation was calculated. These calculations allow comparing the average remaining power from the top of the building with the power needed in order to pump the floodwater from the rest of the H1 area. It was also taken into consideration an efficiency of a turbine pump averaged to 65%.

.

The calculations are shown in Table 7.3 and Table 7.4. Figure 7.2, Figure 7.3, Figure 7.4 and Figure 7.5 visualize the remaining head and power for different rainstorm return periods.

Table 7.3 Head Losses for Different Rainfall Frequencies Data for the Drainage System Designed for One-hour Peak 25-Year Storm.

Rain Storm Return Period	Head Losses [ft]	Velocities [ft/sec]	Average Remaining Head for [ft]	Average Remaining Power [HP]	Power Needed to Pump from Ground to MHHW [HP]
One hour peak 6-months	2.86	2.11	50.2	406	113
One hour peak 1-year storm	4.21	2.61	48.9	489	140
One hour peak 2-year storm	6.06	3.19	47.0	577	171
One hour peak 5-year storm	9.52	4.08	43.6	683	219
One hour peak 10-year storm	13.04	4.85	40.1	741	260
One hour peak 25-year storm	19.24	6.00	33.9	776	322
One hour peak 50-year storm	25.4	6.97	27.7	739	375
One hour peak 100-year storm	33	8.04	20.1	618	432

.

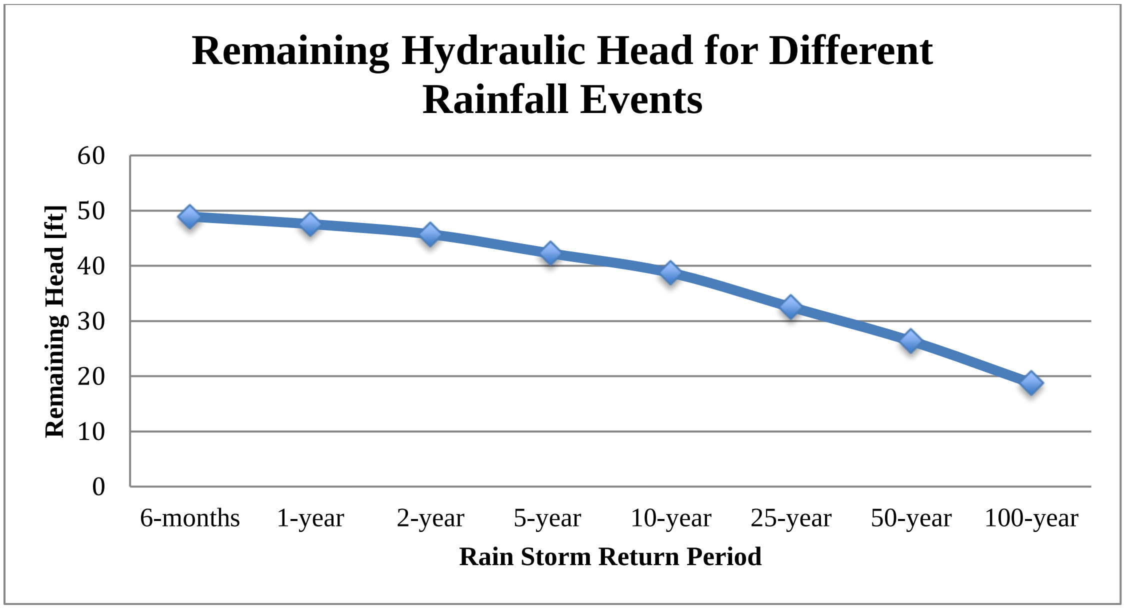


Figure 7.9 Remaining Hydraulic Head for Different Rainfall Events for Drainage System Designed for One-hour Peak 25-Year storm.

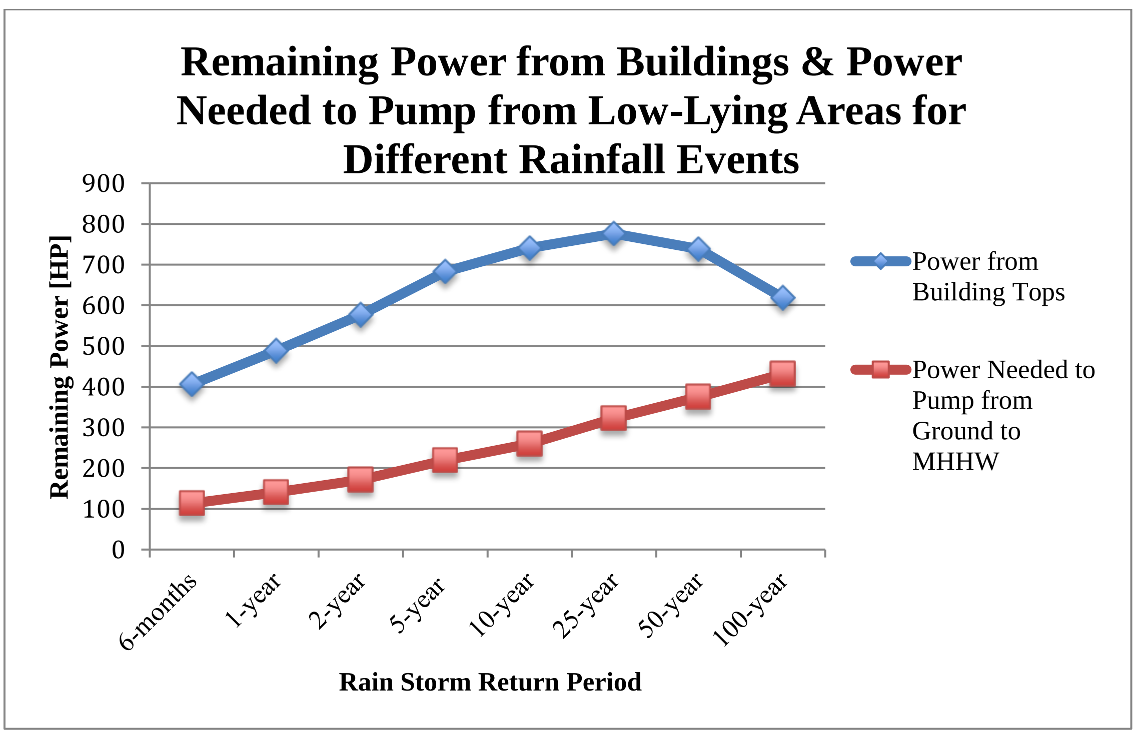


Figure 7.10 Remaining Power from Buildings & Power Needed to Pump from Low-Lying Areas for Different Rainfall Events for Drainage System Designed for One-hour Peak 25-Year storm.

.

Table 7.4 Head Losses for Different Rainfall Frequencies Data for the Drainage System Designed for One-hour Peak 10-Year Storm.

Rain Storm Return Period	Head Losses [ft]	Velocities [ft/sec]	Average Remaining Head [ft]	Average Remaining Power [HP]	Power Needed to Pump from Ground to MHHW [HP]
One hour peak 6-months storms	4.78	2.61	48.3	391	113
One hour peak 1-year storm	7.01	3.23	46.0	460	140
One hour peak 2-year storm	10.16	4.85	42.9	526	171
One hour peak 5-year storm	15.96	5.06	37.1	582	219
One hour peak 10-year storm	21.87	6.00	31.2	578	260
One hour peak 25-year storm	32.33	7.42	20.8	477	322
One hour peak 50-year storm	42.64	8.64	10.5	279	375
One hour peak 100-year storm	55.43	9.96	-2.34	-71.9	432

.

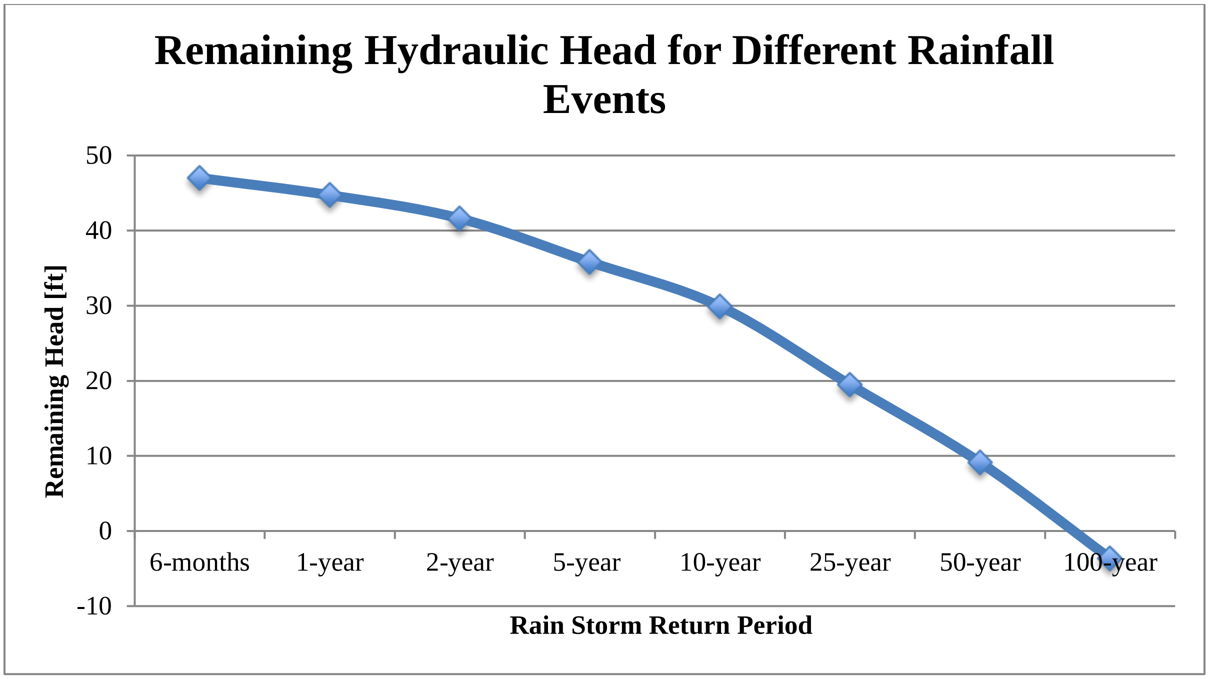


Figure 7.11 Remaining Hydraulic Head for Different Rainfall Events for Drainage System Designed for One-hour Peak 10-Year storm.

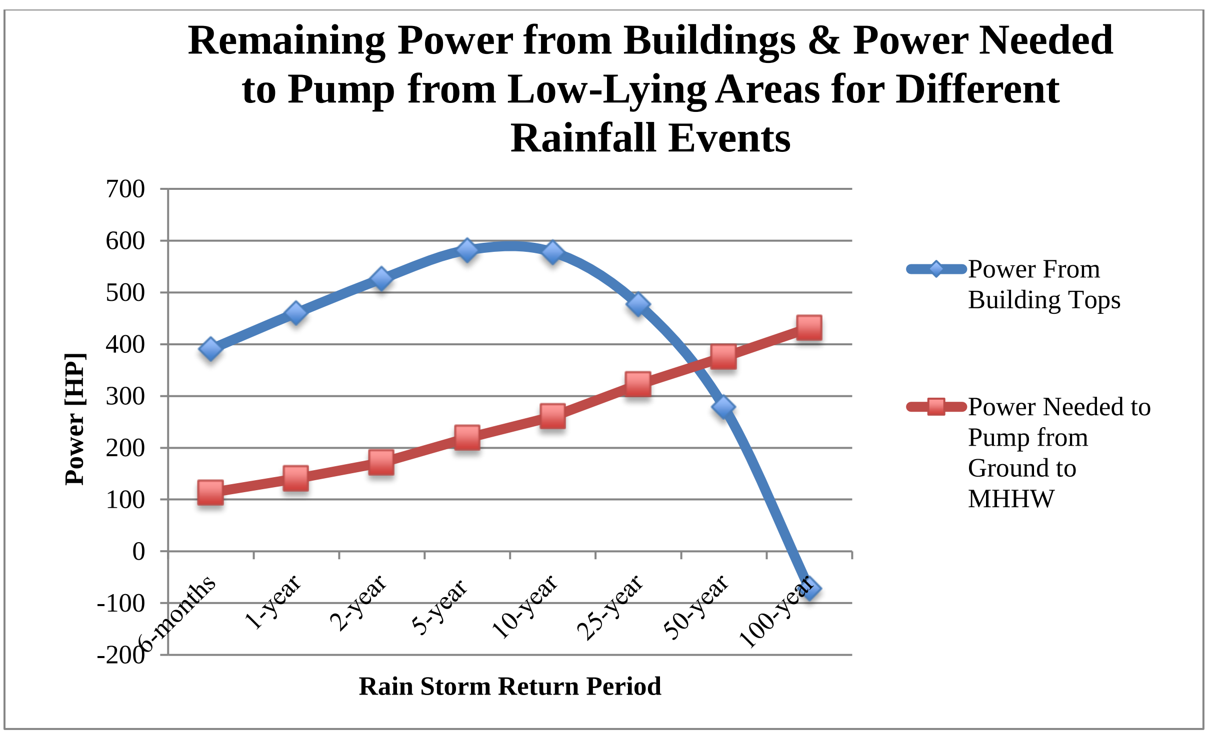


Figure 7.12 Remaining Power for Different Rainfall Events for Drainage System Designed for One-hour Peak 10-Year storm.

.

7.1.8 Future Work

As this study is concluded further investigation is suggested for "Rainwater Driven Pump" measure. At this point furthers investigation will be completed through storm water management modeling. There are many different software programs that can be used. One of them is the Storm Water Management (SWMM). SWMM from EPA is used throughout the world in order to plan, analyze and design related storm water runoff and drainage systems in urban areas. At this point of the research it is crucial to design our own storm water system through a model in order to find the head losses from each building and analyze the feasibility of a system to bypass its own runoff water to near water bodies or use its own energy to discharge. Also, up to this point of the research many assumptions were made. In our calculations we only are taking into consideration energy losses from friction of the pipe system and we are ignoring head losses from fittings. So it is important to model our system in order to take in consideration different types of looses as well.

After modeling the drainage system it is essential to do a cost benefit analysis. Every project comes with a cost so for this project as well we should calculate and compare the costs and benefits of this alternative flood mitigation measure.

.

7.2 Projects Currently Proposed and Comparison

7.2.1 City of Hoboken

City of Hoboken's Community Resiliency & Readiness Plan (2013) recommends flood pumps, storm surge protection/flood barriers, green infrastructure/storm water management, etc. Hoboken has already received over half a million dollars from Re.Invest Initiative, a public/private partnership, for technical assistance in the design of large-scale underground flood mitigation engineering solutions to be incorporated into new parks, among other measures. Together North Jersey's Hoboken Green Infrastructure Strategic Plan (2013) categorizes the city into blue, green, and gray zones and recommends corresponding retention, infiltration and detention stormwater management practices.

The Rebuilt by Design team recommends both hard infrastructure and soft landscape for coastal defense, a green circuit and water pumps to support drainage and policies like green roofs, bio swales and storm water planters to delay the rainwater at the urban areas. Figure 7.13 shows a general approach of flood prevention for the City.

.

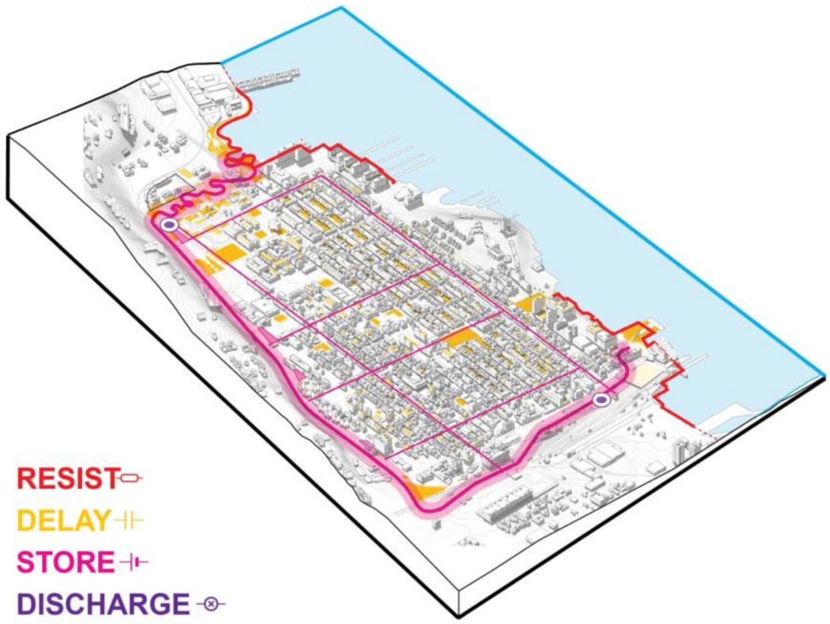


Figure 7.13 Flood Prevention Approach for Hoboken, NJ Source: (OMA, 2014)

NJDEP has funded 230,000,000$ to Rebuilt by Design. Dewberry Engineering Inc., and architectural firms Office of Metropolitan Architecture and SCAPE Landscape in order to conduct a more developed and in detail plan on how to protect in fall force the region of Hoboken.

This project is currently in the feasibility phase. Some of the main tasks during this phase are to collect and analyze data; assess the overall project feasibility; develop concept drawings; address impacts and critical issues; and develop general timeline and budget for the different project phases (Rebuild by Design, 2015). It is projected that this phase will cost 13,000,00$ and it to be completed during 2017.

The proposed project intends to address flooding from rainfall events as well as major storms and high tides. Different concepts were taken into consideration as far as it concerns the Resist. Some of the alternatives consist of combinations of free

.

standing in water revetments, floodwalls, T-walls, berms, raised paths, and gates. The height of some floodwalls might reach up to 12 feet. The Delay, Store and Discharge part of the project that is proposed it has only one concept and includes: storm water tanks, pumps and multipurpose storm water facilities. The following (**Error! Reference source not found.**) shows a concept that may consist of one possible Resist alignment. The main difference in the Resist alignments is that some alternatives provide highest level of protection at the waterfront by reducing transportation network and existing vies and access, while others do not impact as much the view and enhance the urban design and public space and they are less costly. However the design has not been finalized yet.

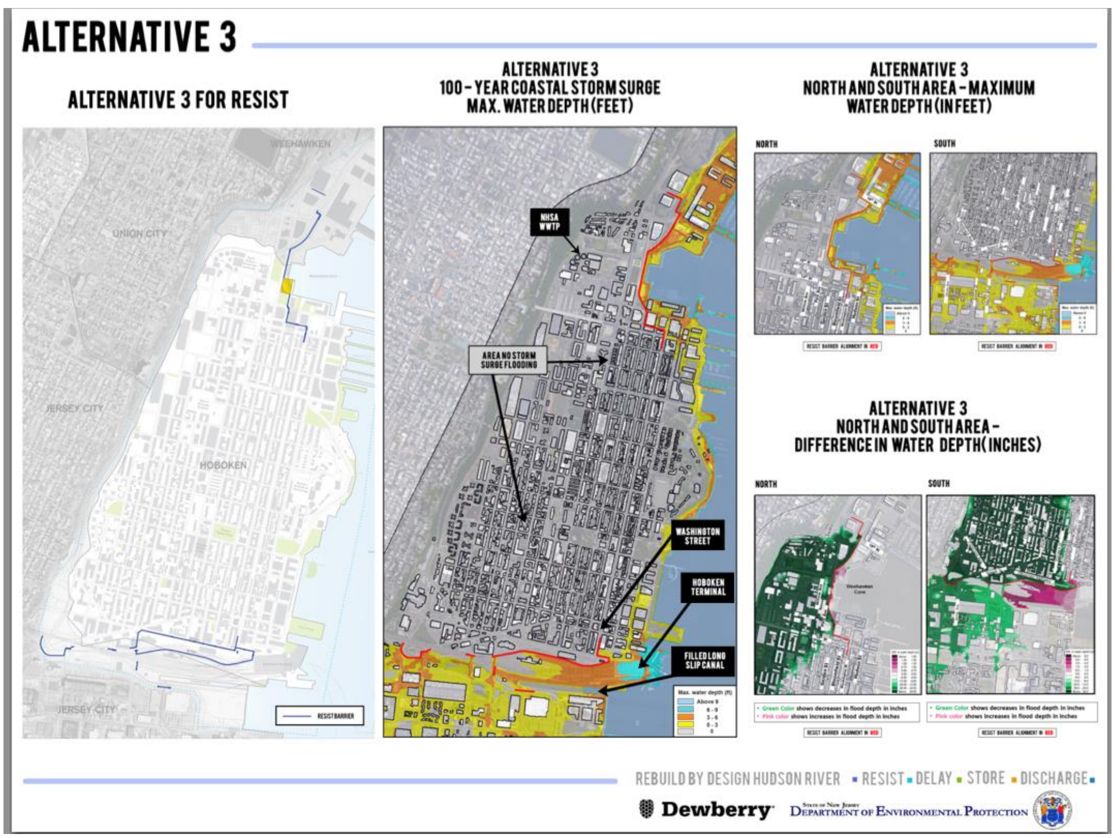


Figure 7.14 Alternative 3: Draft Idea of Resist Alignment, which Provides Storm Surge Risk Reduction Benefits Using Public Right–Of-Way. Source: (Rebuilt by Design , 2016)

.

The three alternatives are the following:

- Alternative 1: The waterfront alignment begins in Weehawken on Harbor Boulevard; heads along Sinatra Drive and it will end the transit yard.
- Alternative 2. The waterfront alignment starts at Weehawken by the 19th Street light rail station and proceeds east on 15th Street before heading south on Washington Street.
- Alternative 3: The waterfront also begins at the same point as the alignment 2 then follows the rail track down into Weehawken Cove and into Harborside Park. It then turns east up the alleyway located between 14th and 15th streets and turns south on Washington Street for about a block. It also known as the "Alleyway Alignment".

Among all 3 alternatives the one getting more attention is the 3rd one. Alternative number 3 is the least expensive; has the lowest estimated annual maintenance cost; it will affect the least the utilities, fewer number of gates; minimal impact to waterfront access and views, the alignments can be constructed with sufficient funds and the least amount of off-site soil disposal.

Further more, The City of Hoboken has financed the H-5 wet weather pump station (WWWPS). H-5 WWPS will benefit The City of Hoboken, as it will minimize street flooding in Northern Hoboken, protect the PSE&G substation and integrate in the overall resilient plan. North Hudson Sewerage Authority (NHSA) will built, operate and maintain the pump station under a 99-year lease with Hoboken. H-5 WWPS will be located at the 11 streets with an outfall at Hudson River (Figure 7.15).

.

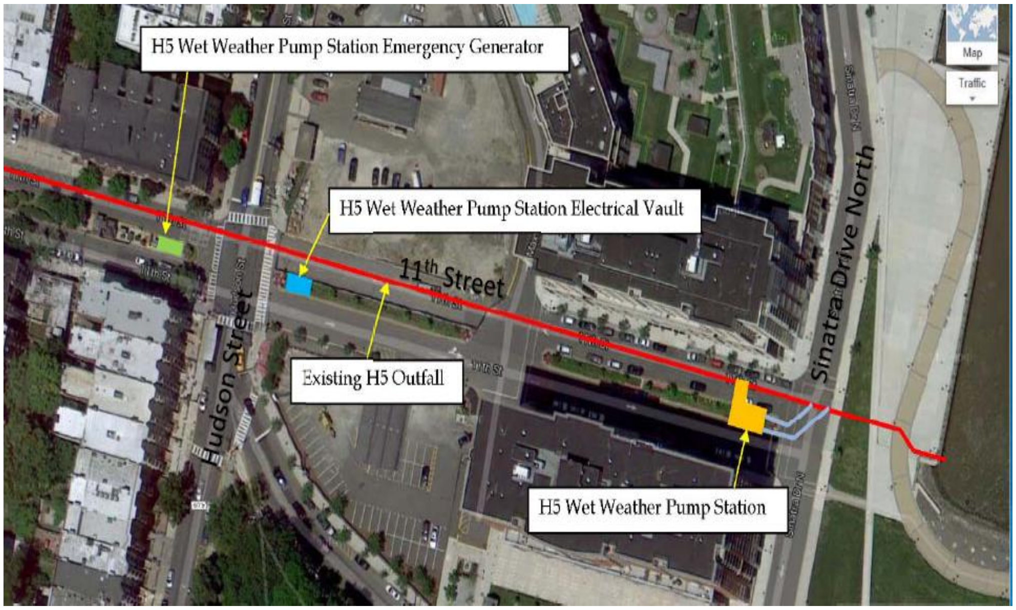


Figure 7.15 Project Site Plan H-5 WWPS. Source: (NHSA, 2015)

H-5 according to NHSA design will include a 40 MGD pump station, a transition vault, an electrical vault and an emergency 725 kW generator (NHSA, 2016).

Figure 7.16 Construction Site of the H-5 WWPS in Hoboken. Source: (The New York Times, 2016)

The measures suggested in the three alternatives for resist alignment are similar to the measures analyzed in this dissertation thesis. Both have analyzed a resist alignment to storm surges. Most of the placements recommended for the floodwalls and flood barriers are almost similar. As one can see in the 3 Alternative the existing structures from the elevated railroad at south will consist a barrier that will be extended to the Observe Highway the same as in this thesis. At north they are planning to construct the Cove Park and then extend the flood barriers to Garden Str., then to Alleyway and finally to Washington Str. Here at the north side of Hoboken the structures from the elevated highway at 14 Str. were taken into consideration and it was suggested to implement along this street fixed floodwalls and movable floodgates. Rebuilt by Design recommends barriers at a height of 12 feet that withstand 100-year storm event while in this work the height of the fixed floodwalls and movable floodgates is around 5 feet and will address a 10 year storm surge. In this work the height a floodwall along the entire waterfront of the City of Hoboken was also investigated.

As far as it concerns the delay, store and discharge part one big difference is the usage of Long Slip. On one side Rebuilt by Design recommends to build up the Long Slip and then to use floodwalls in order to provoke the storm surge to enter the city from the south. On the other side, in this research it is recommended the usage of Long Slip as a surface storage with a gate, where rainwater can be stored in case of a high tide and storm surge event.

.

7.2.1 Jersey City

In 2013, New Jersey Sea Grant Consotrium (NJSGC) with funds from NOAA Sea Grant and a Local Government Capacity Grant awarded Stevens University, NJTPA and Michael Baker International in order to perform a feasibility study for Jersey City. the following Figure 7.17 summarizes their results.

Figure 7.17 Conceptual Flood Adaptation Strategies for the City of Jersey City. Source: (Orton, et al., 2015)

.

Their measures consists of a combination of surge gate at tidewater basin of Morris Marina, earthen levees, street barries and land rise and fill. The 27 adaptation measures were developed for a storm event with flood elevation of 14ft. NAVD88.

Jersey City, during SuperStorm Sandy was impacted on both Hudson River and Hackensack waterfronts. On April 9th, 2015, the New Jersey Department of Community Affairs (DCA) awarded $260,000 to Jersey City, Hudson County in order to help the city to become more resilient against storm events (DCA, 2015).

This Post-Sandy Planning Assistance Grants from DCA will focus on developing a resiliance plan that will adress flood mitigation, preparedness, institutional and adaptation strategies. The following table summarize the main activites anticipated. The complition of all the activites should be completed within a year from the receipt of the grant.

Table 7.5 Anticipated Past Sandy Planning Assistance Grant Activities.

Activity	Funding	Purpose
Resilience Master Plan	$50,000	Adress the institutional, adaptation, preparedness and recovery strategies as descriped in the report
Adaptation Master Plan	$50,000	Describe existing conditions, the nature and extent of adaptation measures, and identify funding sources, implementation agencies, and time frames
Design Standards	$50,000	Ensure that building designs that allow for floodplain management compliance also maintain the desired streetscape environment
Capital Improvement	$30,000	Describe projects, budget, funding sources for capital

.

Plan		investments that improve resiliency
Urban Environmental Design Plan	$50,000	To prepare environmental plans regarding storm impact and building community resiliency, in particular a study to advance findings/recommendations of the *Collaborative Climate Adaptation Planning for Urban Coastal Flooding* study.
Zoning and Redevelopment Code	$40,000	Develop and codify zoning and flood damage protection ordinances that describe approaches to building rehabilitation and new construction that are more resistant to damage from future storm events and that are context sensitive and maintain the character of Jersey City's existing neighborhoods

* (Greenfeld, Hsu, & Wenger, 2014)

Also the U.S. Department of Interior's Hurricane Sandy Coastal Resilience Grant Program funded $25.3 million in different restoration projects (Water Environment Federation, 2015). One of these projects is the enhancing of Liberty's State Park's Marshes and Upland Habitats. The total project funds are $396,968. During this project 40 acres of salt marsh will be restored and created, as well as 100 acres of upland habitat in Jersey City. The purpose of this project is to restore the ecosystem, create a more resilient and publicly accessible area, and address coastal flood hazards (NFWF, 2014). In 2015, Abt Assocaties published a report with the performance metrics. These metrics

.

measure the changes in ecological resilience, beach habitat quality improvement, erosion control, riparian restoration and wetland restoration (Abt Associates , 2015).

The PSE&G Energy Strong Program will enchase the electric and gas systems of New Jersey. The elevation of existing and new equipment in Jersey City's plant will be done according to FEMA's ordinances (PSE&G, 2016).

On May 25 2016, New Jersey Future announced that Jersey City along with two other cities have been selected by the Build It Green (BIG) Competition. BIG collaborated with re-focus and Robert Wood Johnson Foundation New Jersey Health Initiative. The purpose of this grant is to design and implement projects that will reduce the CSO while creating unique opportunities for environmental and health benefits. Jersey City Mayor Steven Fulop said, "Jersey City will develop an integrated, innovative project to take on storm surge flooding, combined sewer overflows, and historic industrial contamination. These are issues that cross neighborhoods and affect some of the city's most vulnerable residents, and we are honored to be selected for this unique opportunity." (New Jersey Future, 2016).

While all these funds have been awarded, JCMUA has not updated their stormwater management plan and ordinance. So little is known to the public about the exact location and design of flood mitigation strategies in Jersey City.

At this point a comparison will be drawn between this thesis and the feasibilities studies published so far.

By comparing the flood measures proposed here with the feasibility study of Stevens University it can be observed that similar measures are suggested in order to protect the City of Jersey City from storm surge. Both in these two studies a combination

.

of barriers and tidal gates are suggested along the waterfront of Hudson River and Newark Bay/ Hackensack River. Stevens University thought suggests levees instead of floodwalls that were examined and proposed here.

As far as it concerns the delay, store and discharge part little has been published so far. In this study a proposed measure that stands out is the “Green-Belt” under route 78. By implementing a green belt for a length of 1.5 miles it will not only benefit the community in terms of flood reduction and storm water management, but also will improve the air quality and increase property. According, to the land use map of Jersey City there are approximately 132 acres of adjacent areas of Route 78 that could be part of the green belt as storm water basins or rain gardens. It was found that if all the areas are used approximately 160MG can be stored. Also any excessive rainwater that cannot be stored to the around areas of Route 78 and in case of extreme events like hurricanes and tropical storms (100-year or 500-year) it was suggested the use of a flood gate at Morris Marina in order to create an additional surface area.

.

.

Chapter 8 Conclusions

Flood vulnerability of coastal highly urbanized communities and the development of measures to mitigate these vulnerabilities are the main focus of this study. Hoboken and Jersey City experienced severe flooding and flood related damage as a result of the storm surge from Hurricane Sandy. These two municipalities were the main focus in order to develop comprehensive strategies to make these coastal areas more resilient to flooding. The strategy development framework includes the consideration of measures in regional and municipal level that address coastal and rainwater flooding.

Based on the pattern of flooding in the Hudson River Study area, two regional coastal flood measures are proposed; flood walls and gates. The height of the flood walls range from 12-20 feet and will be extended a total length of 13 miles of seawall for the side of Hudson River and 11 miles for the Newark Bay. Taking advantage of some existing structures and/or high ground/landscape can shorten the length of the floodwall along the Hudson River and the Newark Bay. In this study a flood barrier is considered that includes a sheet pile bulkhead and cap base with top height 4 feet above grade and then four vertical extensions each 4 feet high combining to create a 20 feet tall barrier. Gates are proposed to the two open canals, the Long Slip in Hoboken and the Morris Marina in Jersey City. Both of these canals represent an entrance for storm surge from the Hudson River. In municipal level only one is proposed. The municipality of Hoboken can take advantage of the existing concrete walls of the elevated road at 14 Street with a length of 1,368 feet as well as the existing elevated railroad above from Long Slip with a

.

length of 2,752 feet in order to protect itself from the coastal flooding by using flood barriers within its municipal border.

During this study different measures and their functions were investigated in order to address flooding due to rainfall. Some that are proposed are green infrastructure, separation, pumping, storage etc. In Hoboken one of the measures that stands out is the surface storage at Long Slip. It is proposed to install a mobile gate that would remain open during rainfall events, when coastal inundation doesn't take place, in order for storm water to drain into Hudson River. However, this channel could also be used to receive and store storm water. The gate could be closed during low tide and through pumping the water level could be maintained or lowered before any storm event. It was calculated that this area could store up to a volume of 25.15 MG with depth of 20 feet.

In Jersey City, a green belt under Route 78 is suggested in order to benefit the community in terms of flood reduction and storm water management. By implementing a green belt for a length of 1.5 miles and taking advantage not only of the area under Route 78, but the adjacent open areas as well, the system will operate both as a recreational area and a storm water management basin. It was found that if all the areas are used approximately 160MG of rainwater could be stored, which represents a return period of 25-year storm. By creating this green belt apart from solving a rainwater flood problem will create more open space for people to use as recreational.

Another measure that is suggested is the surface storage at Morris Marina in the same manner as the one in Long Slip. In this case the hypothetical storage volumes assuming mean depths of 3 feet and 5 feet were calculated. Any excessive rainwater that cannot be stored to the around areas of Route 78 and in case of extreme events like

.

hurricanes and tropical storms (100-year or 500-year) it was suggested the use of Morris Marina in order to create an additional surface area.

Finally in Jersey City it was investigated a strategy in block a lot scale. It was investigated the elevation of the appropriate length of Route 440 as well as the elevation only at the three intersections for the same 5 different elevations and for the entire length of the road.

Apart from the commonly used flood prevention measures like storage, surge barrier, conveyance, diversion, pumping, or rainfall interception, a new idea was introduced. The idea “Rainwater Driven Pump” was investigated. This measure presents a new approach in drainage management in densely populated areas.

By generating the DEM of the H1 area and using the ArcMAP program it became possible to add surface information to the points of terrain selected. So it was possible to calculate the power generated from the ground surfaces. In order to calculate the power generated from the building tops, it was important to identify some of their characteristics like their height and their area.

From the calculations of the power generated by buildings it is evident that a lot of energy is getting lost. Rainfall events with different return periods were investigated.

In this study we examined the remaining hydraulic head, the remaining power for two designed systems, and for eight different rainfall events. The head losses along the pipeline at the upstream end farthest apart from the pump station building have been calculated. It was found that for a rainstorm with return period of 5-years for the system designed for 25 years could generate 682.5 HP. Also, it is shown that excessive power is generated from the building tops and for the system designed for 25-year storm. Actually

.

for all the rainfall return periods the power generated compared to the power need is always higher. On the contrary, for the system of the 10-year storm, for the some rainstorm events, the remaining power is less than the one needed. It was observed that the remaining power increases for rainstorms smaller than the designed one, and then, after it reaches its peak, it will decrease while the power needed is always increasing since the amount of rainfall increases. By comparing the two systems it can be seen that the 25-year system is more efficient.

In this study, it was possible to generate and prove that for a densely populated area with high buildings and low ground elevations it is feasible to by pass the rainwater by its own power. This excessive rainwater instead of draining in the CSS can be directed to the near water bodies by constructing a separate pressurized system.

Analysis of the results confirms that there is enough remaining power not only to by bass but also generate green pumps or other energy usages. There is enough power generated from rainwater, and this power can be used in order to change the traditional way of flood mitigating rainwater flow.

Several recommendations could therefore be forwarded for future strategy production. Firstly, flood mitigation strategies should be addressed according to combination of threat levels and their future changes. Rainwater, storm surge, upstream riverine flow should be taken into consideration. Secondly, recommendations should provide protection in various levels regional, municipal, and neighborhood/block/lot scales of solutions. Thirdly, strategies should demonstrate types of possible mitigation measures and their functions. Some of the types of the measures include maintenance/repair vs. new construction; mobile/adaptable vs. fixed; green/nature-based

.

vs. grey; non-structural (policy, regulation, etc.) vs. structural; micro-grid vs. large-grid powered; innovative vs. conventional; preventative vs. protective; retroactive vs. anticipatory and short-term vs. long-term. While the function of measures considered include rainfall interception; storage; conveyance; upstream flow reduction; diversion; deceleration; tide barrier; pumping; surge barrier; mobile barrier; elevation and avoidance. By following this recommended framework in order to implement flood mitigation measures, the communities will achieve resilience. Our climate is changing so they way humanity should act and address flood issues should change.

.

References

Abt Associates . (2015). *Developing SocioEconomic Metrics to Measure DOI Hurricane Sandy Project and Program Outcomes.* Washington: Abt Associates.

Applied Imagery . (2015). *Quick Terrain Modeler*. Retrieved from http://appliedimagery.com/

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., et al. (2007). *Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis.* Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Bound, R. (2003). *Status and Research and Development Priorities, Wave and Marine Accessed Energy,*. United Kingdom: UK Dept. of Trade and Industry (DTI).

Britanica, E. (2015). *Wastewater treatement.* Retrieved from Encyclopedia Britanica: http://www.britannica.com/technology/wastewater-treatment

Bueno, C., & Carta, J. (2006). Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. *Renewable and Sustainable Energy Reviews* , 312-340.

Burian, S., Nix, S., & Pitt, R. (2000). Urban Wastewater Management in the United States: Past, Present, and Future. *Journal of Urban Technology* , 1466-1853.

Climate Central. (2012). *Sea level rise and coastal flood risk for Hoboken, New Jersey.* Retrieved from Surging Seas: http://ssrf.climatecentral.org/#location=NJ_Town_3432250&state=New+Jersey&level=5&folder=All&geo=County&pt=&p=L.

Climate Central. (2012). *Sea Level Rise and Coastal Flood Risk for Hoboken, New Jersey Surging Seas.* Retrieved from http://ssrf.climatecentral.org/#location=NJ_Town_3432250&state=New+Jersey&level=5&folder=All&geo=County&pt=&p=L.

Cloutier, M., & Rowley, P. (2011). The feasibility of renewable energy sources for pumping clean water in sub-Saharan Africa: A case study for Central Nigeria. *Rewneable energy* , 2220-2226.

DCA. (2015). *April 9, 2015 -Sandy Recovery- Christie Administration Announces Post-Sandy Planning Grant to Jersey City*. Retrieved from DCA News Room 2015: http://nj.gov/dca/news/news/2015/approved/20150409a.html

Drew, B., Plummer, A., & Sahinkaya, M. (2009). A Review of Wave Energy Converter Technology. *Journal of Power and Energy* , 887-902.

EmNet. (2013). *An Evaluation of l/l and Illicit Flow in West New York NJ and Flood Mitigation in Hoboken.* City of Hoboken: North Hudson Sewerage Authority.

EmNet. (2011). *Sewer Monotoring Program Observations and Data Analysis.* City of Hoboken, NJ.

Encyclopedia Britanica. (2015). *Wastewater treatement.* Retrieved from Encyclopedia Britanica: http://www.britannica.com/technology/wastewater-treatment

EPA. (2016). *Climate Change Indicators: Heavy Precipitation*. Retrieved 2016, from Climate Change Indicators: https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation#ref6

.

EPA. (2016, December). *Climate Change Indicators: U.S. and Global Precipitation*. Retrieved from Climate Change Indicators: https://www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-precipitation

European Union. (2010). *Making our cities attractive and sustainable.*

FEMA Map Service Center. (n.d.).

Flood Break . (2016). Retrieved from Flood Break Revolutionary Flood Control: www.floodbreak.com

Gage, J., Yurik, J., & Martin , A. (2016, July). The World's Largest Rain Barrel. *Water Environment Federation* .

Garbrecht, G. (1987). Die Wasserversorgung des antiken Pergamon. *Geschichte der Wasserversorgung* , 11-48.

Gooogle Maps. (2016). Retrieved from www.google.com/maps

Granich, W., & Elmore, C. (2010). An evaluation of the use of renewable energy to pump water in Sacala las Lomas, Guatemala. *Environmental Earth Science* , 837-846.

Greenfeld, D., Hsu, N., & Wenger, J. (2014). *Sandy Recovery Strategic Planning Report.* Jersey City: City of Jersey City.

Guo, Q., Li, Y., Kennish, M., Psuty, N., Lathrop, R., & Trimble, J. (2014). *Strategies for Flood Risk Reduction for Vulnerable Coastal Populations around Barnegat Bay.* Piscataway: New Jersey Governor’s Office of Recovery and Rebuilding and New Jersey Department of Environmental Protection.

Guo, Q., Miskewitz, R., Athanasopoulou, E., & Gharyeh, K. (2014). *Strategies for Flood Risk Reduction for Vulnerable Coastal Populations along Hudson River at Hoboken and Jersey City.* New Jersey Governor’s Office of Recovery and Rebuilding and New Jersey Department of Environmental Protection.

Jevrejeva, S., Moore, J., Grinsted, A., & Woodworth, P. (2008). Recent global sea level acceleration started over 200 years ago. *Geophysical Research Letters , 35*, 4.

Karl, T., Knight, R., Easterling, D., & Quayle, R. (1996). Indices of climate change for the United States. *Bulletin of the American Meteorological Society* , 279-292.

Karl, T., Melillo, J., & Peterson, T. (2009). Global Climate Change Impacts in the United States. *U.S. Global Change Research Program* .

Kemp, A., Horton, B., Donnelly, J., Mann, M., & Rahmstorf, S. (2011). Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences of the United States of America , 108*, 11017-11022.

Knutson, T., Sirutis, J., Vecchi, G., Garner, S., Zhao, M., Kim, H., et al. (2013). Dynamical Downscaling Projections of Twenty-First-Century Atlantic Hnrricane Activity: CMIP3 and CMIP5 Model-Based Scenarios. *Journal of Climate* , 6591-6617.

Kossin , J., Knapp, K., Vimont, D., Murnane, R., & Harper, B. (2007). A globally consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters , 34*, L04815.

La Rotta, J., & Pinilla, A. (2006). Performance evaluation of a commercial positive displacement pump for wind-water pumping. *Renewable Energy* , 1790-1804.

Lamprecht, H. (1988). Bau und Material- technik bei antiken Wasserversorgungs-anlagen in Geschichte der Wasserversorgung. *Frontinus-Gesellschaft e.V.* , 150-155.

Malcolm Pirnie, INC. (2008). *Jersey City Stormwater Management Plan.*

.

Melillo, J., Richmond, T., & Yole, G. (2014). *Climate Change Impacts in the United States: The Third National Climate Assessment.* Washington: U.S Global Change Research Program.

Metcalf, L., & Eddy, H. (1928). *American Sewerage Practice: Volume I, Design of Sewers.* New York: McGraw-Hill Book Company, Inc.,.

Miller, K., Kopp, R., Horton, B., Browning, J., & A.C, K. (2013). *A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast, Earth's Future,.*

Murakami, H., Y., W., Yoshimura, H., Mizuta, R., Shindo, E., Adachi, E., et al. (2012). Future Changes in Tropical Cyclone Activity Projected by the New High-Resolution MRI-AGCM. *Journal of Climate* , 3237-3260.

Mustafa S. G. (2011). Economic Viability of Water Pumping Systems Supplied by Wind Energy Conversion and Diesel Generator Systems in North Central Anatolia, Turkey . *American Society of Civil Engineers* .

National Hurricane Center. (2011). *Tropical Cyclone Report Hurricane Irene.* National Hurricane Center.

National Hurricane Center. (2013). *Tropical Cyclone Report Hurricane Sandy.* National Hurricane Center.

National Oceanic and Atmospheric Administration. (2013). *Service Assessment Hurricane/Post Tropical Cyclone Sandy, October 22-29, 2012.* Silver Spring, Maryland: U.S Department of Commerce.

New Jersey Future. (2016, May). *Built It Green Competition*. Retrieved from New Jersey Future Working for Smart Groth: More Livable Places and Open Spaces: http://www.njfuture.org/issues/environment-and-agriculture/water-sewer/water-infrastructure/build-it-green-competition/

NFWF. (2014, June). *Grants Announced June 16, 2014 from the Hurricane Sandy Coastal Resiliency Competitive Grant Program.* Retrieved from U.S Departement of Interior: https://www.doi.gov/sites/doi.gov/files/migrated/news/upload/2014-grants-list-v2.pdf

NHSA. (2016). Retrieved from H-5 Wet Weather Pump Station: http://www.nhudsonsa.com/Public/H-5_WWPS.html

NHSA. (2013). *Final Report: An Evaluation of I/I and Illicit Flow in Wesr New York, NJ and Flood Mitigation in Hoboken, NJ.*

NHSA. (2002). *Southwest Hoboken Flooding Analysis.*

NHSA. (2015, June 8). *Storm Water Management Improvement Project: H5 Wet Weather Pump.* Retrieved from H5 Wet Weather Pump Station - NHSA: http://www.nhudsonsa.com/Public/H-5_WWPS.html

NJ Flood Mapper. (2013). *Start Viewer*. Retrieved from NJ Flood Mapper: http://slrviewer.rutgers.edu/

NJDEP. (2013, September 12). *Christie Administration Announces Post-Superstorm Sandy Flood Mitigation Studies by New Jersey Universities*. Retrieved from News Releases: http://www.nj.gov/dep/newsrel/2013/13_0091.htm

NJGIN. (2015). *New Jersey Geographic Information Network* . Retrieved from Data Downloads: https://njgin.state.nj.us/NJ_NJGINExplorer/index.jsp

NOAA. (2013). *Mean Sea Level Trends*. Retrieved from https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

.

NOAA. (2016). *National Centers for Environmental Information.*
NYC. (2013). *A Stronger, More Resilient New York.* New York: The City of New York.
NYC DEP. (2016). *Bllue Roof and Green Roof.* Retrieved from NYC Environmental Ptection : http://www.nyc.gov/html/dep/html/stormwater/green_pilot_project_ps118.shtml
OMA. (2014). *Resist, Delay, Store, Discharge: A Comprehensive Urban Water Strategy.* Rebuilt By Design - Team OMA .
Orton, P., Marione-Stanton, T., Hsu, N., Ederbach, S., Vinogradov , S., Blumberg, A., et al. (2015). *Collaborative Design and Dynamic Modeling for Urban Coastal Flood Adaptation* . Hoboken: Stevens Institute of Technology, Hoboken, NJ .
Peterson, T. (2013, June). Monitoring and Understanding Changes in Heat Waves, Cold Waves, Floods, and Droughts in the United States: State of Knowledge. *Bulletin of the American Meteorological Society* .
Pielke, R., Gratz, J., Landsea, C., Collins, D., Saunders, M., & R., M. (2008). Normalized hurricane damages in the United States: 1900-2005. *Natural Hazards Review* , 29-42.
PSE&G. (2016). *Reliability Project Overview*. Retrieved from Elctric Reliability Projects: https://www.psegtransmission.com/reliability-projects/energy-strong/town/jersey-city
Rebuild by Design. (2015). *Rebuild by Design Hudson River: Resist, Delay, Store, Discharge.* NJ Disaster Recovery Documents.
Rebuilt by Design . (2016). *Rebuilt by Design - Hudson River* . Retrieved from State of New Jersey, Department of Environmental Protection, Office of Flood Hazrd Risk Reduction Measures: http://www.nj.gov/dep/floodhazard/docs/rbdh-3-design-alternatives.pdf
Reznicek E.P., E. A. (2014). Performance Characterization of a Wind-Powered Water Pump for Use in Rural Bolivia . *World Environmnental and Water Resources Congress 2014: Water Without Borders* , 1627-1636.
Reznicek, E., & Elmore, A. (2014). Performance Characterization of a Wind-Powered Water Pump for Use in Rural Bolivia. *World Environmnental and Water Resources Congress 2014: Water Without Borders* , 1627-1636.
Spinello, S. (2013, June 18). *Dramatic downgrade for FEMA flood maps but 75% of Hoboken still in high-risk flood areas.* Retrieved from Fund for a Better Waterfront: http://betterwaterfront.org/revised-fema-flood-maps-slightly-downgrade-hobokens flood-risk
The New York Times. (2016, February). *Plan to Flood-Proof Hoboken Runs Into a Wall*. Retrieved from The New York Times: http://www.nytimes.com/2016/02/08/nyregion/plan-to-flood-proof-hoboken-runs-into-a-wall.html?_r=2
Thomas, R., Melillo, J., & Peterson, T. (2009). *Global Climate Change Impacts in the United States.* Cambridge University Press.
Thorne, P. (2012, April 11). Retrieved from Nansen Environmental and Remote Sensing Center: https://www.nersc.no/nb/taxonomy/term/5/0
United States Bureau of Cencus. (1883). *Compendium of the Tenth United States Census, Part I.* Washington D.C.: United States Bureau of Cencus.
United States Environmnetal Protection Agency. (2015). *Climate Change Indicators in the United States: U.S. and Global Precipitation.* EPA.

.

Van Abs, D., McClean, A., Tsoulou, I., Gao, Y., & Evans, T. (2014). *Water Infrastructure in New Jersey's CSO Cities: Elevating the Importance of Upgrading New Jersey's Urban Water Systems*. New Brunswick: Rutgers The State University of New Jersey.

Walsh, S., & Miskewitz, R. (2011). Evaluation of the impacts of Sea Level Rise on upland flooding in tide gate protected areas. Journal of Water Resources Planning and Management.

Water Environment Federation. (2015, April). *New Jersey Advances Resiliency and Flood Protection Projects*. Retrieved from Stormwater Report: http://stormwater.wef.org/2015/04/new-jersey-advances-resiliency-flood-protection-projects/

Wiesmann, U., Choi, I., & Dombrowski, E. (2006). Historical Development of Wastewater Collection and Treatment. In *Fundamentals of Biological Wastewater Treatment.* Weinheim, gERMANY: Wiley-VCH Verlag GmbH & Co. KGaA.

World Wind Energy Assosiation. (2014, September). *WWEA Half Year Report 2014*. Retrieved from http://www.wwindea.org/wwea-publishes-half-year-report-2014/

.