# Strategies for Flood Risk Reduction for Vulnerable Coastal Populations along Hudson River at Hoboken and Jersey City

FINAL REPORT

Submitted to

New Jersey Governor's Office of Recovery and Rebuilding
and
New Jersey Department of Environmental Protection

By

Qizhong (George) Guo[1], Principal Investigator
Robert Miskewitz[2]
Eleni Athanasopoulou[1]
Kaveh Gharyeh[1]
Jun Zhao[1]

[1]School of Engineering, Department of Civil and Environmental Engineering
[2]School of Environmental and Biological Sciences, Department of Environmental Sciences

Rutgers, The State University of New Jersey

August 2014

RUTGERS
School of Engineering
150 Years Engineering Out Front

# Table of Contents

## List of Figures

# List of Tables

# Executive Summary

## Flood Study Overview

The communities of Hoboken and Jersey City are located along the Hudson River waterfront on their east side and the Newark Bay / Hackensack River waterfront borders the west side of Jersey City. Much of the waterfront areas of both of these communities are at very low elevation and are consequently at risk from coastal inundation. The storm surge associated with Hurricane Sandy resulted in severe flooding and flood related damage in these communities.

Following the damage resulting from Hurricane Sandy, Rutgers University was tasked to determine the flood vulnerability of several communities across New Jersey including Hoboken and Jersey City and to develop the mitigation measures.

Dr. Qizhong (George) Guo (Principal Investigator) led a team of flood researchers on this study. The team collected and analyzed flood and infrastructure data from multiple federal and state sources including USGS, FEMA, NOAA, NJDEP and local sources including public works design drawings and flood incident reports, first to assess the communities' vulnerabilities, and then to propose appropriate measures to mitigate these vulnerabilities

## Hudson River Region

In Hudson County, New Jersey, the communities are characterized by urban land uses and high impervious area. As a result communities along the Hudson River waterfront and the Newark Bay / Hackensack River waterfront are not only vulnerable from both coastal flooding and wave action but also from insufficient drainage of high stormwater runoff.

The large spatial extent of areas susceptible to coastal inundation along the Hudson River waterfront and the Newark Bay/Hackensack River waterfront justifies the consideration of regional solutions to mitigate coastal flooding. The most appropriate regional flood mitigation that was investigated is a floodwall installed along the Hudson River, approximately 13 miles, and along the Newark Bay, approximately 11 miles, varying in height from 12 to 19 feet. This floodwall will require several flap gates to facilitate upland drainage and floodgates at the tidal canals to maintain the viability of marinas and ferry stations. The floodwall envisioned includes a sheet pile bulkhead and cap base with top height some distance above grade and then a couple of vertical extensions as needed.

## City of Hoboken

The municipality of Hoboken can also protect itself from coastal flooding by using flood barriers within its borders. It can take advantage of the existing concrete walls of the elevated roadway at 14th Street in the north, with a length of 1,368 feet, as well as the existing elevated railroad along Long Slip in the south with a length of 2,752 feet. For the sections of flood barriers needed to be deployed or constructed, a combination of different types can be utilized: 1) fixed floodwalls and 2) movable floodgates.

Low base elevation and lack of relief in the Hoboken combined sewer system results in local flooding during large rainfall events. This flooding is exacerbated during elevated tidal conditions or during a storm surge when relief flow through combined sewer overflow (CSO) outfalls is restricted. It is recommended that the combined sewer system be separated into stormwater and wastewater conveyance systems that will allow for better management of stormwater since more options are available to handle the storage and disposal of stormwater than there are for sewage. Stormwater storage was also investigated to help relieve the stormwater-related flooding. The Long Slip canal on the south end of Hoboken was identified as a potential location especially given its proximity to the chronically flooded areas in the southwest corner of Hoboken.

Finally, the City of Hoboken like the other communities in this area is highly urbanized and therefore precipitation events produce significant stormwater runoff. It is recommended that green infrastructure mitigation measures be implemented to reduce the amount of stormwater runoff generated.

### Jersey City

Jersey City is vulnerable to coastal flooding from the Hudson River on the east and the Newark Bay / Hackensack River on the west. It is envisioned that the most efficient way to mitigate coastal flooding in the City is to install a floodwall with the combination of a floodgate at Morris Canal as a part of the regional solutions.

Several low-lying areas of Jersey City are susceptible to local flooding during large rainfall events. The existing combined sewer system routes excess flow to either the Hudson River in the east or the Newark Bay/Hackensack River in the west. However during elevated tidal conditions or during a storm surge when relief flow through CSO outfall is restricted excess flow will back up into the streets and basements of Jersey City. It is recommended that the combined sewer system be separated into stormwater and wastewater conveyance systems that will allow for better management of stormwater since more options are available to handle the storage and disposal of stormwater than there are for sewage. Stormwater storage was also investigated to help relieve the stormwater-related flooding. The Morris Canal at the Hudson River waterfront was identified as a potential location for storing excess stormwater, however this would require restriction of tidal flow into the canal using a floodgate at its mouth.

Protection of transportation infrastructure was also investigated with a focus on the chronically flooded areas along NJ Rt. 440 along the western edge of Jersey City. It is proposed to raise the elevation of intersections that experience frequent flooding while providing storage beneath the raised roadway for excess runoff.

Jersey City is highly urbanized and even small precipitation events produce significant stormwater runoff. Reduction of this runoff will reduce the stress on the combined sewer system and potentially reduce flooding throughout the city. It is recommended that green infrastructure mitigation measures be implemented to reduce the amount of stormwater runoff generated. An additional mitigation strategy that was investigated to reduce the stress on the sewer system is the development of a "Green Belt" that stretches 1.5 miles taking advantage of open areas under the elevated roadway of US Rt. 78 and adjacent areas. Stormwater from a large area throughout the city could be routed to the "Green Belt" which would then serve as both a stormwater management basin and a recreational area.

## Approach to Developing Flood Mitigation Strategy and Measures

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 (see Figure 1 below).

The Rutgers University Flood Mitigation Study Team also developed a menu of flood risk-reduction functions and their associated measures. Figure 2 is a schematic showing the application of various flood mitigation measures and Table 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.

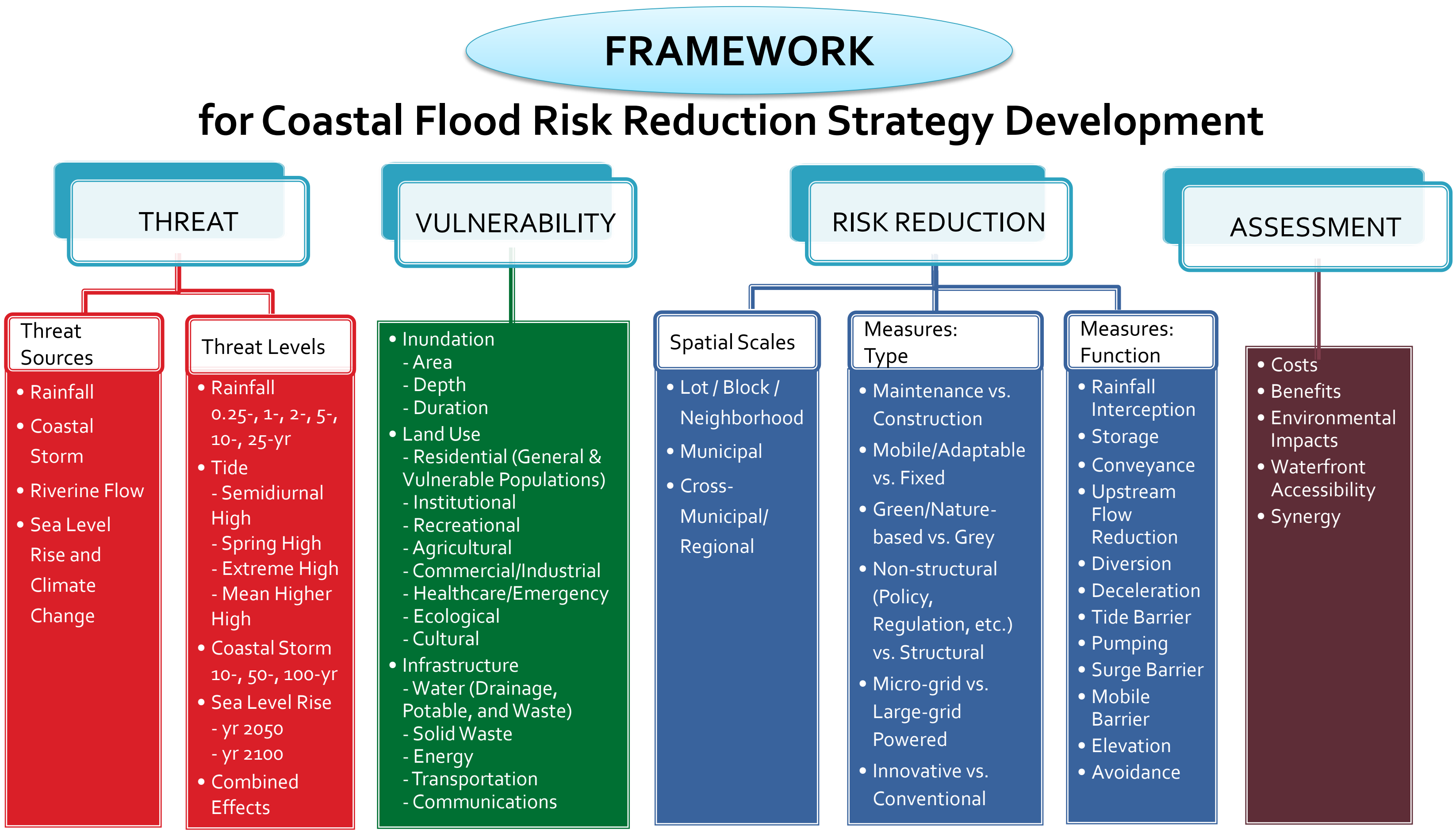


Figure 1: Framework for Flood Risk Reduction Strategy Development

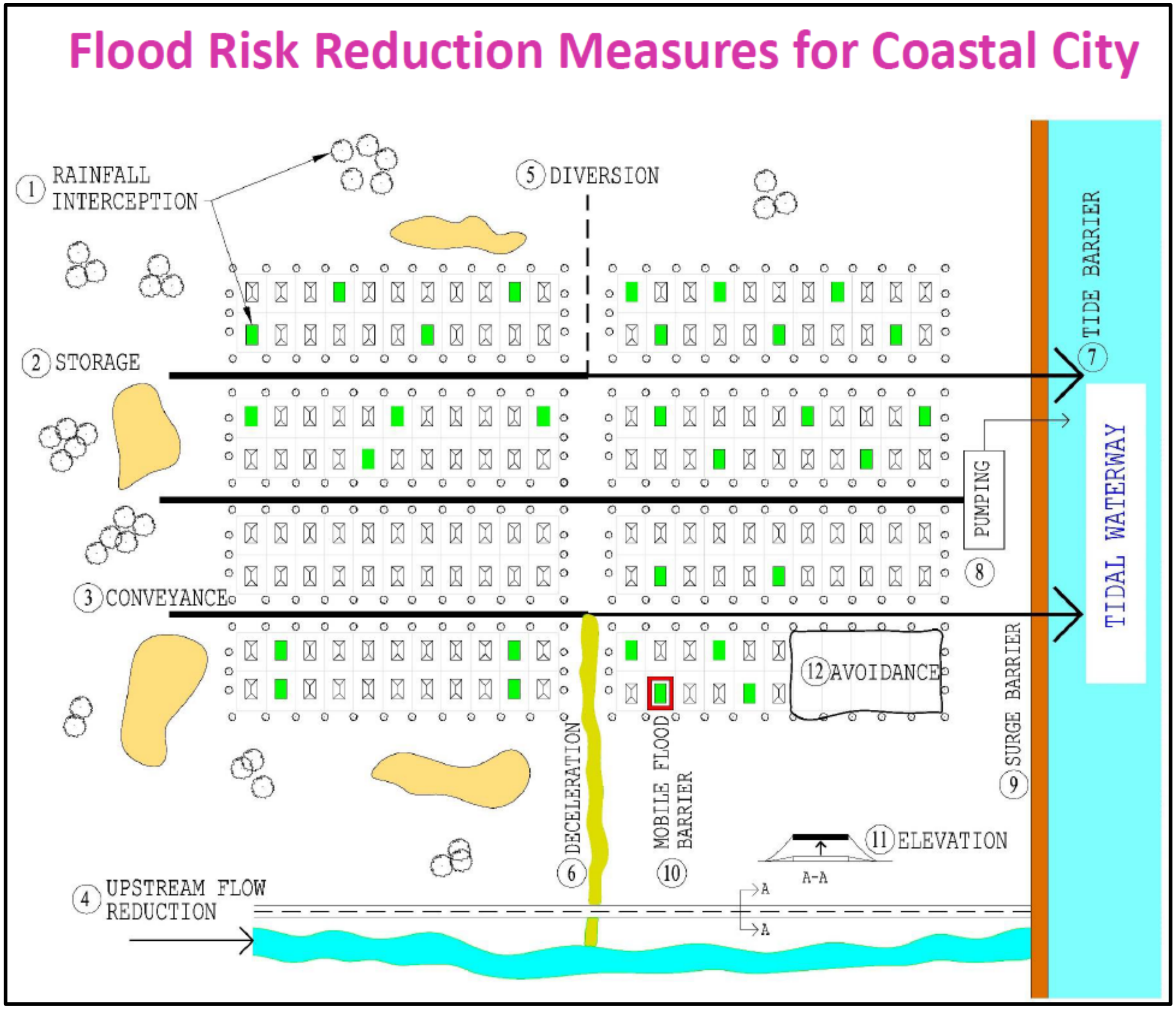


Figure 2: Flood Risk Reduction Measures

## Table 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 | SEWER | DAM | NEW SEWER | VEGETATED SWALE | FLAP GATE | PUMPING STATION | NEW LEVEE | MOVABLE FLOOD WALL | ELEVATE BUILDING | BUYOUT |
| GREEN ROOF | DETENTION | CHANNEL | WATERSHED MANAGEMENT | BYPASS FORCE MAIN* | ARTIFICIAL WETLANDS | SLUICE GATE | EMERGENCY POWER | SEAWALL | FLOOD GATE | ELEVATED ROAD | EVACUATION |
| BIOSWALE | INFILTRATION | DREDGING | | | | HEADWALL | WIND PUMP | TEMPORARY SEAWALL | INFLATABLE BARRIER | | WARNING |
| VEGETATED FILTER STRIP | EXPANSION | COMBINED SEWER SEPARATION | | | | | RAIN PUMP* | ELEVATING LEVEE | | | RISK EDUCATION |
| POROUS PAVING | CONSTRUCTED WETLANDS | CULVERT SIZE | | | | | WAVE PUMP* | NEW DUNES | | | |
| RAIN GARDEN | LAKE EXPANSION | DEBRIS REMOVAL | | | | | CURRENT PUMP* | BEACH NOURISHMENT | | | |
| PLANTER BOX | | DE-SNAGGING | | | | | | ARTIFICIAL WETLANDS | | | |
| RAIN BARREL | | STRAIGHTENING | | | | | | SHEETING BULKHEAD | | | |
| SOIL AMENDMENT | | SEWER FLUSHING | | | | | | CONCRETE BULKHEAD | | | |
| VERTICAL WALL | | | | | | | | REPAIR LEVEE | | | |
| | | | | | | | | VEGETATED LEVEE | | | |
| | | | | | | | | BREAKWATER | | | |
| | | | | | | | | IN-WATER BARRIER | | | |
| | | | | | | | | RESTORED WETLANDS | | | |
| | | | | | | | | LIVING SHORELINE | | | |
| | | | | | | | | FLOATING BARRIER | | | |
| | | | | | | | | EXTENDABLE FLOOD PANEL* | | | |
| | | | | | | | | CAUSEWAY WITH OPERABLE FLOOD GATE* | | | |

*Newly proposed.

# Storm Surge and Stormwater Threats

## 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.

***Regional Map of Hoboken & Jersey City, NJ***


Figure 3: Regional Map of Jersey City & Hoboken, NJ.
Source: New Jersey Geographic Information Network.
(https://njgin.state.nj.us/NJ_NJGINExplorer/index.jsp)

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.

***Regional Digital Elevation Model of Jersey City & Hoboken, NJ***

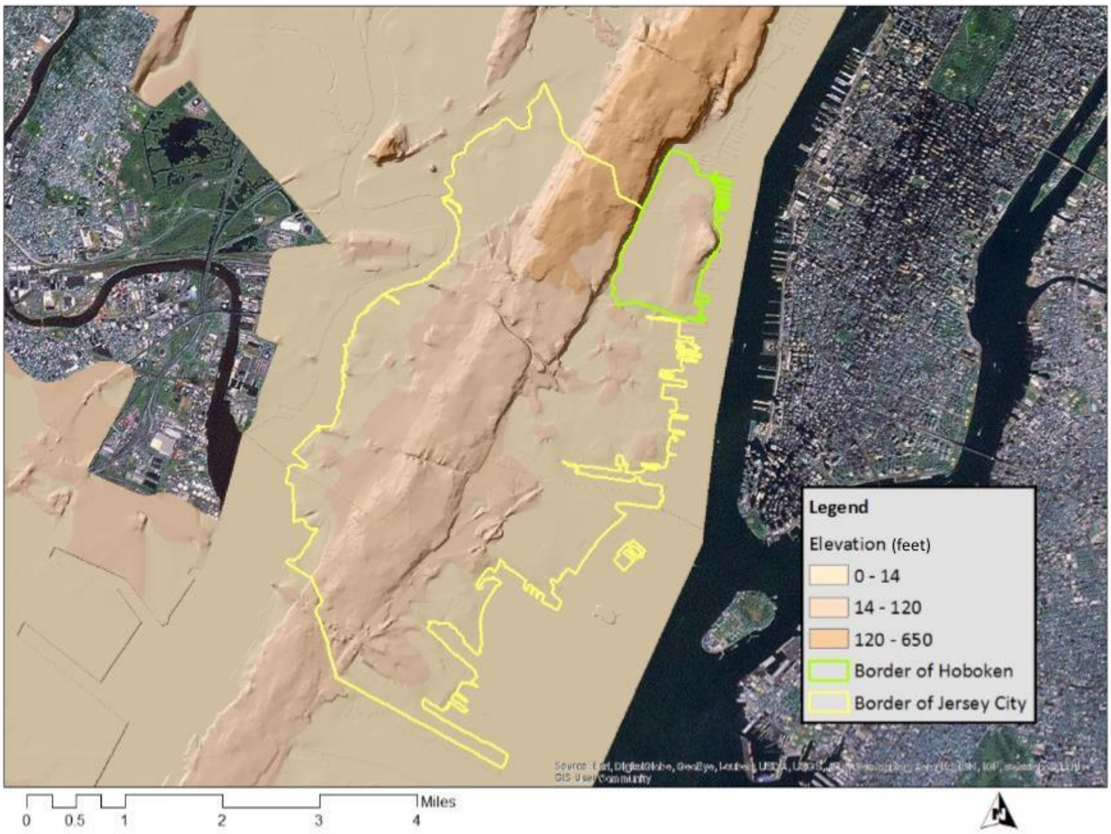


Figure 4: Map of Regional Digital Elevation Model of Jersey City & Hoboken, NJ.
Source: New Jersey Geographic Information Network.
(https://njgin.state.nj.us/NJ_NJGINExplorer/index.jsp)

In this study, the flood remedies that were 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 upgrades to existing infrastructure to protect areas from flooding that occur on a 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.

### Storm Surge Threat

This section describes the estimated water levels that are associated with conditions of future coastal inundation events (FEMA Map Service Center, National Flood Hazard Layer Database). 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. 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 (Figures 5-7) were 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 scenarios of coastal storms.

***10 - Year Coastal Storm***

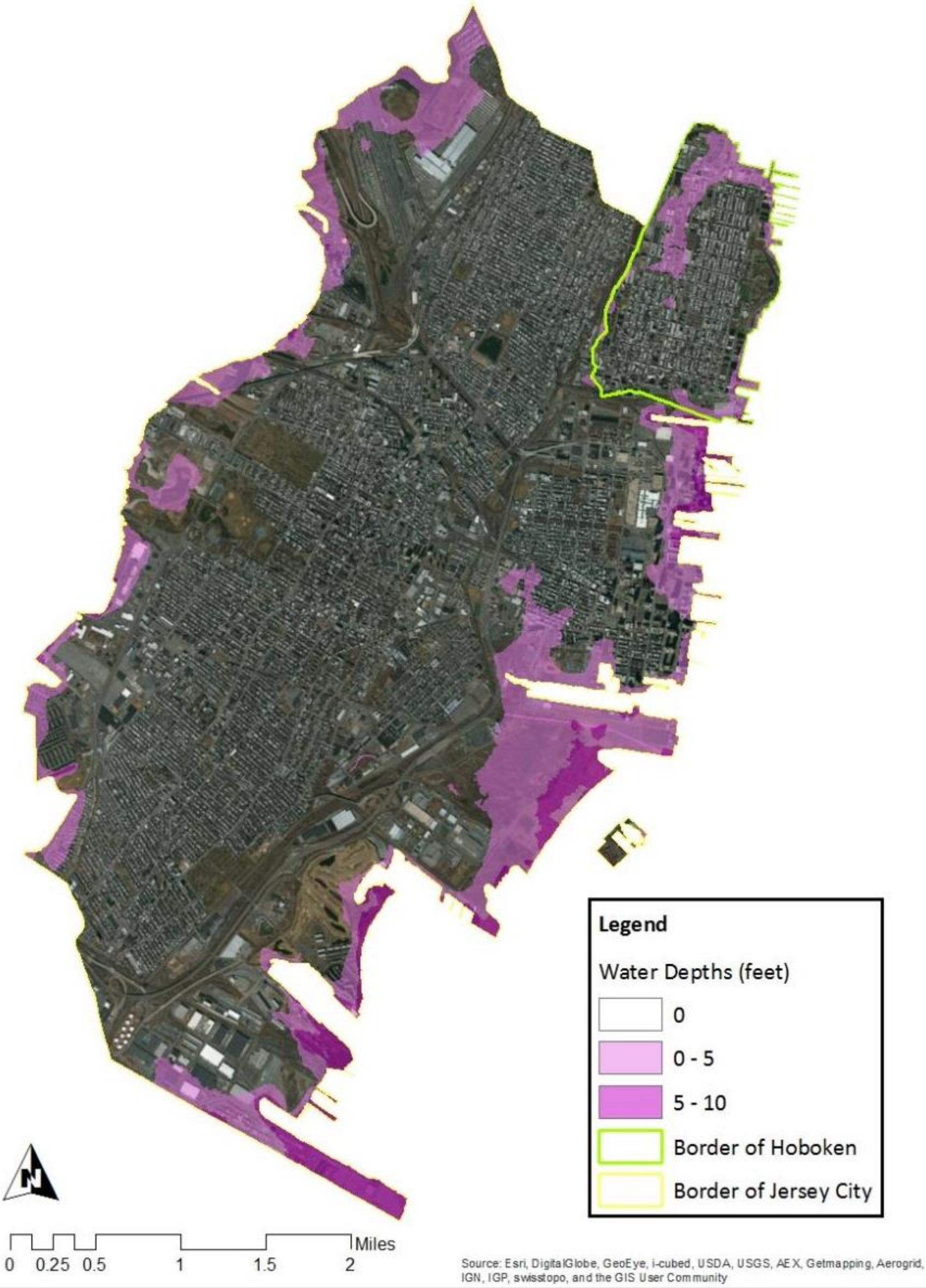


Figure 5: 10-Year Storm Map, Jersey City & Hoboken, NJ.
Source: FEMA Map Service Center.

***50 - Year Coastal Storm***

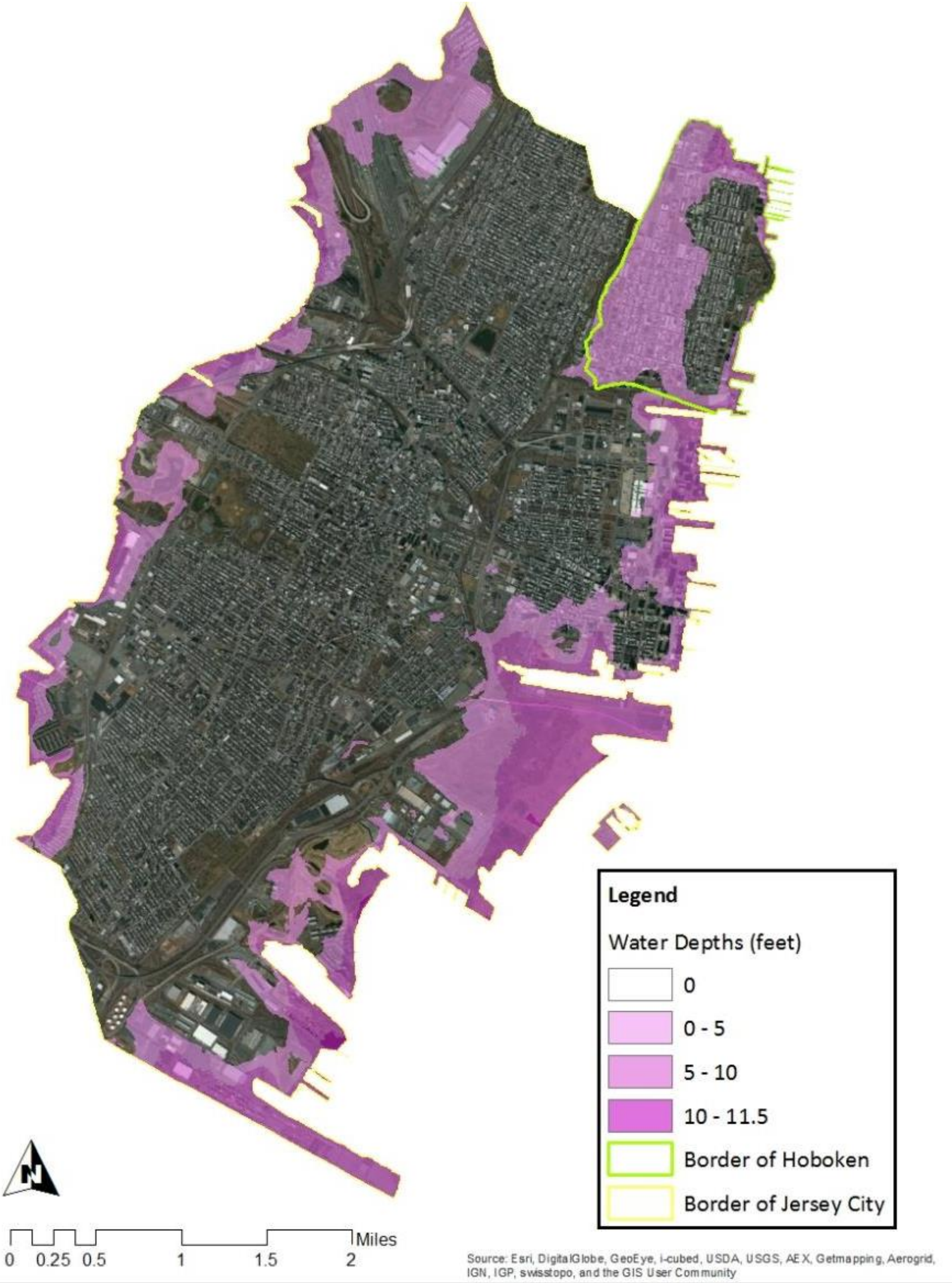


Figure 6: 50-Year Storm Map, Jersey City & Hoboken, NJ.
Source: FEMA Map Service Center.

*100-Year Coastal Storm*

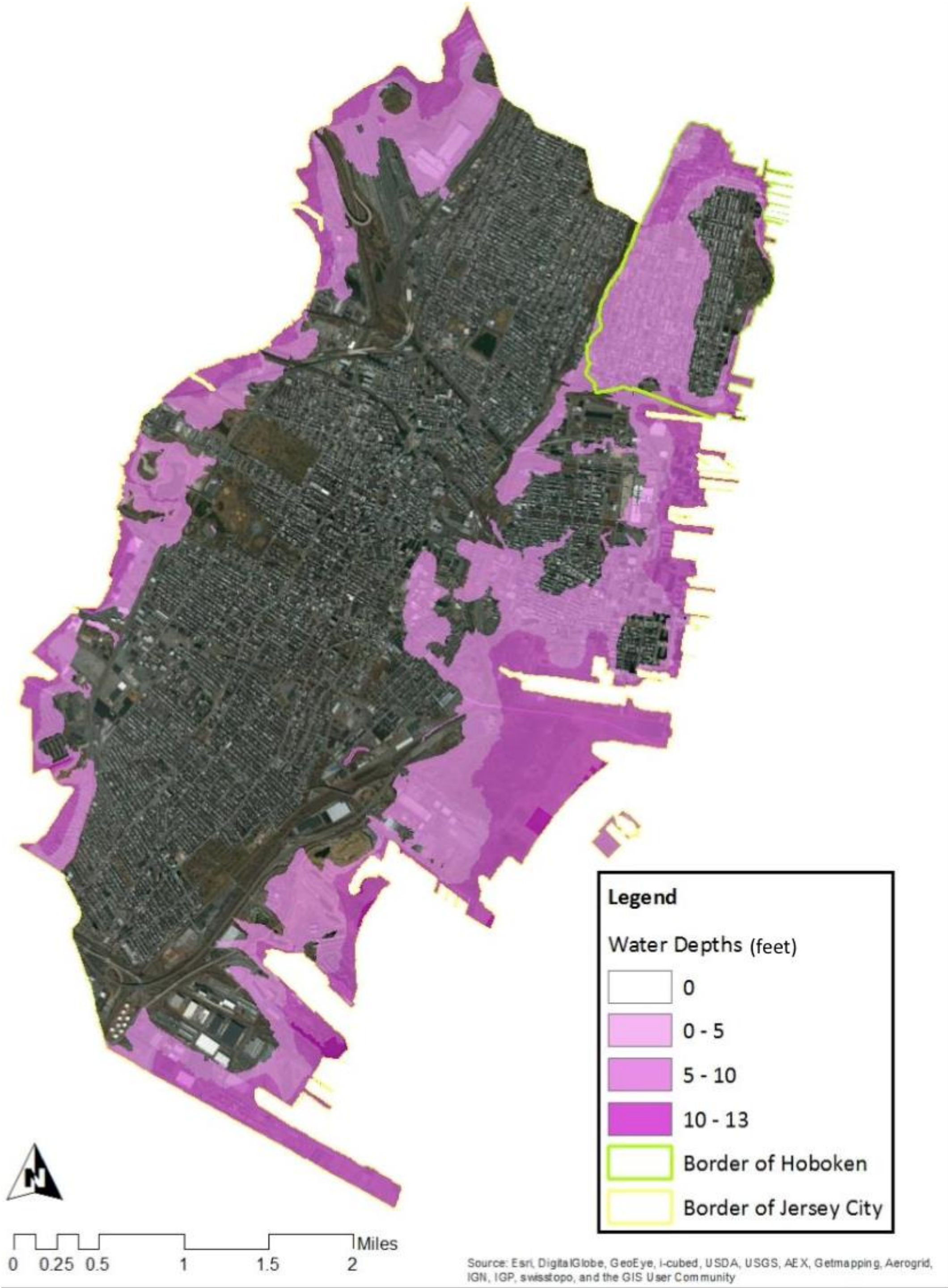


Figure 7: 100-Year Storm Map, Jersey City & Hoboken, NJ.
Source: FEMA Map Service Center.

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 7$^{th}$ street. In some locations water depths reach up to 2 feet around Jefferson St (Figure 8).

Figure 8: 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 9).

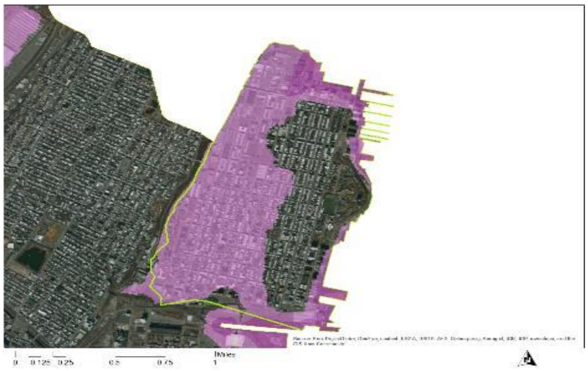

Figure 9: 50-Year Storm, Hoboken, NJ.
Source: FEMA Map Service Center.

*100-Year Coastal Storm:* In most parts of the western areas of Hoboken water depth reaches almost 6 feet (Figure 10).

Figure 10: 100-Year Storm, Hoboken, NJ.
Source: FEMA Map Service Center.

According to the FIRM map (FEMA Map Service Center, National Flood Hazard Layer Database) Jersey City floods for 10, 50 and 100-year storm surges 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 (Figure 11).

Figure 11: 10-Year Storm, at south downtown Jersey City, NJ.
Source: FEMA Map Service Center.

Figure 12: 10-Year Storm, at north Jersey City, NJ.
Source: FEMA Map Service Center.

*50- Year Coastal Storm:* Water at Grant Street reaches depths up to 3.5 feet (Figure 13).

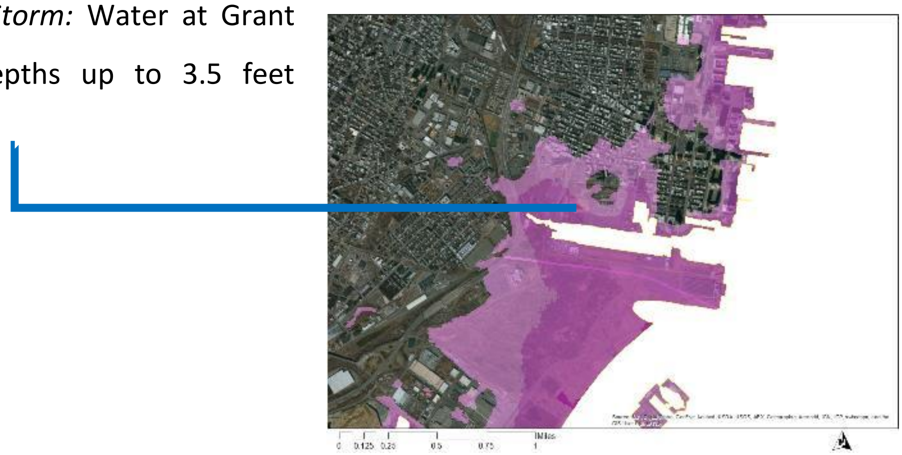

Figure 13: 50-Year Storm, Jersey City, NJ
Source: FEMA Map Service Center.

*100-Year Coastal Storm:* Floodwater reaches depths up to 2 feet under the elevated Route 78 at south (Figure 14), while water elevations around Morris Marina reach 5 to 7 ft NAVD88.

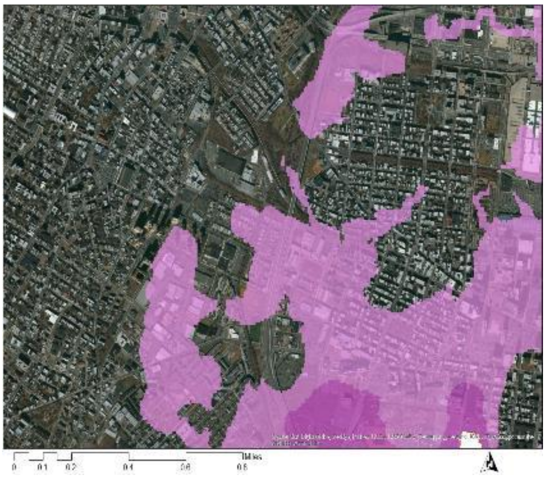

Figure 14: 100-Year Storm, at Route 78, Jersey City, NJ
Source: FEMA Map Service Center.

Figure 15: 100-Year Storm, Downtown Jersey City, NJ.
Source: FEMA Map Service Center.

### 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 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 (2013) 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 16). 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 et al. 2014).

Figure 16: Flap Gate at Morris Marina, Jersey City, NJ

# Regional Flood Mitigation Measures

### Hoboken and Jersey City Joint Coastal 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 the Figure 17 and Tables 3 & 4.

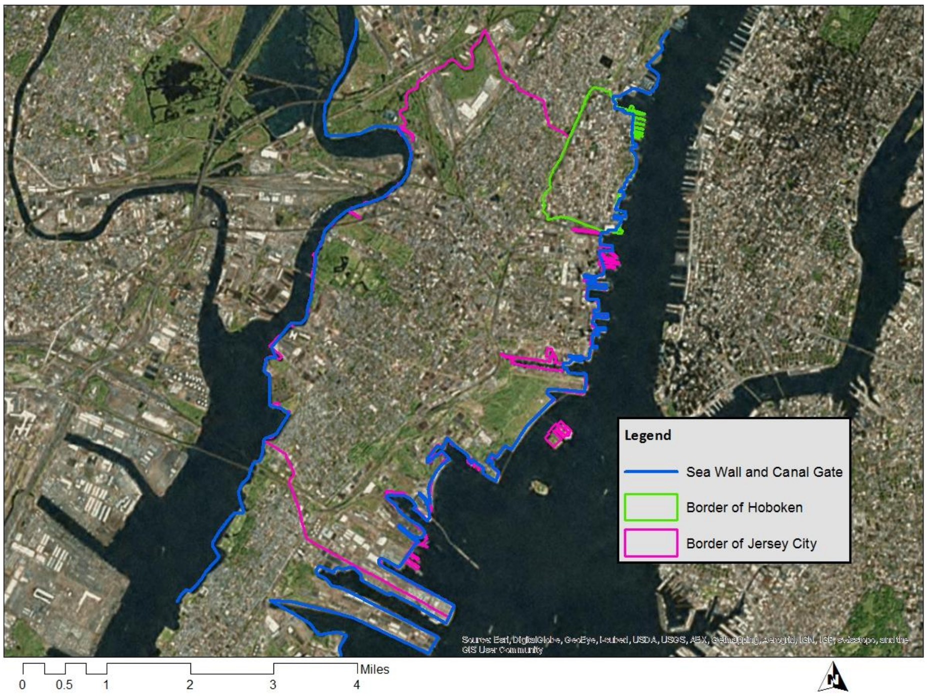


Figure 17: Flood Mitigation Measures Map, Jersey City & Hoboken, NJ.

***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 18) is estimated at $4000 per foot. The 4-feet high extensions (Figure 19) are estimated at $400 per foot. Please note that the cost of maintenance has not been examined.

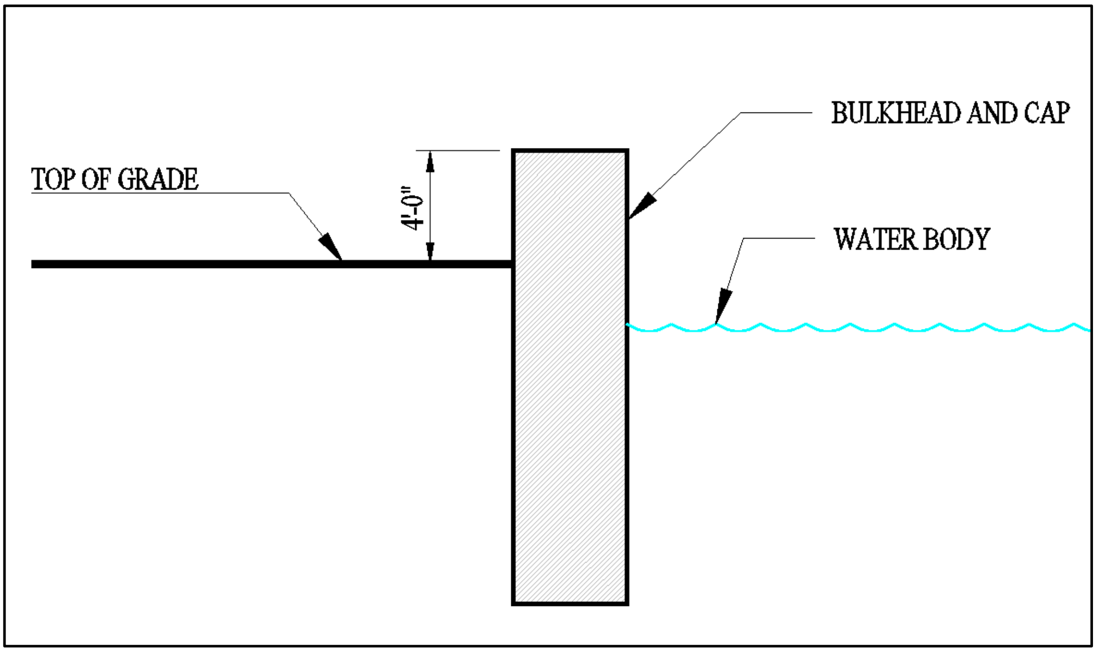


Figure 18: Floodwall Schematic showing Bulkhead

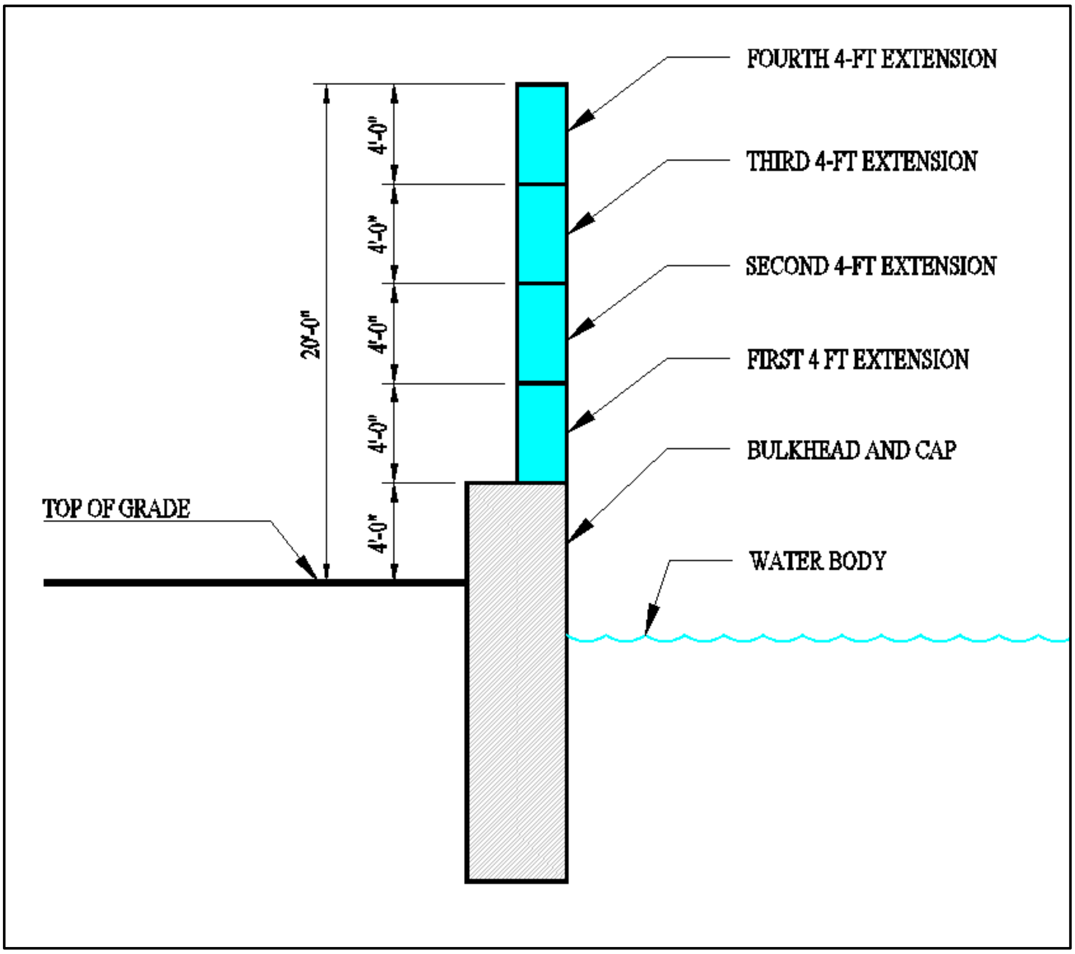


Figure 19: Floodwall Schematic showing Bulkhead and Extensions

### Table 3. Regional Flood Measure, Bulkhead and Steel Flood Wall along Hudson River

| Protection Level | Wall Height | Cost |
|---|---|---|
| **10 - Year Storm** | 12 feet | $330,000,000 |
| **50 - Year Storm** | 16 feet | $360,000,000 |
| **100 - Year Storm** | 16 feet | $360,000,000 |
| **100 – Year Storm + 2050 SLR** | 16 feet | $360,000,000 |
| **100 – Year Storm + 2100 SLR** | 20 feet | $380,000,000 |

**Table 4. Regional Flood Measure, Bulkhead and Steel Flood Wall along Newark Bay**

| Protection Level | Wall Height | Cost |
|---|---|---|
| **10 - Year Storm** | 12 feet | $280,000,000 |
| **50 - Year Storm** | 16 feet | $300,000,000 |
| **100 - Year Storm** | 16 feet | $300,000,000 |
| **100 – Year Storm + 2050 SLR** | 16 feet | $300,000,000 |
| **100 – Year Storm + 2100 SLR** | 20 feet | 330,000,000 |

Length of the floodwall along the Hudson River and the Newark Bay could be shortened by taking advantage of some existing structures and/or high ground/landscape. It could also be shortened by using alternative protective options such as elevating and/or barricading the individual buildings.

Other floodwall options are available and 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.

It is important to 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.

The effectiveness of the regional floodwall measure will be addressed in greater detail by a concurrent investigation conducted by Stevens Institute of Technology.

***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 5 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 5. Regional Flood Measure, Canal Gates**

| Long Slip | Length | Height | Cost |
|---|---|---|---|
| **100 – Year Storm + 2100 SLR** | 100 feet | 24 feet | $32,000,000 |

| Morris Marina | Length | Height | Cost |
|---|---|---|---|
| **100 – Year Storm + 2100 SLR** | 200 feet | 24 feet | $64,000,000 |

In order to preserve the Morris Marina as a recreational boating resource a sliding gate or other moveable structure should be implemented.

## Hoboken Coastal Flood Mitigation Measures

Alternatively, 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 14th 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 depths at the western part of Hoboken reach 2 and 10 feet for 10-year to 100-year coastal storms, respectively. Flood barriers to cover 3,281 feet of length at north along 14th Street and 2,636 feet along the railroads of NJ Transit Terminal, above Long Slip are recommended.

The following map (Figure 20) shows the location of the measures suggested for the coastal storm flood threat for Hoboken.


Figure 20: Flood Mitigation Measures Map, Hoboken, NJ.

In this study a combination of different types of flood barriers were 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 21), if 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 21: Conventional Concrete Floodwall
Source: http://floodbreak.com/

Movable flood mitigation systems like roadway gates are designed for continuous traffic service and heavy use on local roads and highways. It is hidden underground to allow uninterrupted vehicle traffic until deployed. A hinged roadway gate (Figure 22) cost $15,000 for a panel of 5 feet height and 12 feet width.

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.

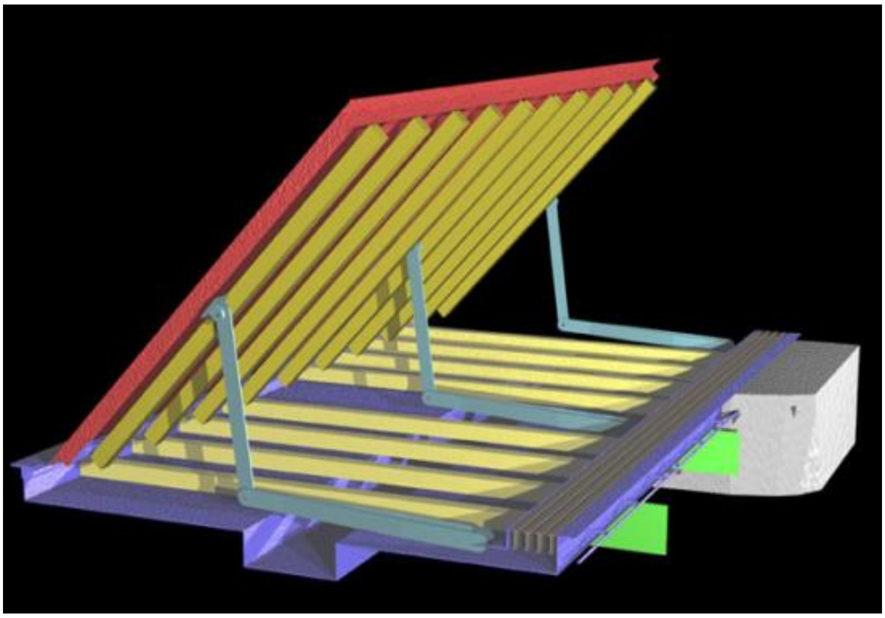

Figure 22: Automatic Roadway Floodgate
Source: http://floodbreak.com/

**Table 6. Flood Barriers for Hoboken Only**

| Measure | Dimensions | Cost |
|---|---|---|
| Roadway Floodgate | 612 feet length and 5 feet height | $765,000 |
| Conventional Concrete Floodwall | 5,305 feet length and 5 feet height | $5,000,000 |

# City of Hoboken

## Background

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 23 that a three-foot rise in sea level above MHHW would result in catastrophic flooding in this area.

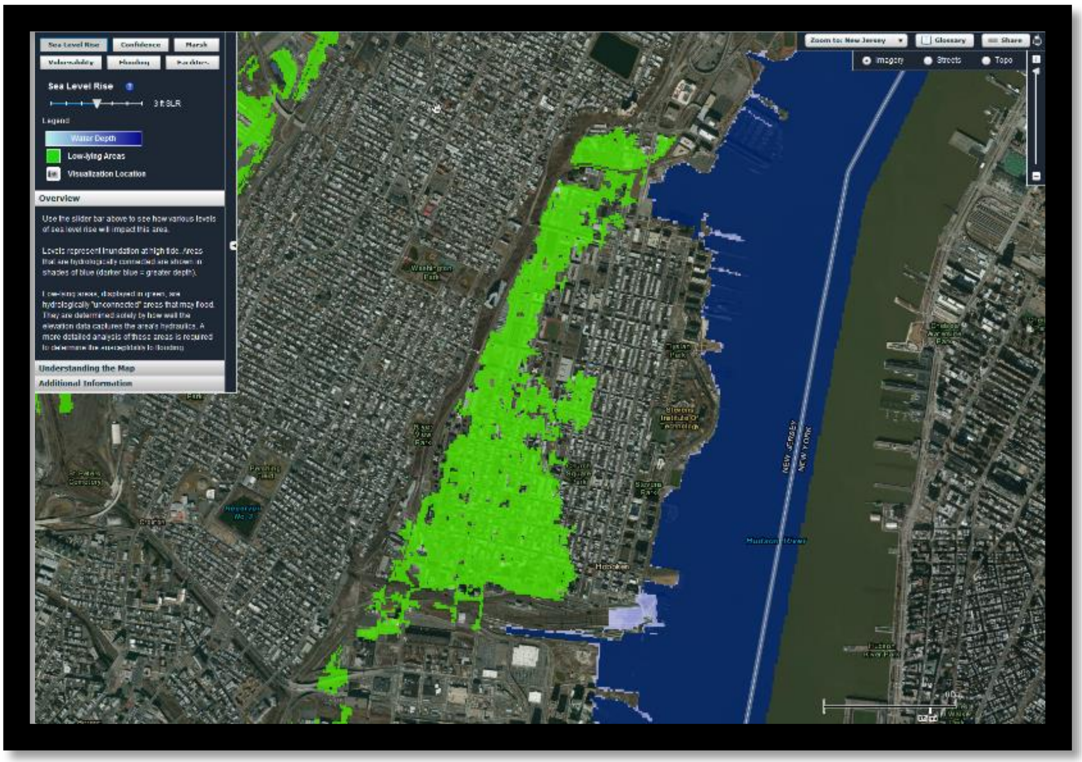


Figure 23: Flood Prone areas in Hoboken along Hudson River Waterfront under 3 feet Level Rise Scenario. Source: Flood Mapper, Rutgers University, in partnership with the Jacques Cousteau National Estuarine Research Reserve (JCNERR), and in collaboration with the NOAA Coastal Services Center (CSC).

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).

***Drainage System:***

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 the CSO outfalls. Figure 24 shows the drainage areas of Hoboken.


Figure 24: Map of Drainage Basins & CSO Outfalls, Hoboken, NJ.
Source: North Hudson Sewer Authority.

### Projects Currently Proposed

The City of Hoboken's Community Resiliency & Readiness Plan (2013) recommends flood pumps, storm surge protection/flood barriers, green infrastructure/stormwater 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 (Rebuild by design, 2013) 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 25 shows a general approach of flood prevention for the City.

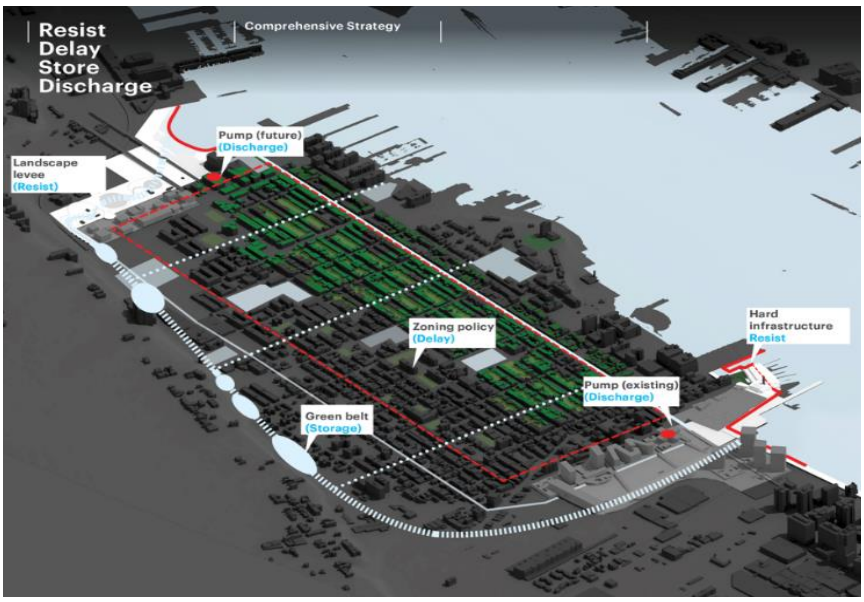


Figure 25: Flood Prevention Approach for Hoboken, NJ
Source: http://www.rebuildbydesign.org/project/comprehensive-strategy/

## Stormwater Threat

<u>Flooding during Rainfall events</u>

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 2$^{nd}$ Street, which corresponds to the most low-lying area in the H1 drainage basin and sub-basin H1-4 (Figure 26), 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 26).

Installation of two different capacity 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 26).

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 expected 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 26: Sub-Basins of Drainage Basin H1.
Source: The Routine Flooding Analysis, on the Southwestern Side of Town.

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 (L:\SSCC\Watershed Work\Hydrology\24 hr rainfall revised 2004).

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 65 MGD of pumping capacity (split between the H1 area and the H5 area to the north) be added in order to prevent flooding in all but the largest observed storm event.

## Municipal Stormwater Flood Mitigation Measures

Rainfall and MHHW

***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 27) 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 7 gives hypothetical storage volumes assuming mean depths of 3 feet, 5 feet, 10 feet, 15 feet or 20 feet for each column.

**Table 7. 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 27: Location of Long Slip, Hoboken, NJ
Source: New Jersey Geographic Information Network.
(https://njgin.state.nj.us/NJ_NJGINExplorer/index.jsp)

The amount of water that could be drained into this canal is calculated from the adjacent drainage area H1 (Figure 28). Table 8 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 47,694 ft and the curve number is 92.6.

**Table 8. Calculations of Runoff from H1 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 | 1.9342 | 1,664,675 | 12.45 |
| 2- year | 3.3 | 2.5053 | 2,156,194 | 16.12 |
| 5-year | 4.2 | 3.3753 | 2,904,962 | 21.73 |
| 10-year | 5.0 | 4.1567 | 3,577,476 | 26.76 |
| 25-year | 6.2 | 5.3370 | 4,593,305 | 34.36 |


Figure 28: Drainage Area H1, Hoboken, NJ.
Source: North Hudson Sewer Authority.

For the level of threat of a 5-year rainfall event a runoff of 21.73 MG from the drainage area of H1 is created. It was shown before in Table 7 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 prior to 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). The capital cost of this pump is given in Table 17.

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

***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 29) 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 9.

**Table 9. 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 | 1.8261 | 1,066,706 | 7.98 |
| 2- year | 3.3 | 2.388 | 1,394,936 | 10.43 |
| 5-year | 4.2 | 3.2482 | 1,897,417 | 14.19 |
| 10-year | 5.0 | 4.0233 | 2,350,188 | 17.58 |
| 25-year | 6.2 | 5.1966 | 3,035,564 | 22.71 |


Figure 29: Northwest Drainage Area, Hoboken, NJ.
Source: North Hudson Sewer Authority.

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

The costs for both arrangements have been calculated (Table 17). A stormwater 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.

***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. The feasibility of implementing green infrastructure to absorb a portion of the surface water runoff has been assessed for this study. Table 10 shows runoff depths to be produced from 1- and 2-year rainfalls. The land use map and associated curve number technique is applied to quantify the runoff for 1 and 2 year storm rainfalls. A description of the Green Infrastructure implementation software is included in Appendix A.

**Table 10. Runoff & Rainfall**

| | Rainfall from 1 year storm (in) | Rainfall from 2 year storm (in) | Runoff from 1 year storm (in) | Runoff from 2 year storm (in) | Area ($ft^2$) |
|---|---|---|---|---|---|
| **Hoboken** | 2.8 | 3.4 | 1.93 | 2.4 | 34,562,119 |

The minimum cost and optimal combination of green infrastructures are presented in the following Tables 11 and 12. Costs include the initial capital cost, replacement cost and yearly maintenance cost. However, according to planning time horizons that we select (10 year and 50 year), no green infrastructure is to be replaced.

**Table 11. Maximum Runoff Removal and Associated Cost by Converting All Potential Areas to Green**

| Maximum runoff removal by converting all potential areas to green (in) | 1.2 |
|---|---|
| 1 year storm: runoff removal percentage by converting all potential areas to green | 62 |
| 2 year storm: runoff removal percentage by converting all potential areas to green | 50 |
| | |
| Cost ($) – 10 year | 138,935,172 |
| Cost ($) – 50 year | 155,253,652 |

**Table 12. Optimal Combination of Green Infrastructure and Associated Cost to Remove 1 inch of Runoff**

| | Optimal area ($ft^2$) for 1 inch runoff removal | Maximum potential area ($ft^2$) |
|---|---|---|
| Green roof | 3,257,671 | 5,253,440 |
| Swales | 985,019 | 985,019 |
| Planter box | 52,534 | 52,534 |
| Vegetated filter strips | 985,019 | 985,019 |
| Permeable sidewalk | 919,005 | 919,005 |
| Permeable driveway | 1,116,355 | 1,116,355 |
| Permeable parking | 335,598 | 335,598 |
| Rain garden | 262,670 | 262,670 |
| Total cost ($) – 10 year | 106,058,083 | |
| Total cost ($) – 50 year | 119,645,933 | |

As a part of analysis, green infrastructure cost is compared to the cost of gray infrastructure implementation to remove the same amount of runoff (Table 13).

**Table 13. Comparison of Costs of Green and Gray Infrastructures**

| Time Horizon | Gray Infrastructure Cost ($) | Gray Infrastructure /Green Infrastructure cost |
|---|---|---|
| **10 year** | 71,660,474 | 0.67 |
| **50 year** | 89,732,905 | 0.74 |

This green infrastructure implementation scenario also involves full utilization of all potential sites that are located within the 100-year flood zone. The scenario was assessed to determine the amount of runoff reduced, and the associated costs. The amount of runoff for rainfall events with 1 year return periods were investigated (Table 14).

Potential sites were identified using land use maps. Only the areas characterized as commercial, industrial, residential, athletic fields, urban lands and built up lands are taken into consideration for green infrastructure implementation.

Maximum runoff capture: 1.2 inch

Cost to remove 1.2 inch of runoff (10 year horizon) = $ 87,657,162

Cost to remove 1.2 inch of runoff (50 year horizon) = $ 93,526,491

**Table 14. Characteristics of the Areas in 100-Year Flood Zone in Under Study Towns**

| | Rainfall amount (1-Year Storm) (in) | Runoff from 1 year storm (in) | Total area ($ft^2$) | Area in 100 year flood zone ($ft^2$) | Excluded area ($ft^2$) | Area used for analysis ($ft^2$) | Percentage of area in the town |
|---|---|---|---|---|---|---|---|
| **Hoboken** | 2.8 | 1.93 | 34,562,119 | 26,283,746 | 5,463,141 | 20,820,605 | 60 |

The optimal combination of green Infrastructure measures to remove one inch of runoff within the 100-yr flood zone and their associated costs are shown in Table 15.

**Table 15. Optimal Combination of Green Infrastructure and Associated Cost to Remove 1 Inch of Runoff within 100-yr Flood Zone**

| | Optimal area ($ft^2$) for 1 inch runoff removal | Maximum potential area ($ft^2$) |
|---|---|---|
| **Green roof** | 1,962,454 | 3,164,731 |
| **Swales** | 593,386 | 593,387 |
| **Planter box** | 31,646 | 31,647 |
| **Vegetated filter strips** | 593,386 | 593,387 |
| **Permeable sidewalk** | 553,618 | 553,619 |
| **Permeable driveway** | 672,504 | 672,505 |
| **Permeable parking** | 202,167 | 202,168 |
| **Rain garden** | 158,235 | 158,236 |
| **Total cost ($) – 10 year** | 63,890,533 | |
| **Total cost ($) – 50 year** | 72,076,005 | |

As a part of analysis, green infrastructure cost is compared to the cost of gray infrastructure implementation to remove the same amount of runoff (Table 16).

**Table 16. Comparison of Costs of Green and Gray Infrastructures within 100-Year Flood Zone**

| Time Horizon | Gray Infrastructure Cost ($) | Gray Infrastructure /Green Infrastructure cost |
|---|---|---|
| **10 year** | 47,828,193 | 0.74 |
| **50 year** | 65,071,351 | 0.9 |

**Table 17. Summary of Measures for Rainfall**

| Measure | Dimensions | Cost |
|---|---|---|
| Canal Gate at Long Slip (also for storm surge protection) | 100 feet length 24 feet height | $32,000,000 |
| Separation 1st Arrangement | 81,615 feet length | $48,969,000 |
| Separation 2nd Arrangement | 57,226 feet length | $34,335,600 |
| Flap Gate | 3 feet diameter | $4,500 |
| Pumping | 7MGD | $570,000[a] |
| Pumping | 84MGD | $3,200,000[a] |
| Green Infrastructure 10-year | 20,820,605ft$^2$ | $63,890,533 |
| Green Infrastructure 50-year | 20,820,605ft$^2$ | $72,076,005 |

[a] The pump station costs are based on the storm water. Since it is a combined sewer system, the pump station costs could be as high as that for the wastewater, which would be $5M and $50M, respectively.

# Jersey City

### Background

Using the NJ Flood Mapper Software, low lying areas have been identified along the Hudson River waterfront in Jersey City (Figure 30). Water levels are shown, as they would appear during highest tides excluding the one's driven by wind. In the following Figure 30, 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.

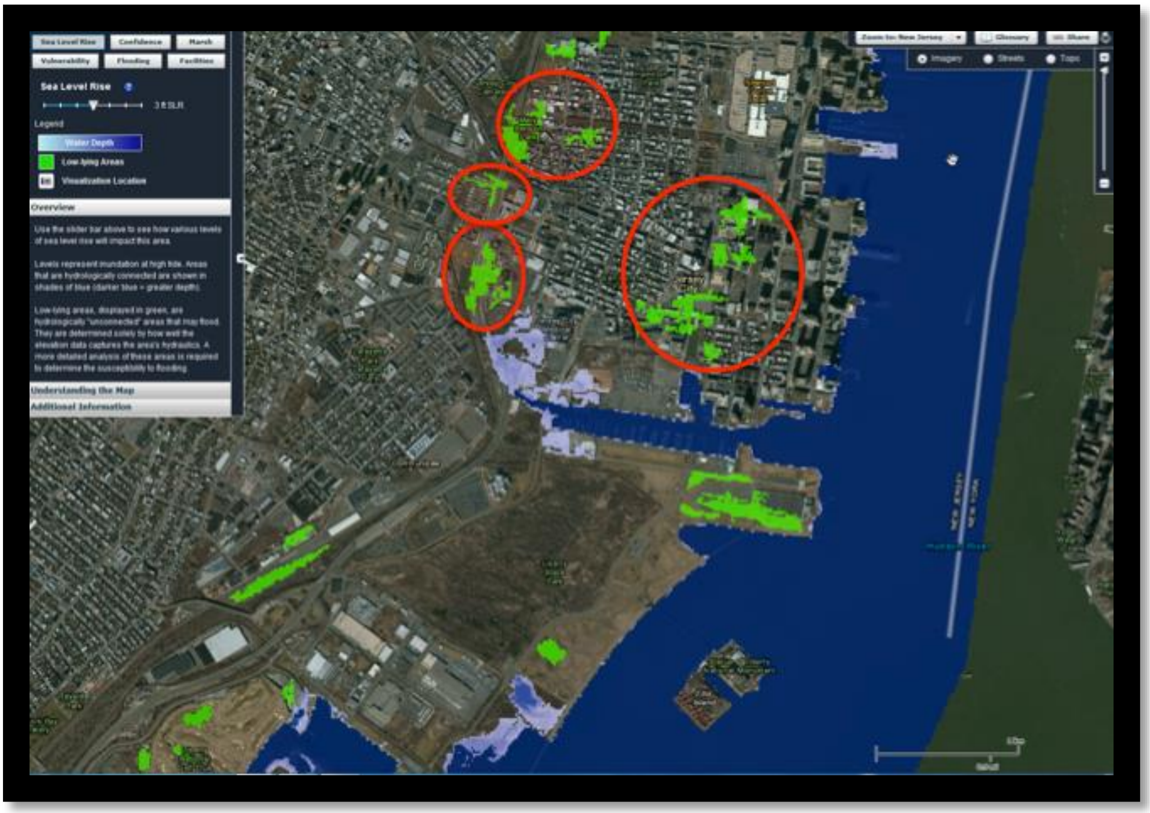


Figure 30: Flood Prone areas in Jersey City along Hudson River waterfront under 3 feet level rise scenario. Source: Flood Mapper Source: Flood Mapper, Rutgers University, in partnership with the Jacques Cousteau National Estuarine Research Reserve (JCNERR), and in collaboration with the NOAA Coastal Services Center (CSC).

The areas identified in Figure 30 as prone to flooding were investigated further to determine the impact of Hurricanes Sandy and Irene. The red circle drawn on Figure 30, 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 were also investigated (Figure 31).


Figure 31: Flood Prone areas in Jersey City along Newark Bay/Hackensack River Waterfront under 3 feet Level Rise Scenario.
Source: Flood Mapper, Source: Flood Mapper, Rutgers University, in partnership with the Jacques Cousteau National Estuarine Research Reserve (JCNERR), and in collaboration with the NOAA Coastal Services Center (CSC).

The areas identified in Figure 31 as prone to flooding were investigated further to determine the impact of Hurricanes Sandy and Irene. The red circles drawn on Figure 31 are specific areas, identified by the JCMUA as chronic flood areas.

***Drainage System:***

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 receiving waters 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. These pumps were delivered by July 2013 with the last one 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 protect the Downtown area from sewer water backing up during heavy rain.

Officials also commented that Jersey City should eventually move toward the separation of the sewer system. More options are available to handle the storage and disposal of stormwater 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 Figures 32 to 35 give the exact locations of these basins. Furthermore, Table 18 gives the area of each storm water basin.

**Table 18. 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 |

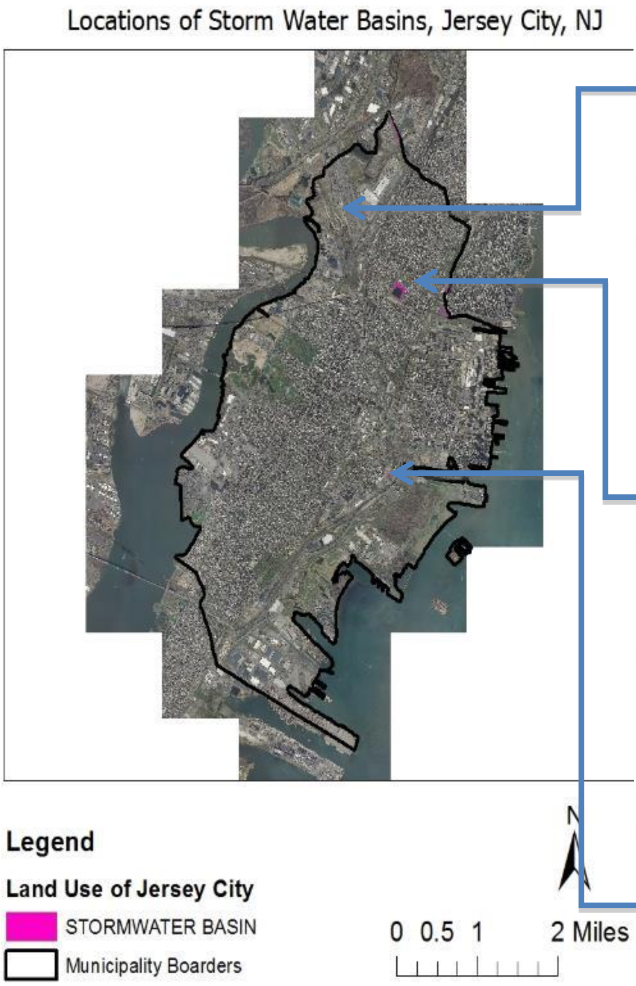


Figure 32: Storm Water Basin, Jersey City, NJ. Source: Jersey City Municipal Utilities Authority.

Figure 33: Storm Water Basin, Carol Ave, Jersey City, NJ

Figure 34: Storm Water Basin, Pershing Field, Jersey City, NJ

Figure 35: Storm Water Basin, Communipaw Ave, Jersey City, NJ

### Stormwater Threat

Rainfall and MHHW

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 (Figures 30 and 31).

### Municipal Stormwater Flood Mitigation Measures

0.25-year, 1-year, 2-year, 5-year-, 10-year & 25-year flood event with MHHW

***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 walkable 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
- I 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 36).


Figure 36: Direction of Existing Sewer System at Route 78, in Jersey City.
Source: Jersey City Municipal Utilities Authority.

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 37 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 19.

**Table 19. 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 | 1.8629 | 5,503,346 | 41.17 |
| 2- year | 3.3 | 2.4281 | 7,173,050 | 53.66 |
| 5-year | 4.2 | 3.2917 | 9,772,600 | 73.10 |
| 10-year | 5.0 | 4.0691 | 12,020,863 | 89.92 |
| 25-year | 6.2 | 5.4012 | 15,956,129 | 119.36 |


Figure 37: Drainage Area 1 Affected by the Green Belt under Route 78

Source: Jersey City Municipal Utilities Authority.

Some of the largest areas under Route 78 are green open spaces with no recreational development. The following Figures depict the existing conditions of the open spaces under Route 78. Areas of the route 78 between 9$^{th}$ and 8$^{th}$ 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 (Figures 38 -41).


Figure 38: Route 78, Jersey City. Source: Google Maps.

Figure 39: Area under Route 78 and 9th Str. Source: Google Maps.

Figure 40: Area under Route 78 and 8th Str. Source: Google Maps.

Figure 41: Area under Route 78 and Columbus Dr. Source: Google Maps.

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, RICS 2013). According to the land use map of Jersey City there are approximately 100 acres of land adjacent to 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 15 areas are ideal for green implementation around Route 78 (Figure 42). Also Table 20 gives the area of open spaces divided accordingly to its land use.

**Table 20. Division of Total Area Around Route 78 According to Land Use**

| Land Use | Total Area (acres) |
|---|---|
| Recreational/ Forest/ Deciduous Brush | 66 |
| Wetland | 2.20 |
| Urban & Built up Area | 31.80 |

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


Figure 42: Land Use of Open Spaces around Route 78.
Source: New Jersey Geographic Information Network.

***Measure 2: Surface Storage at Morris Marina***

It was discussed in the report at the level of threat of coastal storms 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

43) 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 following Table 21 gives hypothetical storage volumes assuming mean depths of 3 feet, 5 feet or 10 feet for each column. The surface storage volume for Morris Marina was calculated at 10 feet depth because this marina has the functionality of recreational boating and there is a limitation of the water depth that can be drained.

**Table 21. Surface Storage at Morris Marina**

| Total Area ft$^2$ | Volume with 3 feet depth (ft$^3$) | Volume with 5 feet depth (ft$^3$) | Volume with 10 feet depth (ft$^3$) |
|---|---|---|---|
| 1,857,312 | 5,571,936 | 9,286,560 | 18,573,210 |
| | **Volume with 3 feet depth (MG)** | **Volume with 5 feet depth (MG)** | **Volume with 10 feet depth (MG)** |
| | 41.68 | 69.46 | 138.94 |


Figure 43: Morris Marina Area, Jersey City, NJ
Source: New Jersey Geographic Information Network.
(https://njgin.state.nj.us/NJ_NJGINExplorer/index.jsp)

The amount of water that drains to this canal is determined from the adjacent drainage areas (Figure 44). Table 22 shows the amount of water that drains from those areas for 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 22. 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 | 1.9516 | 534,137 | 3.99 |
| 2-year | 3.3 | 2.5239 | 690,771 | 5.17 |
| 5-year | 4.2 | 3.3954 | 929,293 | 6.95 |
| 10-year | 5.0 | 4.1769 | 1,143,184 | 8.55 |
| 25-year | 6.2 | 5.5208 | 1,510,779 | 11.28 |


Figure 44: Drainage Area 2 located along the Morris Marina
Source: New Jersey Geographic Information Network.
(https://njgin.state.nj.us/NJ_NJGINExplorer/index.jsp)

A pump is recommended at Morris Marina in order to convey storm water to Hudson River. For the level of threat of 5-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 80 MG. It was shown earlier in Table 21 that the volume of the surface storage at Morris Marina for 10 feet depth is 138 MG of storage. A pump of 27 MGD is recommended in order to lower the water elevation in Morris Marina in three days prior to 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.

***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 drainage area 1 around Route 78 and the drainage basin area 2 next to Morris Marina (Figures 37 and 44). A total length of 180,638 sewer pipes has been calculated for separation.

***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. Table 23 summarizes the problem, our approach and source of floodwater. It represents associated runoff values for 1 and 2 year storm rainfalls. Land use map and associated curve number technique is applied to find the generated runoff for 1 and 2 year storm rainfalls. A description of the Green Infrastructure implementation software is included in Appendix A.

**Table 23. Runoff & Rainfall**

| | Rainfall from 1 year storm (in) | Rainfall from 2 year storm (in) | Runoff from 1 year storm (in) | Runoff from 2 year storm (in) | Area ($ft^2$) |
|---|---|---|---|---|---|
| **Jersey City** | 2.8 | 3.4 | 1.98 | 2.5 | 442,267,655 |

The minimum cost and optimal combination of green infrastructures are presented in Tables 24 and 25. Costs include the initial capital cost, replacement cost and yearly maintenance cost. However, according to planning time horizons that we select (10 year and 50 year) no green infrastructure is replaced.

**Table 24. Maximum runoff removal and associated cost by converting all potential areas to green**

| | |
|---|---|
| **Maximum runoff removal by converting all potential areas to green (in)** | **1.2** |
| **1 year storm : runoff removal percentage by converting all potential areas to green** | 60 |
| **2 year storm : runoff removal percentage by converting all potential areas to green** | 48 |
| **Cost ($) – 10 year** | 1,776,219,575 |
| **Cost ($) – 50 year** | 1,985,015,296 |

**Table 25. Optimal combination of green infrastructure and associated cost to remove 1 inch of runoff**

| | Optimal area ($ft^2$) for 1 inch runoff removal | Maximum potential area ($ft^2$) |
|---|---|---|
| **Green roof** | 41,545,106 | 67,454,398 |
| **Swales** | 12,648,286 | 12,648,286 |
| **Planter box** | 674,544 | 674,544 |
| **Vegetated filter strips** | 12,648,286 | 12,648,286 |
| **Permeable sidewalk** | 11,763,350 | 11,763,350 |
| **Permeable driveway** | 14,303,935 | 14,303,935 |
| **Permeable parking** | 4,298,331 | 4,298,331 |
| **Rain garden** | 3,372,720 | 3,372,720 |
| **Total cost ($) – 10 year** | 1,355,514,084 | |
| **Total cost ($) – 50 year** | 1,529,367,818 | |

As a part of analysis, green infrastructure cost is compared to the cost of gray infrastructure implementation to remove the same amount of runoff (Table 26).

**Table 26. Comparison of costs of green and gray infrastructures**

| Time Horizon | Gray Infrastructure Cost ($) | Gray Infrastructure /Green Infrastructure cost |
|---|---|---|
| **10 year** | 916,021,255 | 0.67 |
| **50 year** | 1,146,965,517 | 0.74 |

This green infrastructure implementation scenario also involves full utilization of all potential sites that are located within the 100-year flood zone. The scenario was assessed to determine the amount of runoff reduced, and the associated costs. The amount of runoff for rainfall events with 1 year return periods were investigated (Table 27). Potential sites were identified using land use maps. Only the areas characterized as commercial, industrial, residential, athletic fields, urban lands and built up lands are taken into consideration for green infrastructure implementation.

Maximum runoff capture: 1.2 inch

Cost to remove 1.2 inch of runoff (10 year horizon) = $ 403,325,484

Cost to remove 1.2 inch of runoff (50 year horizon) = $ 435,272,222

**Table 27. Characteristics of the areas in 100-year storm in under study towns**

| | Rainfall amount (1-Year Storm) (in) | Runoff from 1 year storm (in) | Total area ($ft^2$) | Area in 100 year flood zone ($ft^2$) | Excluded area ($ft^2$) | Area used for analysis ($ft^2$) | Percentage of area in the town |
|---|---|---|---|---|---|---|---|
| **Jersey City** | 2.8 | 1.98 | 442267655 | 247266169 | 150286147 | 96980022 | 22 |

The optimal combination of green Infrastructure measures to remove one inch of runoff within the 100-yr flood zone and their associated costs are shown in Table 28.

**Table 28. Optimal Combination of Green Infrastructure and Associated Cost to Remove 1 Inch of Runoff within 100-yr Flood Zone**

| | Optimal area ($ft^2$) for 1 inch runoff removal | Maximum potential area ($ft^2$) |
|---|---|---|
| **Green roof** | 9109970 | 14791335 |
| **Swales** | 2773504 | 2773504 |
| **Planter box** | 147913 | 147913 |
| **Vegetated filter strips** | 2773504 | 2773504 |
| **Permeable sidewalk** | 2579456 | 2579456 |
| **Permeable driveway** | 3136553 | 3136553 |
| **Permeable parking** | 942534 | 942534 |
| **Rain garden** | 739567 | 739567 |
| **Total cost ($) – 10 year** | 297,235,809 | |
| **Total cost ($) – 50 year** | 335,358,286 | |

As a part of analysis, green infrastructure cost is compared to the cost of gray infrastructure implementation to remove the same amount of runoff (Table 29).

**Table 29. Comparison of costs of green and gray infrastructures**

| Time Horizon | Gray Infrastructure Cost ($) | Gray Infrastructure /Green Infrastructure cost |
|---|---|---|
| **10 year** | 222,566,038 | 0.74 |
| **50 year** | 302,813,413 | 0.9 |

**Table 30. Summary of Measures for Rainfall**

| Measure | Dimensions | Cost |
|---|---|---|
| Green Belt | 100 acres | $12,196,800 |
| Canal Gate at Morris Canal (also for Storm Surge Protection) | 200 feet length 24 feet height | $64,000,000 |
| Separation | 180,638 feet length | $108,382,800 |
| Flap Gate | 3 feet diameter | $4,500 |
| Pumping | 27MGD | $1,500,000[b] |
| Green Infrastructure 10-year | 96,980,022 $ft^2$ | $297,235,809 |
| Green Infrastructure 50-year | 96,980,022 $ft^2$ | $335,358,286 |

[b] The pump station cost is based on the stormwater. Since it is a combined sewer system, the pump station cost could be as high as that for the wastewater which would be $20M.

## Block and Lot Scale

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.

In 2011, Hurricane Irene left much of Route 440 flooded and impassable and resulted in major traffic and transit delays. The intersections identified to be constantly flooded are:

- Intersection of Route 440 and Communipaw Avenue (Figure 46).
- Intersection of Route 440 and Pollock Avenue (Figure 47).
- Intersection 440 and Culver Avenue (Figure 48).

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. Table 31 shows the cost of elevating the road from the intersection at Communipaw Avenue up to Culver Avenue, of the length of 0.68 miles, for 5 different elevations. This length consists the part of Route 440, which experiences frequent flooding.

**Table 31. Cost of Elevating Route 440, Jersey City for the Entire Length of Road**

| Measure Elevation of Road | 1 feet | 2 feet | 3 feet | 4 feet | 5 feet |
|---|---|---|---|---|---|
| Cost | $1,088,000 | $2,176,000 | $3,264,000 | $4,352,000 | $5,440,000 |

In this report, only the appropriate length of Route 440 at the above three intersections for the same 5 different elevations was investigated (Table 32). 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.

**Table 32. Cost of Elevating Route 440, Jersey City at Intersections Only**

| Measure Elevation of Road | 1 feet | 2 feet | 3 feet | 4 feet | 5 feet |
|---|---|---|---|---|---|
| Cost | $86,400 | $172,800 | $259,200 | $345,600 | $432,000 |

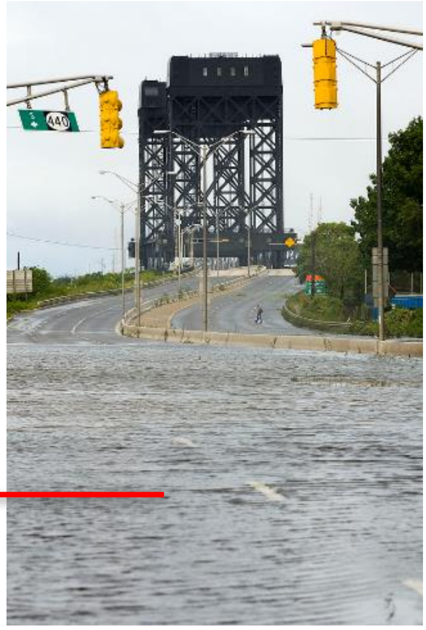

Figure 46: Intersection Route 440 & Communipaw Avenue.
Source: http://reenarose.com/blog/?p=4236.

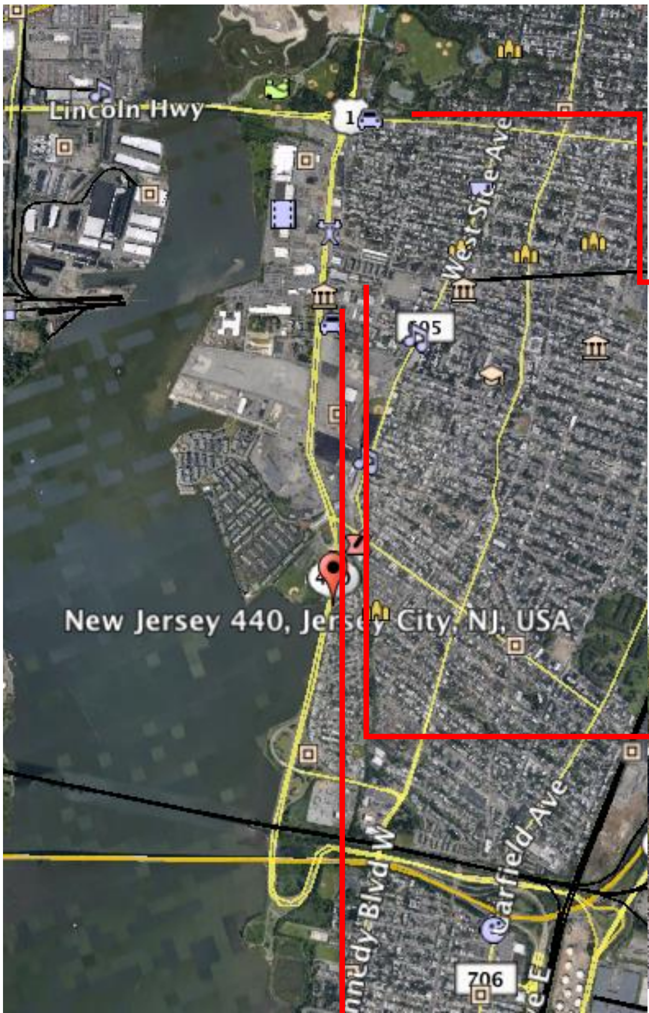


Figure 45: Route 440, Jersey City.
Source: Google Maps.


Figure 47: Intersection Route 440 & Pollock Avenue.
Source: [http://www.nj.com/hudson/index.ssf/](http://www.nj.com/hudson/index.ssf/)
2011/08/you_dont_see_this_every_day_je.html.


Figure 48: Intersection Route 440 & Culver Avenue.
Source: http://reenarose.com/blog/?p=4236.

*Summary Cost Table for Coastal Flood Mitigation Measures*

**Table 33. Summary of Coastal Flood Mitigation Measures**

**Regional Flood Measure, Bulkhead and Steel Flood Wall along Hudson River**

| Protection Level | Wall Height | Cost |
|---|---|---|
| **10 - Year Storm** | 12 feet | $330,000,000 |
| **50 - Year Storm** | 16 feet | $360,000,000 |
| **100 - Year Storm** | 16 feet | $360,000,000 |
| **100 – Year Storm + 2050 SLR** | 16 feet | $360,000,000 |
| **100 – Year Storm + 2100 SLR** | 20 feet | $380,000,000 |

**Regional Flood Measure, Bulkhead and Steel Flood Wall along Newark Bay**

| Protection Level | Wall Height | Cost |
|---|---|---|
| **10 - Year Storm** | 12 feet | $280,000,000 |
| **50 - Year Storm** | 16 feet | $300,000,000 |
| **100 - Year Storm** | 16 feet | $300,000,000 |
| **100 – Year Storm + 2050 SLR** | 16 feet | $300,000,000 |
| **100 – Year Storm + 2100 SLR** | 20 feet | $330,000,000 |

**Regional Flood Measure, Canal Gates**

| Long Slip | Length | Height | Cost |
|---|---|---|---|
| **100 – Year Storm + 2100 SLR** | 100 feet | 24 feet | $32,000,000 |

| Morris Marina | Length | Height | Cost |
|---|---|---|---|
| **100 – Year Storm + 2100 SLR** | 200 feet | 24 feet | $64,000,000 |

**Flood Barriers for Hoboken Only**

| Measure | Dimensions | Cost |
|---|---|---|
| Roadway Floodgate | 612 feet length and 5 feet height | $765,000 |
| Conventional Concrete Floodwall | 5,305 feet length and 5 feet height | $5,000,000 |

*Summary Cost Table for Stormwater Flood Mitigation Measures*

**Table 34. Summary of Stormwater Flood Mitigation Measures**

| Municipality | Threat | Measure | Dimensions | Cost |
|---|---|---|---|---|
| **Hoboken** | **Storm Surge (also)** | Canal Gate at Long Slip | 100 feet length 25 feet height | $32,000,000 |
| | **Rainfall +MHHW** | Separation 1st Arrangement | 81,615 feet length | $48,969,000 |
| | | Separation 2nd Arrangement | 57,226 feet length | $34,335,600 |
| | | Flap Gate | 3 feet diameter | $4,500 |
| | | Pumping | 7MGD | $570,000 |
| | | Pumping | 84MGD | $3,200,000 |
| | | Green Infrastructure 10-year | $20{,}820{,}605 ft^2$ | $63,890,533 |

| | | | | |
|---|---|---|---|---|
| | | Green Infrastructure 50-year | 20,820,605ft$^2$ | $72,076,005 |
| **Jersey City** | **Storm Surge (also)** | Canal Gate at Morris Canal | 200 feet length 25 feet height | $64,000,000 |
| | **Rainfall +MHHW** | Green Belt | 100 acres | $12,196,800 |
| | | Separation | 180,638 feet length | $108,382,800 |
| | | Flap Gate | 3 feet diameter | $4,500 |
| | | Pumping | 27MGD | $1,500,000 |
| | | Green Infrastructure 10-year | 96,980,022 ft$^2$ | $297,235,809 |
| | | Green Infrastructure 50-year | 96,980,022 ft$^2$ | $335,358,286 |

## References

**Climate Central, 2012.** Sea level rise and coastal flood risk for Hoboken, New Jersey. Surging Seas. Online at

http://ssrf.climatecentral.org/#location=NJ_Town_3432250&state=New+Jersey&level=5&folder=All&geo=County&pt=&p=L.

**City of Hoboken, 2013**. Community Resiliency & Readiness Plan. Online at http://www.hobokennj.org/resiliency/. Accessed December 23, 2013.

**European Union, 2010.** Making our Cities Attractive and Sustainable. Online http://ec.europa.eu/environment/pubs/pdf/urban/cities_of_the_future.pdf

**FEMA Map Service Center**. National Flood Hazard Layer Database. Online https://hazards.fema.gov/femaportal/NFHL/

**Flood Mapper**, Rutgers University, in partnership with the Jacques Cousteau National Estuarine Research Reserve (JCNERR), and in collaboration with the NOAA Coastal Services Center (CSC). Online http://slrviewer.rutgers.edu

**Jersey City, 2008**. Jersey City Stormwater Management Plan.

**Miller, K. G., R. E. Kopp, B. P. Horton, J. V. Browning, and A. C. Kemp, 2013.** A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast, Earth's Future, doi:10.1002/2013EF000135.

**National Hurricane Center, 2013.** Tropical Cyclone Report Hurricane Sandy 22-29 October 2012. Online http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf

**North Hudson Sewer Authority (NHSA), 2002.** Southwest Hoboken Flooding Analysis.

**North Hudson Sewerage Authority (NHSA), 2011.** North Hudson Sewerage Authority Opens Hoboken H-1Wet Weather Pump Station. Press Release, October 17.

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

**RICS, 2013.** Green Infrastructure in Urban Areas. Online http://www.joinricsineurope.eu/uploads/files/GreenInfrastructureInformationPaper1stEdition.pdf

**Spinello, Steve, 2013.** Dramatic downgrade for FEMA flood maps but 75% of Hoboken still in high-risk flood areas. June 18. Fund for a Better Waterfront. Online at http://betterwaterfront.org/revised-fema-flood-maps-slightly-downgrade-hobokens flood-risk/.

**Together North Jersey, 2013**. Hoboken Green Infrastructure Strategic Plan. http://togethernorthjersey.com/wp-content/uploads/2014/04/20140404_Hoboken-Report_sm.pdf

**Van Abs, Daniel, Alexander McClean, Ioanna Tsoulou, Yuling Gao and Tim Evans, 2014.** Water Infrastructure in New Jersey's CSO Cities: Elevating the Importance of Upgrading New Jersey's Urban Water Systems. Rutgers-The State University of New Jersey, New Brunswick, NJ.

RELATED REPORTS AND PUBLICATIONS

Guo, Qizhong, Bertrand Byrne, Jie Gong, Raghav Krishnamoorthy, and Henry Mayer, 2014. Strategies for Flood Risk Reduction for Vulnerable Coastal Populations along Arthur Kill at Elizabeth, Linden, Rahway, Carteret and Woodbridge. Rutgers, The State University of New Jersey, August.

Guo, Qizhong, Yunjie Li, Michael J. Kennish, Norbert P. Psuty, Richard G. Lathrop Jr., James L. Trimble, 2014. Strategies for Flood Risk Reduction for Vulnerable Coastal Populations around Barnegat Bay. Rutgers, The State University of New Jersey, August.

Guo, Qizhong, David Bushek, Richard G. Lathrop Jr., Junghoon Kim, Bertrand Byrne, James L. Trimble, 2014. Strategies for Flood Risk Reduction for Vulnerable Coastal Populations around Delaware Bay. Rutgers, The State University of New Jersey, August.

Guo, Qizhong, Robert Miskewitz, Manoj Raavi, Carolyn Loudermilk, Meiyin Wu, Josh Galster, Clement Alo, Robert Prezant, Jason Beury, Tony Macdonald, Jim Nickels, 2014. Strategies for Flood Risk Reduction for Vulnerable Coastal Populations along Hackensack River at Little Ferry and Moonachie. Rutgers, The State University of New Jersey, August.

Guo, Q. (2013). Automatic Vacuum Flushing Technology for Combined Sewer Solids, IWA Publishing, ISBN: 9781780400471.

Guo, Q. and Correa, C. A., 2013. "The Impacts of Green Infrastructure on Flood Level Reduction for the Raritan River: Modeling Assessment." Proceedings of the ASCE/EWRI World Environmental & Water Resources Congress, Cincinnati, Ohio, May 19-23.

Guo, Q., Kantor, P., Roberts, F., and Robinson, D., 2012. Risk Analysis for Flood Mitigation on the Raritan, Final Report, CCICADA - Command, Control, and Interoperability Center for Advanced Data Analysis, Submitted to Federal Emergency Management Agency via Rutgers Bloustein Planning School, April 30.

# Appendices

### Appendix 1-Stormwater Green Infrastructure Methodology

## Green Infrastructure Deployment: Introduction and Methodology

By Qizhong Guo, Kaveh Gharyeh, and Manoj Raavi

**1) Green Infrastructure**

Green Infrastructure or Blue-green infrastructure is a network providing the "ingredients" for solving urban and climatic challenges by building with nature. The main components of this approach include storm water management, climate adaptation, less heat stress, more biodiversity, food production, better air quality, sustainable energy production, clean water and healthy soils, as well as the more anthropocentric functions such as increased quality of life through recreation and providing shade and shelter in and around towns and cities. Figure 1 shows several green infrastructures that are commonly implemented in different locations.

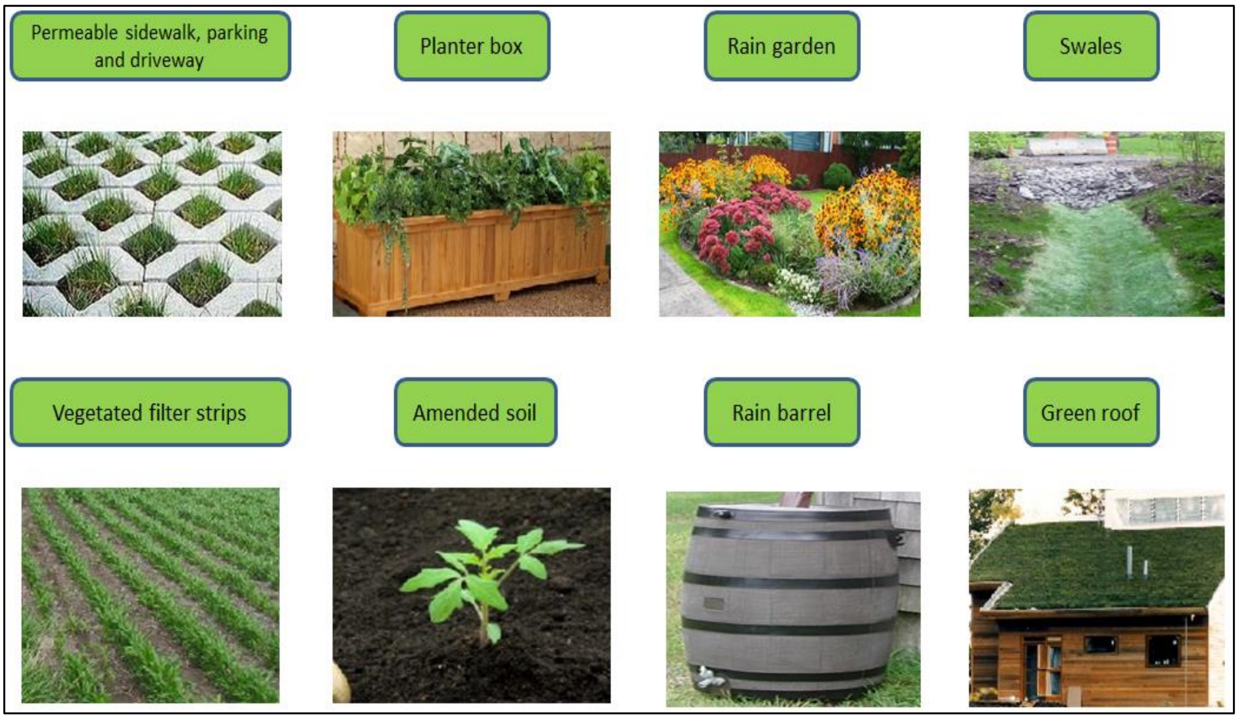


Figure 3 : Green Infrastructure types

US Department of Environmental Protection (DEP) is conducting a comprehensive research to quantify non-stormwater benefits of green infrastructure deployment [1]. For instance, City of Hoboken, New Jersey, is conducting a green infrastructure strategic plan to develop place–based stormwater management and flood control strategies and identify implementable climate adaptation action steps. More details of the Hoboken Green Infrastructure Strategic plan is available on [2]. There are other ongoing green infrastructure projects in a number of cities all around the U.S such as Philadelphia, New York City, San Francisco, Chicago, Seattle and St. Louis. More details of these projects are available on [3], [4], [5], [6], [7] and [8] respectively.
Green infrastructure can reduce the volume of water going into combined systems during precipitation events by removing surface runoff, which may reduce number and volume of overflows. Green infrastructure can also slow the delivery of wet weather flows to sewer systems, helping to mitigate peak flows while providing filtration through soil for some portion of the release into the sewer system, thereby reducing pollutant loads. The implementation of green infrastructure practices may allow communities to downsize certain grey infrastructure components of their CSO control plans. This may provide some CSO communities with significant cost savings [9]. By implementing Green Infrastructure, need for piping, pumping and storage of stormwater could be reduced. In this project, the main reason to consider green infrastructures deployment is also to reduce the stormwater inflow to the drainage

---

[1] NYC Environmental Protection website: http://www.nyc.gov/html/dep/html/stormwater/nyc_green_infrastructure_pilot_monitoring_results.shtml
[2] http://togethernorthjersey.com/?grid-portfolio=hoboken-green-infrastructure-strategic-plan
[3] http://www.phillywatersheds.org/whats_in_it_for_you/businesses/green-infrastructure-projects
[4]http://www.nyc.gov/html/dep/html/stormwater/green_infrastructure_slideshow.shtml
[5] http://sfwater.org/index.aspx?page=614
[6]http://www.seattle.gov/util/MyServices/DrainageSewer/Projects/GreenStormwaterInfrastructure/index.htm
[7] http://www.stlmsd.com/educationoutreach/msdgreeninitiatives
[8] http://www.epa.state.il.us/water/financial-assistance/igig.html
[9] http://water.epa.gov/infrastructure/greeninfrastructure/upload/EPA-Green-Infrastructure-Factsheet-2-061212-PJ.pdf

system by removing fraction of runoff. Table 1 summarizes the problem, our approach and source of floodwater.

**Table 1: Problem and solution description**

| | |
|---|---|
| **Problem to solve** | Reduce surface floodwater inlet to the drainage system |
| **Approach** | Removal of runoff by using optimal combinations of green infrastructures |
| **Source of floodwater** | Rainfall only (1 year and 2 year return periods) |

**2) Software developed**

Online software is developed to calculate the total cost (capital, maintenance and replacement) of implementing the green infrastructures. Unlike available online softwares, the developed software is capable of fining out the most cost effective combination of different green infrastructures that can be implemented in any location. Spatial limitations for implementing any of the green infrastructure types are taken into consideration. Net Present Value (NPV) approach is used to calculate the total cost of implementing green infrastructure. Total cost includes the initial capital cost, maintenance cost and also replacement cost. Figure 2 shows a snap shot of a page of the developed software.

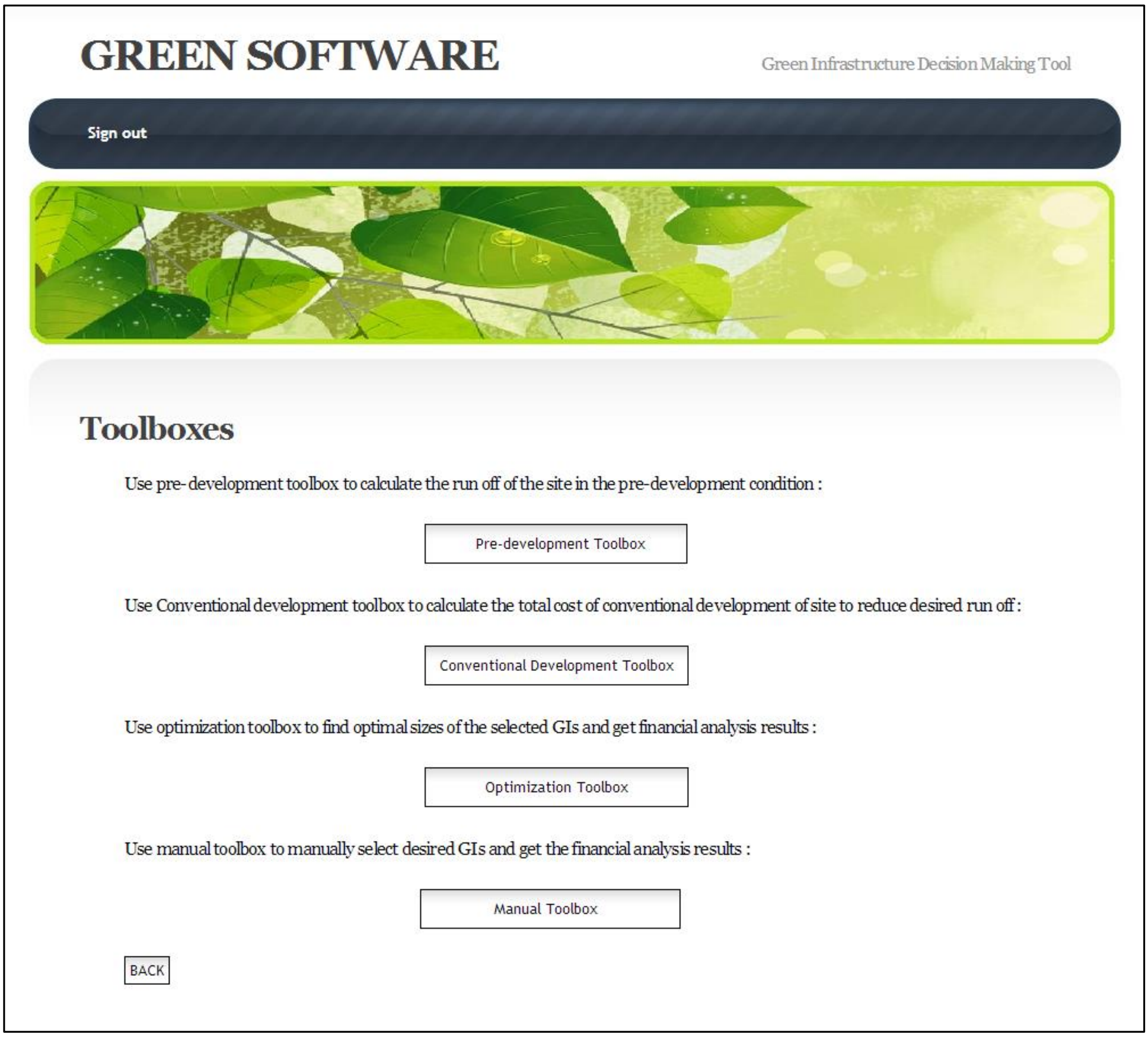


Figure 4 : Snapshot of the Green Software

The software interface is developed in JAVA, however the inside optimization engine is coded in MATLAB and then converted to JAVA packages.

**3) Different sites spatial characteristics and limitations**

In order to find out the total area of each site under research, GIS data is used. In addition the maximum area for implementing each of the green infrastructure types is found out via the following procedure for residential, industrial and commercial units.

3.1) Procedure

Step 1: Selection of Municipality

From the New Jersey state map of municipalities, select the municipalities required and make a layer from the selected municipality. Figure 2, shows a sample layer.

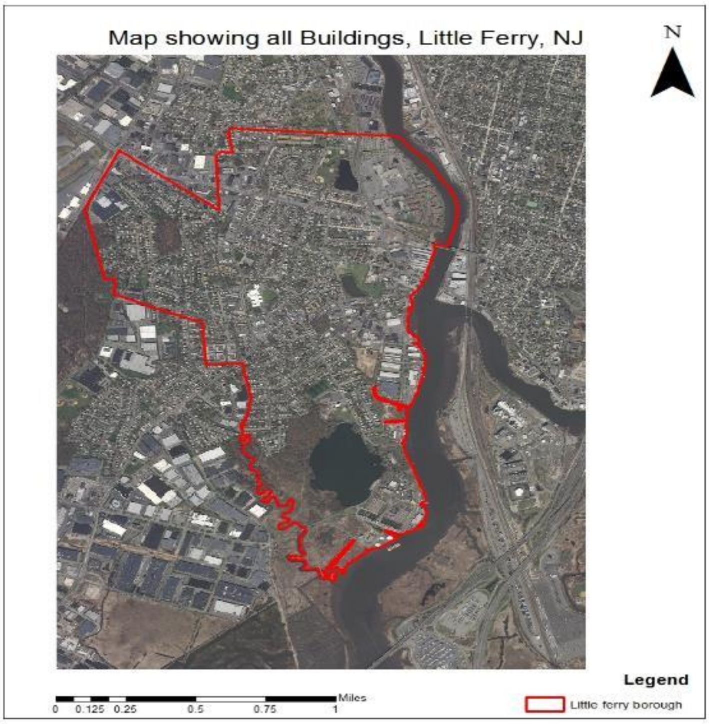


**Figure 5 : Sample layer of a municipality**

Step 2: Finding out maximum area to implement green roofs, permeable driveway and parking

For each type of residential units (i.e. low, medium and high density), three unique polygons are chosen. For each polygon the area of roof, parking and driveway are extracted. The average ratio of roofs, parking and driveway is multiplied to the total area of residential area of the municipality to find out the approximate total areas of roofs, parking and driveways. The same procedure repeats for the industrial and commercial sectors. For example, in order to find out the total area of roof, parking and driveway of the high density or multiple dwelling residential units in Hoboken, New Jersey, three sample polygons of high density residential units are selected. Table 2 shows the extracted information of the aforementioned polygons.

**Table 2 : Extracted information for three selected polygons**

| | Total Area($ft^2$) | Roof($ft^2$) | Parking($ft^2$) | Driveway($ft^2$) |
|---|---|---|---|---|
| **Polygon 1** | 216372 | 68388 | 18448 | 19041 |
| **Polygon 2** | 91164 | 29973 | 11780 | 9383 |
| **Polygon 3** | 119191 | 47149 | 14733 | 12434 |

Table 3 represents the ratio of roof, parking and driveway area to the total area for each polygon.

**Table 3: Ratio of roof, parking and driveway in each polygon**

| | Percentage of roof area in polygon | Percentage of parking area in polygon | Percentage of driveway area in polygon |
|---|---|---|---|
| **Polygon 1** | 31.6 | 8.5 | 8.8 |
| **Polygon 2** | 32.9 | 12.9 | 10.3 |
| **Polygon 3** | 39.5 | 12.3 | 10.4 |
| **Average** | 34.6 | 11.2 | 9.8 |

By using the average ratios and multiplying in the total high density residential units' area, the total area of roof, parking and driveway of this class of residential units are calculated as shown in Table 4.

**Table 4: Hoboken high density residential units estimated roof, parking and driveway area**

| Roof($ft^2$) | Parking($ft^2$) | Driveway($ft^2$) | Total area of high density residential units ($ft^2$) |
|---|---|---|---|
| 6221824 | 2014001 | 1762250 | 17982151 |

Exactly the same procedure is carried out for industrial and commercial sectors of the municipality and the results are summed up to come up with the maximum spatial limitation to deploy each of the green infrastructures.

Step 3: Finding out maximum area to implement permeable roadway and sidewalk

By getting the map of NJ road networks and clipping it for the area of the required municipality, we can find the total length of the road network. From this we can find the length of the road where sidewalks is present. By multiplying the width of the side walk we can find the area of the pavement where we can apply permeable sidewalk. The average width of the side walk for the major highway is calculated from the widths measured at several selected locations (by using the GIS measure tool). The average width was found to be 6ft on each side of the roadway. Considering the intersections of roadways, roadways with sidewalk on only one side and roadways without a sidewalk on both sides, only 50% of the total length of roadways in the town is used to calculate the area of sidewalk.

Step4: Finding out maximum area to implement rain gardens, swales, vegetated filter strips and planter box

For calculating the area of the site where rain gardens can be installed, we have assumed that the area of rain gardens will be 5% of the roof area. For calculating the area where vegetative swales and vegetative filter strips can be installed, we assumed a percentage of 80% of the length of sidewalk will be accessible for installing swales and remaining 20% will be used to install vegetated filter strip. For planter box implementation, we need to assume a percentage of area of the total roof area to find the area where the planter boxes can be installed. We assumed it to be 1% of total roof area.

**4) Default values used in the software**

In order to carry out the cost and the optimal combination calculations, the porosity and depth of each of green infrastructures are set to default values as shown in Table 5. However, values other than default values can simply be entered as inputs to the developed software.

**Table 5: Default values for porosity and depth of green infrastructures**

| | |
|---|---|
| Permeable sidewalk depth (in) | 12 |
| Permeable sidewalk porosity | 0.35 |
| Permeable parking depth (in) | 12 |
| Permeable parking porosity | 0.35 |
| Permeable driveway depth (in) | 12 |
| Permeable driveway porosity | 0.35 |
| Bioswales depth (in) | 12 |
| Bioswales porosity | 0.35 |
| Green roof depth (in) | 12 |
| Green roof porosity | 0.35 |
| Planter box prepared soil depth (in) | 12 |
| Planter box aggregate soil depth (in) | 12 |
| Planter box prepared soil porosity | 0.35 |
| Planter box aggregate soil porosity | 0.35 |
| Rain garden prepared soil depth (in) | 12 |
| Rain garden aggregate soil depth (in) | 12 |
| Rain garden prepared soil porosity | 0.35 |
| Rain garden aggregate soil porosity | 0.35 |
| Vegetated filter strips depth (in) | 12 |
| Vegetated filter strips porosity | 0.35 |

Unit capital and maintenance costs along with life time of each type of green infrastructure are also presented in table 6. Long lifetime of green infrastructure types is considered.

**Table 6: Unit capital and maintenance costs and life time of each green infrastructure type**

| Green Infrastructure type | Capital cost ($/ft$^2$) | Yearly maintenance cost ($/ft$^2$) | Life time (Years) |
|---|---|---|---|
| Permeable sidewalk, driveway and parking (Asphalt) | 6.65 | 0.17 | 50 |
| Permeable sidewalk, driveway and parking (Cement) | 7.70 | 0.16 | 50 |
| Permeable sidewalk, driveway and parking (Gravel) | 4.01 | 0.02 | 50 |
| Bioswale | 14.80 | 0.13 | 50 |
| Planter Box | 11 | 0.61 | 50 |
| Rain Garden | 9.4 | 0.41 | 50 |
| Green Roof | 18.76 | 0.15 | 50 |
| Vegetated Filter Strip | 1.6 | 0.07 | 50 |

Reference: [[10]]

As a part of analysis, green infrastructure cost is compared to the cost of gray infrastructure implementation to remove the same amount of runoff. The gray infrastructure cost includes onsite underground retention/detention system [[11]] cost, and required cost of standard roof, pavement, driveway and parking lot. In our methodology, we do not take into consideration the replacement cost of standard roof, pavement, driveway and parking lot to green infrastructure. In other words, we assume that we conduct a new development. Table 7 provides detailed information applied for gray infrastructure cost calculation.

[10] http://greenvalues.cnt.org/national/cost_detail.php
[11] http://water.epa.gov/scitech/wastetech/upload/2002_06_28_mtb_runoff.pdf

Also note that some existing green infrastructure measures such as amended soil, rain barrels, and vertical walls are not included in the software. The software can be expanded to include these existing measures as well as the future emerging measures.

**Table 7: Detailed data required for Gray Infrastructure cost calculation**

| Infrastructure type | Capital cost | Yearly maintenance cost ($/ft$^2$) | Life time (Years) |
|---|---|---|---|
| Concrete Sidewalk | 5.19 ($/ft$^2$) | 0.029 | 80 |
| Concrete Driveway | 5.19 ($/ft$^2$) | 0.029 | 80 |
| Parking Lot | 5.51 ($/ft$^2$) | 0.15 | 30 |
| Standard Roof | 7.5 ($/ft$^2$) | 0.05 | 30 |
| onsite underground retention/detention system | 11.55 ($/ft$^3$) | 0.03 | 30 |

## Appendix 2-Unit Cost Tables

# Unit Cost Tables

## Table 1 Unit Costs for Storm Surge Barrier

| Measures | Unit & Unit | Reference |
|---|---|---|
| Levee | Clay levee: 4000 to 8000 $/linear foot | http://www.stronglevees.com/cost/ |
| | T-walls: 14000 to 19000 $/linear foot | http://www.stronglevees.com/cost/ |
| | Double wall levee: 5000 to 6000 $/linear foot | http://www.stronglevees.com/cost/ |
| Levee raise | 1) Levee raise with a floodwall (unit cost per linear foot)<br>1-foot raise: $37<br>1-to 3-foot raise: $120<br>Greater than 3-foot raise: $875<br><br>2) Levee raise by fill (unit cost per linear foot)<br>1-foot raise: $31<br>1-to 3-foot raise: $45<br>Greater than 3-foot raise: $87 | http://www.papiopartnership.org/projects/damsite_15a_2_221441182.pdf |
| Sea Wall | 300 $/linear foot | Contacted Jeff Patterson |
| | 300 to 400$ per foot for walls 7' in height | Contacted Gary Kalke |
| Beach Nourishment | 6.67 $ /cy @ 2011 @ Florida | Page 6 of : http://fsbpa.com/2012TechPresentations/AlBrowder.pdf |
| Bulkhead | 3000 $/lf | Contacted : Tom Levy |
| Elevate Buildings | @New Jersey $ 60 per square feet | http://www.markofexcellence.com/house-lifting.html |
| Wetland Restoration | Very wide range, $900-$90,000/acre | http://www.edc.uri.edu/restoration/html/tech_sci/socio/costs.htm |
| Flood wall sheet pile | @2014 : 25 $/sf | http://www.icgov.org/site/CMSv2/Auto/construction/bid338/212201431318.pdf |
| Road elevation | ~ 1.6 M$ per mile per foot elevation | http://marylandreporter.com/2013/08/01/rising-seas-5-800-miles-of-roads-at-risk-especially-in-shore-counties/ |
| Removable Flood Wall | 100$ per square feet | Contacted : Mr. Bryan Fryklund @ Flood Control America (FCA) |

**Table 2 Unit Costs for Mobile Flood Barrier**

| Measures | Cost & Unit | Reference |
|---|---|---|
| Muscle Wall | -2' Muscle Wall 50 $/LF excludes tax, installation, liner, sandbags, Muscle Wall accessories<br>-4' Muscle Wall 99 $/LF excludes tax, installation, liner, sandbags, Muscle Wall accessories<br>-8' Muscle Wall 525 $/LF excludes tax, installation, liner, sandbags, Muscle Wall accessories | Contacted Organic Industries Flood, LLC |
| Slide gate (12X6 ft^2) | @ 2014: 47,000 $ EA | http://www.icgov.org/site/CMSv2/Auto/construction/bid338/212201431318.pdf |
| Flood barrier (In water closure) | $880 x length (ft) x height (ft) x design head difference (ft) | Reconnaissance Level Study Mississippi Storm Surge Barrier, by Van Ledden et al. (2011) |
| Sand bag | Average cost of a pre-filled 50 lbs sandbag = $2.25 | http://barriersystemsllc.com/make-money.php |

**Table 3 Unit Costs for Diversion**

| Measures | Unit & Unit | Reference |
|---|---|---|
| Sewer | PVC Sewer Pipe, 8 Inch Diameter: Unit: LF cost: $300<br><br>10/12 inch can be installed with a box, use $300-$350 per foot | Bid Tabulation for Horseshoe Bend Levee Improvements Project ( Phase II) – Bidder : SCI Infrastructure, LLC |

**Table 4 Unit Costs for Tide Barrier**

| Measures | Cost & Unit | References |
|---|---|---|
| Flap gates | Diameter: 2 ft : $3,000<br>Diameter: 3 ft : $4,500<br>Diameter: 6 ft :$15,000 | Contacted: hydro power company : http://www.hydrogate.com/sales-reps.aspx?S=NJ |
| | 72" X 72" FLAP gate @ 2008 : 35,000 $ | http://www.rcgov.org/pdfs/Public-Works/1736%20Levee%20Storm%20Sewer%20Flap%20Gates.pdf |
| | @2012 @CITY OF KENT : Flap Gate for 24 Inch Pipe 1 EA 5,200<br>Flap Gate for 8 Inch Pipe 1 EA 2,500<br>Flap Gate for 12 Inch Pipe 1 EA 3, 000<br>Flap Gate for 48 Inch Pipe 1 EA 9, 000 | Bid Tabulation for Horseshoe Bend Levee Improvements Project ( Phase II) – Bidder : SCI Infrastructure, LLC |
| | @ 2013 @ Kansas:<br>Flap gate: 24" cost: 2500 EA<br>Flap gate: 30" cost: 3000 EA | http://www.hutchgov.com/egov/docs/13831420807713.pdf |
| Sluice gate | Sluice gates, cast iron<br><br>Hydraulic structures, 18" x 18", HD, self cont with crank, sluice Detail $ 7,764.89 / EA<br>Hydraulic structures, 24" x 24", HD, self cont with crank, sluice Detail $ 10,011.41 / EA<br>Hydraulic structures, 30" x 30", HD, self cont with crank, sluice Detail $ 11,828.56 / EA<br>Hydraulic structures, 36" x 36", HD, self cont with crank, sluice Detail $ 13,627.37 / EA<br>Hydraulic structures, 42" x 42", HD, self cont with crank, sluice Detail $ 16,221.16 / EA<br>Hydraulic structures, 48" x 48", HD, self cont with crank, sluice Detail $ 19,026.87 / EA<br>Hydraulic structures, 54" x 54", HD, self cont with crank, sluice Detail $ 26,137.59 / EA<br>Hydraulic structures, 60" x 60", HD, self cont with crank, sluice Detail $ 31,611.97 / EA<br>Hydraulic structures, 66" x 66", HD, self cont with crank, sluice Detail $ 36,680.48 / EA | http://www.allcostdata.info/browse.html/059110009 |

| | | |
|---|---|---|
| | Hydraulic structures, 72" x 72", HD, self cont with crank, sluice Detail $ 43,605.95 / EA<br>Hydraulic structures, 78" x 78", HD, self cont with crank, sluice Detail $ 48,429.74 / EA<br>Hydraulic structures, 84" x 84", HD, self cont with crank, sluice Detail $ 64,999.97 / EA<br>Hydraulic structures, 90" x 90", HD, self cont with crank, sluice Detail $ 60,630.76 / EA<br>Hydraulic structures, 96" x 96", HD, self cont with crank, sluice Detail $ 67,440.10 / EA<br>Hydraulic structures, 108" x 108", HD, self cont with crank, Detail $ 87,380.36 / EA<br>Hydraulic structures, 120" x 120", HD, self cont with crank, Detail $ 117,696.03 / EA<br>Hydraulic structures, 132" x 132", HD, self cont with crank, Detail $ 168,117.06 / EA | |

**Table 5 Unit Costs for Pumping Station**

| Measures | Cost & Unit | References |
|---|---|---|
| Pump station | For stormwater, $C = 149055\ Q^{0.6907}$, where C = cost ($), Q = pump flow rate (cfs) | C-111 Spreader Canal Western Project Final Project Implementation Report (PIR) and Environmental Impact Statement (EIS) Final - January 2011: Appendix B - Cost Estimates http://www.evergladesplan.org/pm/projects/docs_29_c111_pir.aspx |
| | For wastewater, $ 750,000 at 0 – 0.99 MGD, $ 2M at 1.00 – 4.99 MGD, $ 5M at 5.00 – 9.99 MGD, $12.5M at 10.00 – 24.99 MGD, $ 22.5M at 25.00 – 49.00 MGD, $ 35M at 50.00 – 74.00 MGD, and $ 50M at 75.00 or larger MGD. | New Hampshire Department of Environmental Services - Water Division http://des.nh.gov/organization/divisions/water/wweb/documents/ar_appendix_g.pdf |

,

## Table 6 Unit Costs for Conveyance

| Measures | Cost & Unit | | References |
|---|---|---|---|
| Culvert | | | |
| Size | material | Price | |
| 12” x 10” | Steel | 104 | https://shop.mccoys.com/farm-ranch-yard/culverts/steel-culverts-and-accessories/steel-culverts |
| 12” x 12” | Steel | 124 | |
| 12” x 20” | Steel | 199 | |
| 12” x 24” | Steel | 246 | |
| 15” x 10” | Steel | 155 | |
| 15” x 16” | Steel | 204 | |
| 15” x 20” | Steel | 289 | |
| 15” x 30” | Steel | 385 | |
| 18” x 16” | Steel | 249 | |
| 18” x 20” | Steel | 335 | |
| 18” x 24” | Steel | 369 | |
| 18” x 30” | Steel | 469 | |
| 24” x 20” | Steel | 395 | |
| 24” x 24” | Steel | 475 | |
| 24” x 30” | Steel | 599 | |
| 30” x 30” | Steel | 749 | |
| 36” x 30” | Steel | 949 | |
| Dredging | Cost to design and build the spoil area, and dredge the material: $4.00 to $8.00 per cubic yard. Combined charge for mobilization and de-mobilization: $20,000 to $50,000. For preliminary cost estimates, use the average of the above costs. | | http://www.dredgingspecialists.com/Dredging101.htm |
| | Hydraulic: 5-15 $/CY and Mechanical: 8-30 $/cy | | http://www.epa.state.il.us/water/conservation/lake-notes/lake-dredging.pdf |
| Sewer | PVC Sewer Pipe, 8 Inch Diameter: Unit: LF cost: 300.00 $<br><br>10/12 inch can be installed with a box, use $300-$350 per foot | | Bid Tabulation for Horseshoe Bend Levee Improvements Project ( Phase II) – Bidder : SCI Infrastructure, LLC |

**Table 7 Unit Costs for Rainfall Interception**

| Measures | Cost & Unit | Reference |
|---|---|---|
| Green Roof | 15.75 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Permeable pavement/ driveway/ parking (Material :Asphalt) | 6.34 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Permeable pavement/ driveway/ parking (Material :Asphalt) | 6 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Permeable pavement/ driveway/ parking (Material : Gravel) | 4.32 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Swales | 15 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Vegetated Filter Strips | 1.45 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Planter Box | 8 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Rain Garden | 7 ( $ /sq ft) | http://greenvalues.cnt.org/national/cost_detail.php |
| Amended Soil | 30 ( $ / CY) | http://greenvalues.cnt.org/national/cost_detail.php |

**Table 8 Unit Costs for Storage**

| Measures | Cost & Unit | Reference |
|---|---|---|
| Excavation | 35 ($ / CY) | http://www.state.nj.us/transportation/business/procurement/ConstrServ/documents/BidTabs13454.pdf |