Strategies for Flood Risk Reduction for Vulnerable Coastal Populations along Arthur Kill at Elizabeth, Linden, Rahway, Carteret and Woodbridge

FINAL REPORT

Submitted to

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

By

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150 Years Engineering Out Front

Arthur Kill Study Area

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A. Flood Study Overview

The communities of Carteret, Elizabeth, Linden, Rahway and Woodbridge (Arthur Kill Study Area) are located on the western bank of the Arthur Kill waterway which is under the hydraulic influence of Newark Bay to the north and Raritan Bay to the south. These communities experienced severe flooding and flood related damage as a result of the storm surge from Hurricane Sandy. Notable damages to the communities include:

- Marina in Elizabeth was destroyed
- Approximately 5,000 new cars were destroyed in Port Elizabeth
- 20 to 30 homes were damaged in Tremley Point, a community in Linden
- The levee in Rahway was overtopped and flooded the first floor of many homes and businesses
- Electrical substations were flooded in Rahway causing power outages in the area
- Oil refining facilities in Linden and Perth Amboy spilled thousands of gallons of fuel in nearby waterways when they were flooded.

Following the damage that was wrought on these communities by flooding from Hurricane Sandy, Rutgers University was tasked to determine the flood vulnerability of several communities across New Jersey, including the communities along the Arthur Kill waterway and to develop mitigation measures to address these vulnerabilities.

Accordingly, with Dr. Qizhong (George) Guo as the Principal Investigator, flood researchers embarked on the study of Arthur Kill Study Area using data from multiple federal and state sources such as USGS, FEMA, NOAA, NJDEP etc. first to assess the communities vulnerabilities and then proposing appropriate mitigation measures to address the vulnerabilities that were identified.

B. Arthur Kill Regional Flood Study

The Arthur Kill region is characterized by heavy urbanization with associated high stormwater runoff and in some areas existing wetlands are in need of improvement. Also, communities along the banks of the Arthur Kill are vulnerable to coastal flooding and in some cases are vulnerable to both coastal flooding and wave velocity hazard. Given the relationship between the Arthur Kill and the communities along its banks, it is clear that regional solutions to mitigate coastal flooding are appropriate.

Accordingly, it is recommended that a floodwall be installed along the Arthur Kill from the City of Elizabeth to the Township of Woodbridge (approximately 15 miles) varying in height from 8 to 10 feet. It is envisioned that the floodwall will be adaptable such that its height can be readily increased to deal with future sea level rise. The floodwall will need to be combined with in-water closure devices at all tributaries of the Arthur Kill, most notably the Elizabeth River, Rahway River and Woodbridge River along with all the small creeks that will interrupt the floodwall.

To mitigate stormwater drainage-related flooding, each community requires unique tactics to address their unique conditions. However, it is clear that green infrastructure mitigation measures can be applied throughout the study area to help reduce stormwater runoff regionally given the highly urbanized nature of the study area.

C. City of Elizabeth Flood Study

The City of Elizabeth is vulnerable to coastal flooding from Newark Bay and the Arthur Kill on its eastern side. Installation of a new floodwall along the banks of the bay and the river with an in-water channel closure device at the confluence of the Elizabeth River and the Arthur Kill will mitigate both the coastal and riverine flooding threat faced by the community. It is envisioned that the floodwall will be adaptable such that its height can be readily increased to deal with future sea level rise.

The City also experiences local flooding when its combined sewer overflow (CSO) system cannot flow naturally into discharging waterways due to elevated tidal conditions. 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.

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

D. City of Linden

The City of Linden is vulnerable to coastal flooding from the Arthur Kill on its eastern side and inland along the Rahway River and its tributaries such as Marshes Creek. Installation of a new floodwall along the banks of the river with in-water channel closure devices at the confluence of the Rahway River and the Arthur Kill and at the confluences of the smaller Arthur Kill tributaries Piles and Morses Creek will mitigate both the coastal and riverine flooding threat faced by the community. It is envisioned that the floodwall will be adaptable such that its height can be readily increased to deal with future sea level rise.

The City also experiences local flooding due to inadequate conveyance capacity in downstream stormwater channels caused by excessive sedimentation in Orchard Brook, Peach Orchard and Morses Creek where these channels were widened to form reservoirs in the past. It is also likely that since these waterways are tidally impacted conveyance in these channels are restricted when precipitation occurs during elevated tidal periods. It is recommended that the channels be de-silted on a regular basis to ensure that downstream conveyance is maximized thereby reducing localized flooding.

Then there is the case of Tremley Point where low lying portions of this community are flooded regularly due to inadequate conveyance in Marshes Creek coupled with restricted flow during elevated tidal periods. It is suggested that flooding can be mitigated in this community by improving conveyance in Marshes Creek by, removing the bottleneck where the creek passes under a railroad track, straightening the creek where it meanders adjacent to the community and by installing a sluice gate that can be operated as needed to control the inflow of coastal floods.

Finally, the City of Linden like the other communities in this area is highly urbanized and therefore precipitation events produce significant stormwater runoff for which there is insufficient conveyance capacity and insufficient storage as stated earlier. It is recommended that green infrastructure mitigation measures be implemented to reduce the amount of stormwater runoff generated.

E. City of Rahway

The City of Rahway is vulnerable to coastal flooding from the Rahway River. The City was flooded by Hurricane Sandy's coastal surge when the levee that protects the City was overtopped. It is envisioned that the most efficient way to mitigate coastal flooding in the City is to install an in-water channel closure device at the confluence of the Rahway River and the Arthur Kill that will be open on most occasions except when there is a major threat of coastal flooding.

The City also experiences local flooding when the stormwater conveyance system is unable to discharge into the Rahway River during elevated tides. It appears that by upgrading the City's existing stormwater pumping station and providing them with backup generators that are resilient to flooding will allow for the pumping of stormwater when the storage capacity is exhausted.

Finally, the City of Rahway like the other communities in this area is highly urbanized and therefore precipitation events produce significant stormwater runoff for which there is insufficient conveyance capacity and insufficient storage as stated earlier. It is recommended that green infrastructure mitigation measures be implemented to reduce the amount of stormwater runoff generated.

F. Borough of Carteret

The Borough of Carteret is vulnerable to coastal flooding from the Arthur Kill on its eastern side and inland along the Rahway River on its north. Installation of a new floodwall along the banks of the river with an in-water channel closure device at the confluence of the Rahway River and the Arthur Kill and at the smaller confluence of the smaller Noes Creek will mitigate both the coastal and riverine flooding threat faced by the community. It is envisioned that the floodwall will be adaptable such that its height can be readily increased to deal with future sea level rise.

The Borough also experiences local flooding due to inadequate conveyance capacity in the Noes Creek watershed. It is also likely that since these waterways is tidally impacted, conveyance in this channel is restricted if precipitation occurs during elevated tidal periods. It is recommended this study be evaluated hydrological and hydraulically to determine the most effective option to alleviate the localized flooding problems in the Noes Creek watershed.

Finally, the Borough of Linden like the other communities in this area is highly urbanized and therefore precipitation events produce significant stormwater runoff for which there is insufficient conveyance capacity and insufficient storage. It is recommended that green infrastructure mitigation measures be implemented to reduce the amount of stormwater runoff generated.

G. Woodbridge Township

Woodbridge Township is vulnerable to coastal flooding from the Arthur Kill on its eastern side and inland along the Rahway and Woodbridge Rivers. Installation of a new floodwall along the banks of the Arthur Kill with in-water channel closure devices at the confluence of the Rahway River and the Arthur Kill and at the confluence of the smaller Arthur Kill tributary Woodbridge River will mitigate both the coastal and riverine flooding threat faced by the community. It is envisioned that the floodwall will be adaptable such that its height can be readily increased to deal with future sea level rise.

The Township also experiences local flooding due to inadequate conveyance capacity in the Woodbridge River. This waterways is tidally impacted and so conveyance in this channels is restricted if precipitation occurs during elevated tidal periods. It is recommended that the channel be de-silted on a regular basis and straightened to improve downstream conveyance during low tide conditions.

Finally, Woodbridge Township like the other communities in this area is highly urbanized and therefore precipitation events produce significant stormwater runoff for which there is insufficient conveyance capacity and insufficient storage as stated earlier. It is recommended that green infrastructure mitigation measures be implemented to reduce the amount of stormwater runoff generated.

II. Introduction

The Arthur Kill Study Area includes the Cities of Elizabeth, Linden and Rahway, the Borough of Carteret and Woodbridge Township all situated along the western bank of the Arthur Kill tributary, see Figure 1 below for a map of the entire study area. In late October 2012, hurricane Sandy exposed the vulnerabilities of these communities to coastal flooding that resulted in millions of dollars in property damage.

This study seeks first to determine the causes of flooding in these communities, then to determine what flood mitigation measures are currently employed and/or envisioned by the officials in these communities and then offer recommendations to mitigate these flood risks. It is useful to note that although these communities are located in the same general location, there are enough differences between them to warrant individual assessment of each city separately. By the same token there are also some synergies that exist between the communities that may allow them to share the flood mitigation benefits of some proposed measures.

Rutgers University visited with City officials in the communities that make up the Arthur Kill Study Area (Study Area) to discuss historical flooding problems and to determine what flood mitigation efforts were already in place and what efforts were already planned or being considered for the future in their individual cities. These visits were extremely beneficial to the study because the city officials were able to share their extensive knowledge of their communities with the University and provide valuable information and insight with regards to locations that are vulnerable to flooding and how their communities fared during large weather events like Hurricanes Irene and Sandy.

Using the information gleaned from city officials, along with technical information from United States Geological Surveys (USGS), National Oceanic and Atmospheric Agency (NOAA), National Weather Service (NWS), New Jersey Department of Environmental Protection (NJDEP), Federal Emergency Management Agency (FEMA) and many other organizations, the flooding risks faced by the Communities in Arthur Kill were investigated and clarified. Based on the flooding risks identified and the sources of flood water, it is possible to provide recommendations of flood mitigation measures that can reduce flooding vulnerability in these communities if implemented.

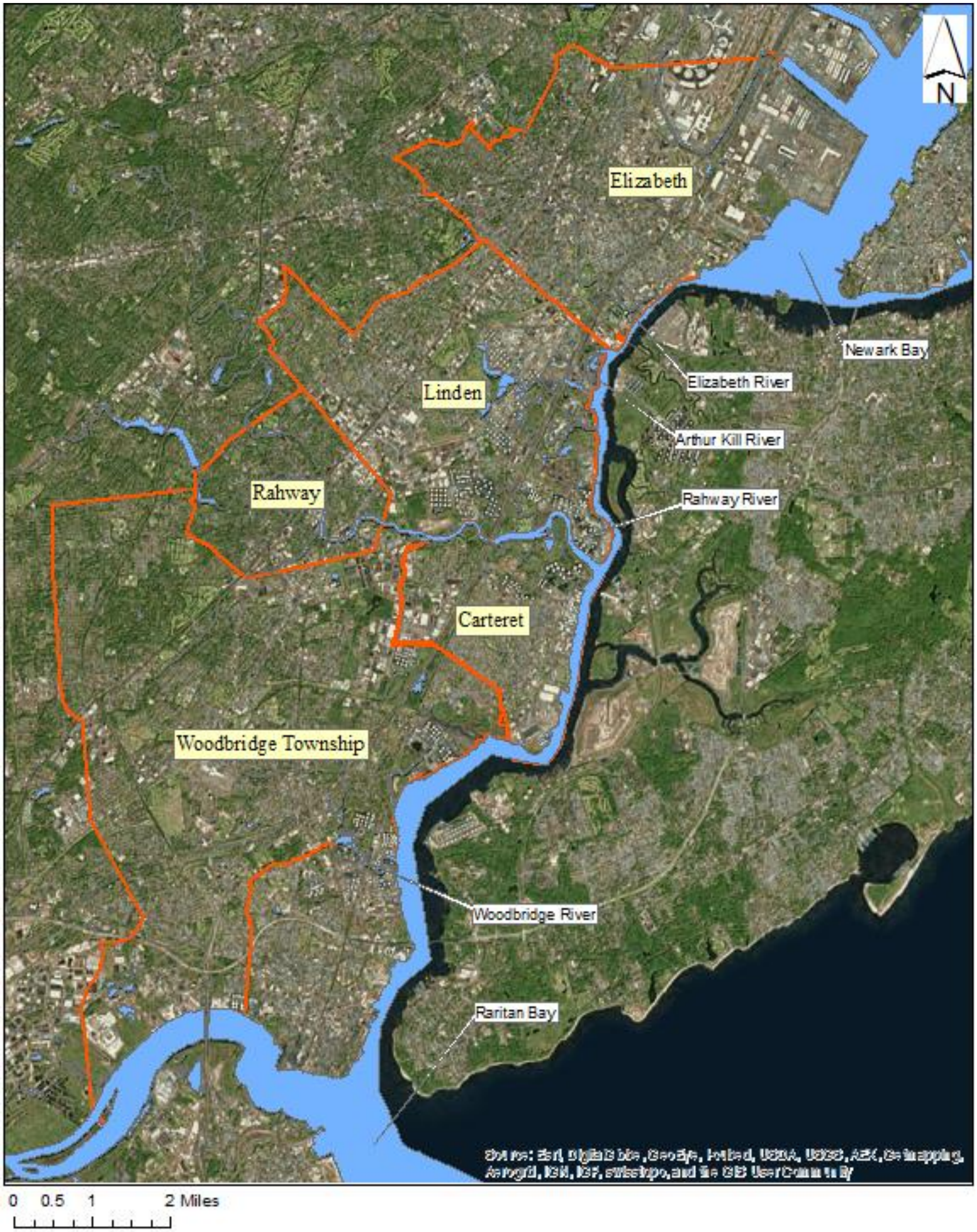

Figure 1-Arthur Kill Study Area

A. Hurricane Sandy

Hurricane Sandy has been a catalyst for the assessment of flooding vulnerability along many coastal and near coastal areas of New Jersey because of the significant flood damage that it inflicted on property and infrastructure. Accordingly, this event must be understood and its effects considered in the study of flooding in the Arthur Kill Study Area.

Hurricane Sandy was a monster storm with tropical force winds extending approximately 1000 miles or approximately three times the size of hurricane Katrina which devastated New Orleans in 2005 (Figure 2). Due to its massive size the hurricane was able to develop a huge storm surge caused by wind set-up at the downwind shore and low pressure inside the storm system, which was captured by tidal gauges in the area (Figure 3 & Figure 4).

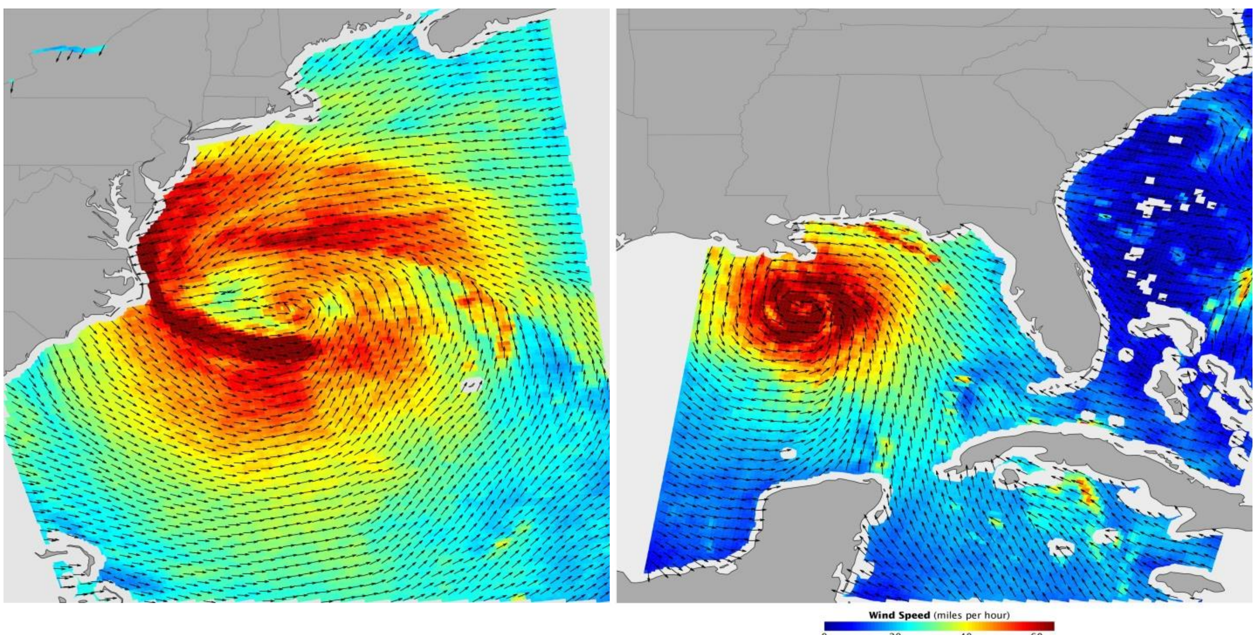

Figure 2 -Comparison between Hurricanes Sandy (Left) and Katrina (Right) (NASA, 2013)

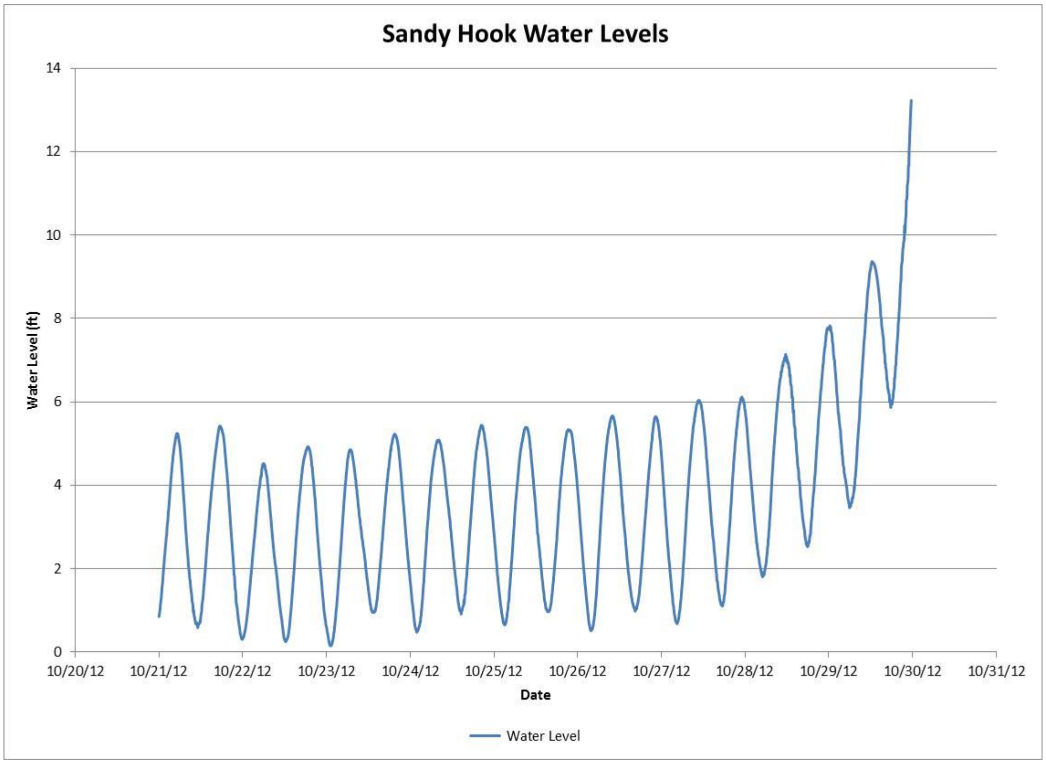

Figure 3-Sandy Hook Tide Gauge Reading: Hurricane Sandy (National Oceanic and Atmospheric Agency, 2013)

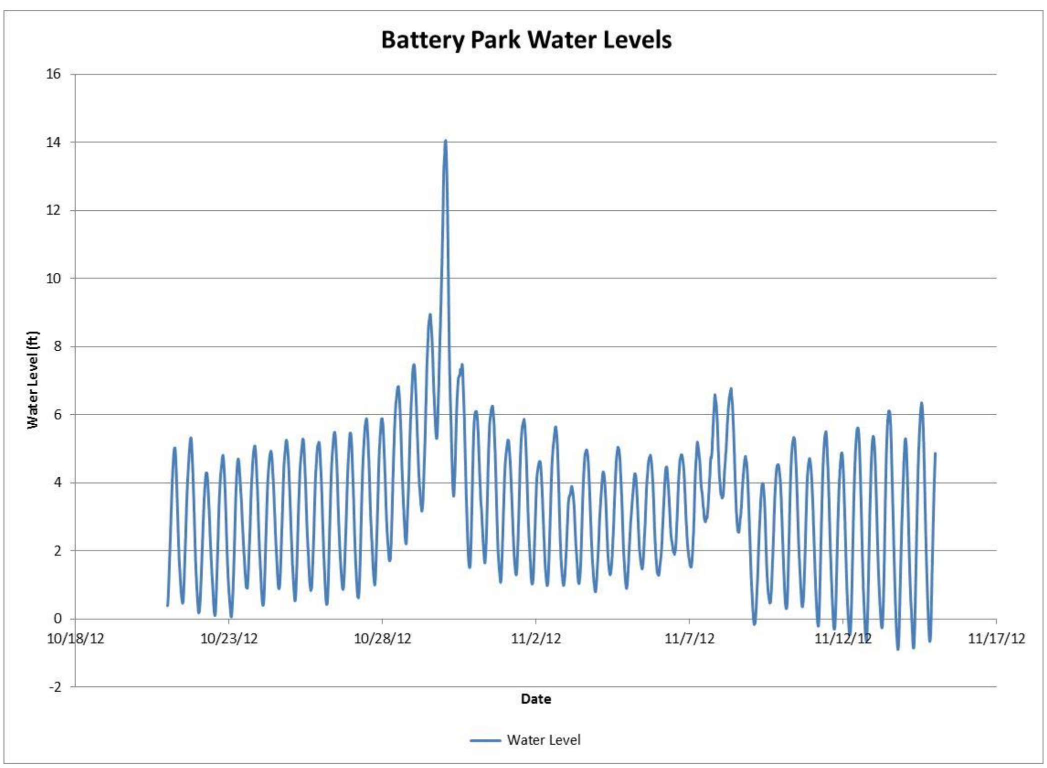

Figure 4- Battery Park Tide Gauge Reading: Hurricane Sandy (National Oceanic and Atmospheric Agency, 2013)

The effects of this storm surge were enhanced by the fact that the hurricane arrived in the NYC Metro area at almost the same time that the spring tide was peaking and because of its path (Figure 5) its storm surge was propelled into a head-on collision with Battery Park and other areas adjoining New York Harbor.

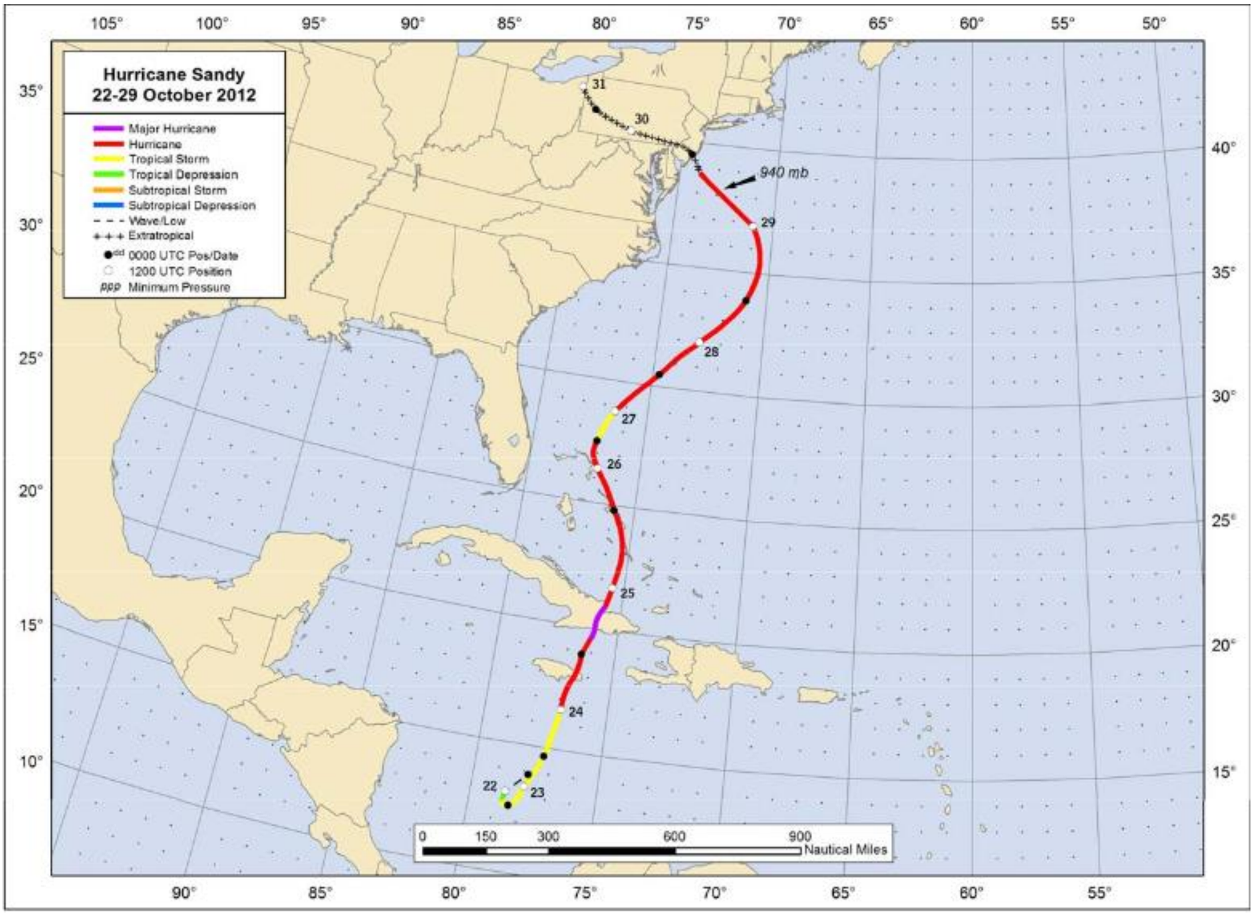

Figure 5-Hurricane Sandy Path (National Weather Service, 2013)

The flooding that resulted from the storm surge was significant throughout the area with Staten Island and Lower Manhattan experiencing massive devastation and a total of 43 deaths (The City of New York, 2013), mostly by drowning. The NYC subway system was flooded and the salt water caused extensive damage that resulted in the system being shut down for many days (Figure 6). Large sections of the area were inundated (Figure 7 & Figure 8) both along the Atlantic coast and inland along the many bays and waterways in the area such as Jamaica Bay, Sheepshead Bay, Newark Bay and Arthur Kill River. The flooding and resulting damage was unprecedented and as a result has triggered action at all levels of government and other interested parties including academia to find ways to protect communities against future events like Hurricane Sandy.

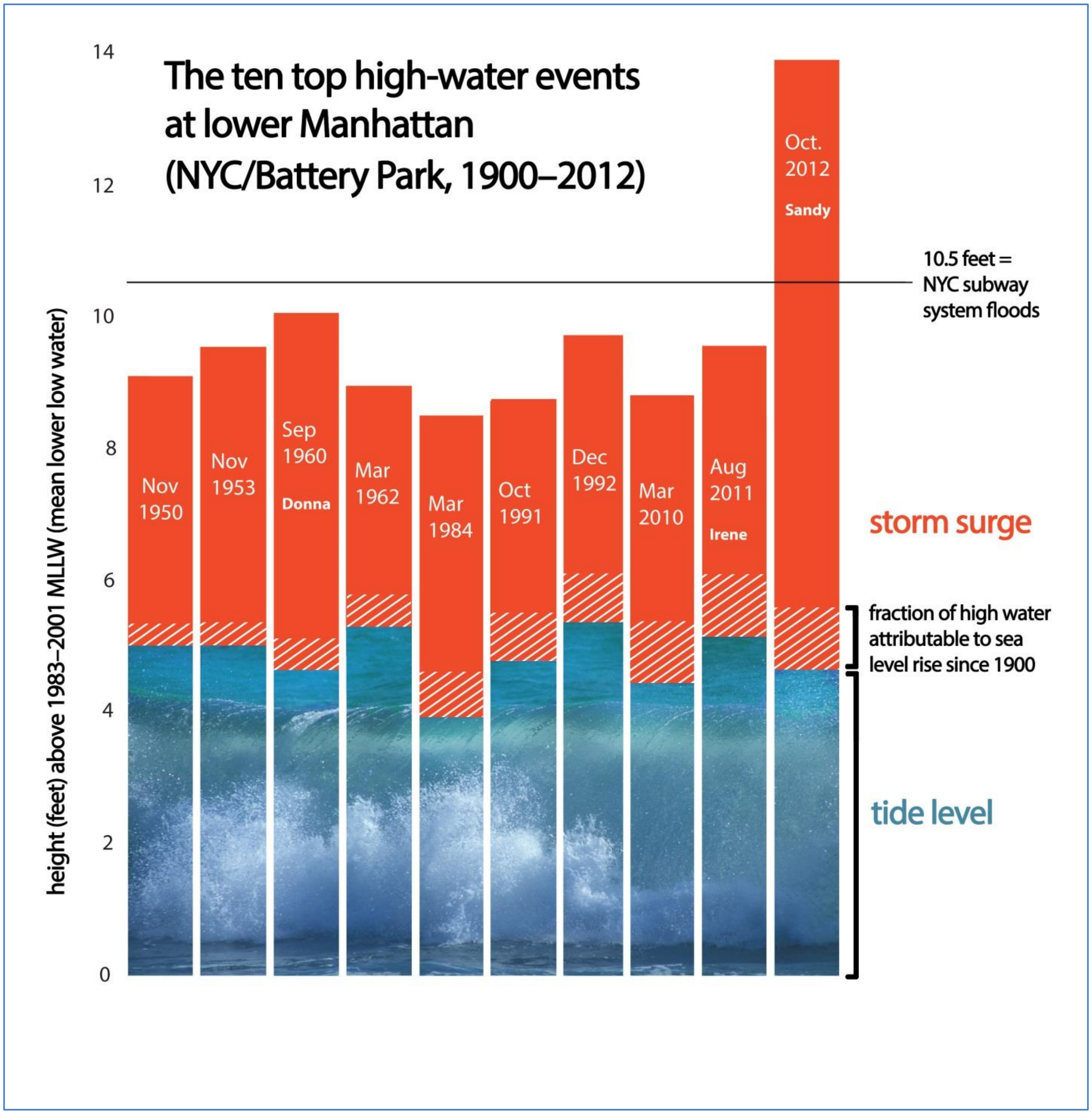

Figure 6-Flooding Data for NYC Subway System (University Corporation for Atmospheric Research, 2013)

In the Arthur Kill Study Area, Hurricane Sandy’s storm surge advanced up the Kill van Kull into Newark Bay, Arthur Kill and the Elizabeth River (Figure 8 below shows how the storm surge impacted Arthur Kill Study Area).

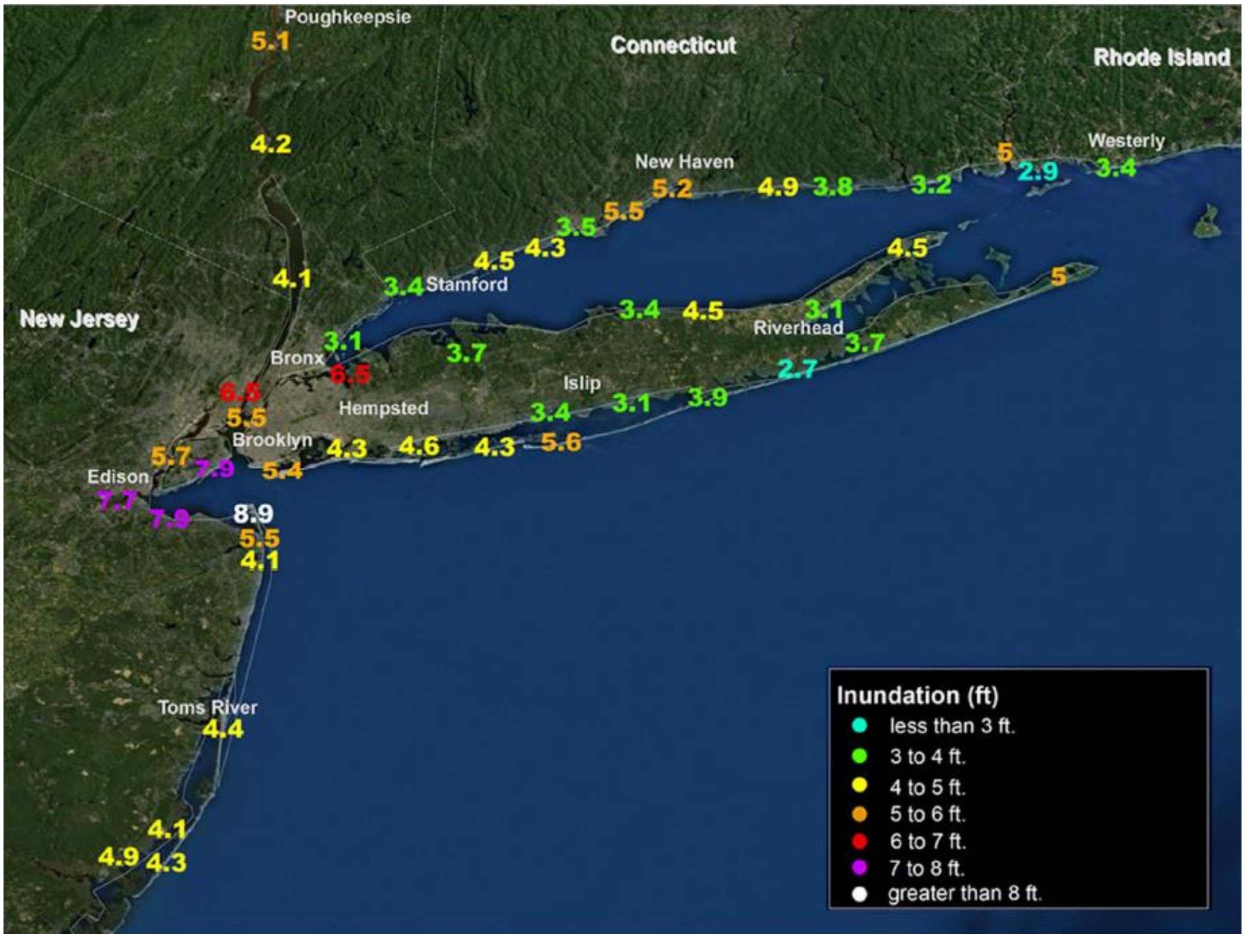

Figure 7-Regional Inundation Depths during Hurricane Sandy (National Weather Service, 2013)

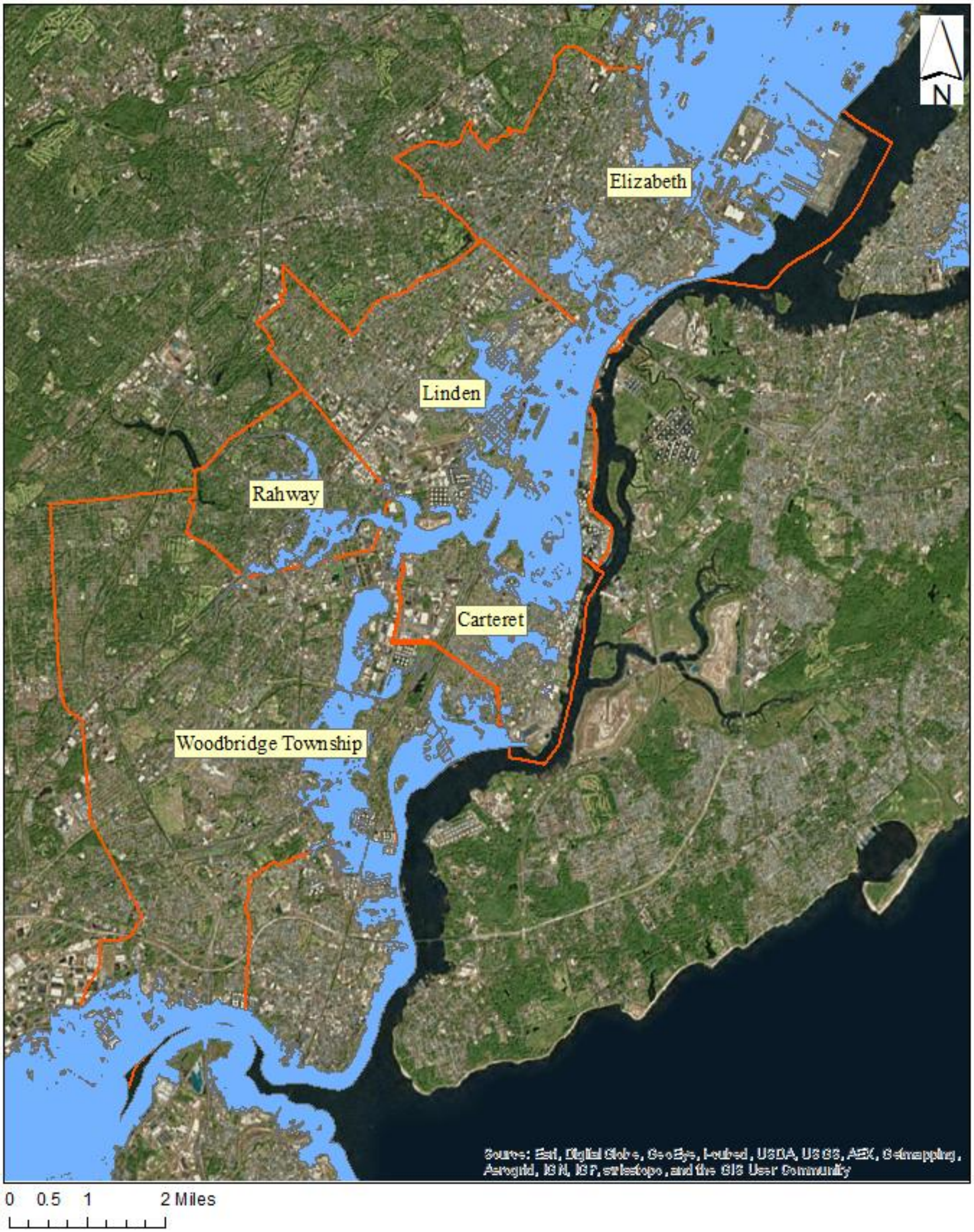

Figure 8-Hurricane Sandy Storm Surge Inundation along Arthur Kill River (United States Geological Service, 2014)

B. Flooding Study Approach

1. Procedure

The following procedure was used to study flooding in the Arthur Kill Study Area:

- Determine what if any historical flooding information is available or whether Federal Emergency Management Authority (FEMA) Flood Insurance Rate (FIRM) Maps are available for the location.
- Overlay FEMA FIRM mapping on the map of the community to determine what part of the community if any would be impacted by the 100 year coastal storm event.
- Assess the of stormwater runoff potential of the community to determine whether runoff generation would be considered as significant or not.
- Determine the potential sources of flood waters that could impact the community.
- Determine the current level of flood protection available to the community.
- Determine mitigation strategies and measures that are applicable to the community and make recommendations accordingly.

2. FEMA FIRM Map

Within the FEMA 100 year flood zones both inundation and wave velocity action are identified and Figure 9 illustrates how these areas are designated.

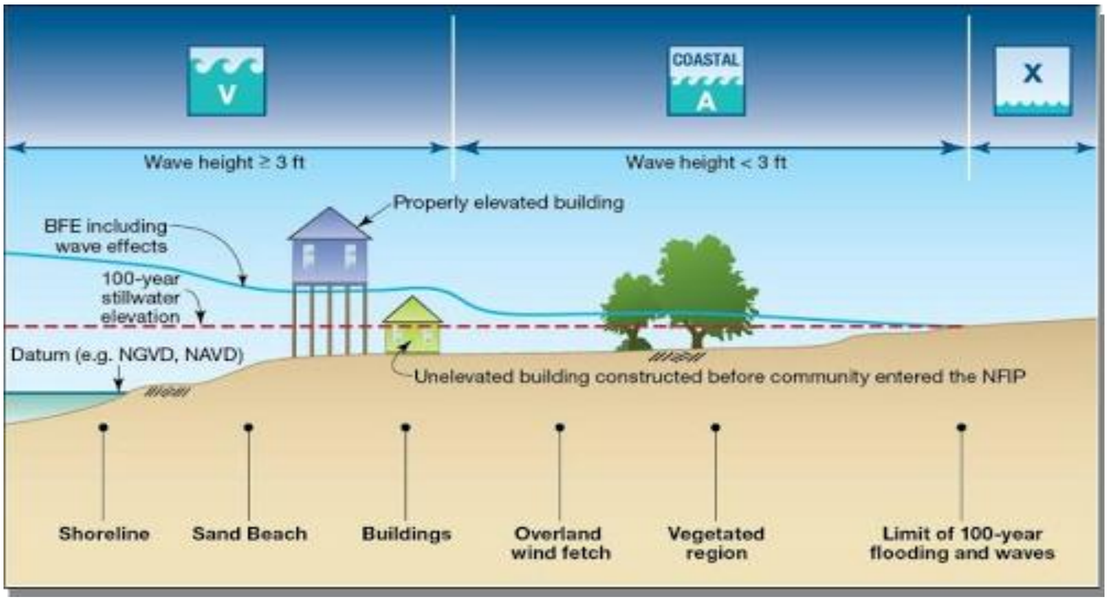

Figure 9-FEMA Flood Zone Mapping Methodology ((FEMA, 2014))

3. Flood Threat Levels

Coastal storm flood water elevation for the communities that comprise the Arthur Kill Flood Study area are shown below in Table 1 . Note that these elevations use the NAVD 88 datum and are located on the banks of the Arthur Kill within the municipalities.

Table 1-Flood Water Elevation (Datum: NAVD 88) (FEMA ABFE, 2013), (FEMA Prelim. FIRM, 2013)

Municipality	Average Grade Elevation	"V" Zone Flood Elevation	"A" Zone Flood Elevation	100 Year + SLR 2100
Elizabeth	6 - 12	14	11 - 13	17.5
Linden	3 - 5	15	13	18.5
Rahway	11	N/A	12	15.5
Carteret	5 - 10	15	13 - 14	18.5
Woodbridge	6 - 20	15 - 22	13 -14	18.5 - 25.5

4. Historical Rainfall Data

Table 2- Table Showing Rainfall Data for Elizabeth ((NOAA, 2013)

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]										
Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.335 (0.306-0.368)	0.399 (0.365-0.438)	0.472 (0.430-0.519)	0.525 (0.478-0.577)	0.590 (0.534-0.648)	0.636 (0.573-0.697)	0.681 (0.611-0.748)	0.722 (0.643-0.793)	0.773 (0.682-0.852)	0.811 (0.710-0.896)
10-min	0.535 (0.489-0.588)	0.638 (0.583-0.700)	0.756 (0.689-0.832)	0.840 (0.764-0.923)	0.940 (0.852-1.03)	1.01 (0.913-1.11)	1.08 (0.970-1.19)	1.14 (1.02-1.26)	1.22 (1.08-1.35)	1.28 (1.12-1.41)
15-min	0.669 (0.611-0.735)	0.801 (0.733-0.881)	0.957 (0.872-1.05)	1.06 (0.967-1.17)	1.19 (1.08-1.31)	1.28 (1.16-1.41)	1.37 (1.23-1.50)	1.44 (1.29-1.59)	1.54 (1.36-1.70)	1.60 (1.40-1.77)
30-min	0.917 (0.838-1.01)	1.11 (1.01-1.22)	1.36 (1.24-1.49)	1.54 (1.40-1.69)	1.77 (1.60-1.94)	1.93 (1.74-2.12)	2.10 (1.88-2.30)	2.25 (2.00-2.47)	2.45 (2.16-2.70)	2.60 (2.27-2.87)
60-min	1.14 (1.04-1.26)	1.39 (1.27-1.53)	1.74 (1.59-1.92)	2.00 (1.82-2.20)	2.35 (2.13-2.58)	2.62 (2.36-2.87)	2.89 (2.59-3.17)	3.15 (2.81-3.46)	3.51 (3.10-3.87)	3.79 (3.32-4.19)
2-hr	1.40 (1.27-1.54)	1.70 (1.55-1.88)	2.16 (1.96-2.39)	2.52 (2.28-2.77)	3.01 (2.71-3.31)	3.41 (3.05-3.76)	3.83 (3.40-4.21)	4.26 (3.76-4.69)	4.87 (4.24-5.38)	5.36 (4.62-5.92)
3-hr	1.55 (1.42-1.72)	1.89 (1.73-2.09)	2.40 (2.19-2.66)	2.80 (2.54-3.09)	3.35 (3.02-3.70)	3.81 (3.41-4.19)	4.[illegible] (3.80[illegible])	[illegible]	[illegible]	[illegible]99 ([illegible]6.62)
6-hr	2.00 (1.82-2.21)	2.43 (2.21-2.68)	3.07 (2.78-3.39)	3.60 (3.25-3.96)	4.34 (3.89-4.77)	4.97 (4.42-5.45)	5.[illegible] (4.96-6.18)	[illegible] (5.55-6.97)	[illegible] (6.35-8.11)	[illegible]24 (7.00-9.06)
12-hr	2.45 (2.23-2.71)	2.98 (2.71-3.29)	3.79 (3.44-4.18)	4.48 (4.04-4.92)	5.48 (4.91-6.00)	6.35 (5.64-6.93)	7.28 (6.40-7.95)	8.32 (7.22-9.09)	9.85 (8.38-10.8)	11.2 (9.35-12.2)
24-hr	2.78 (2.56-3.04)	3.37 (3.10-3.68)	4.32 (3.98-4.72)	5.14 (4.71-5.61)	6.38 (5.80-6.93)	7.45 (6.72-8.09)	8.64 (7.72-9.38)	9.97 (8.81-10.9)	12.0 (10.4-13.1)	13.7 (11.7-15.0)
2-day	3.27 (2.99-3.59)	3.96 (3.62-4.34)	5.06 (4.63-5.55)	5.98 (5.45-6.55)	7.34 (6.65-8.03)	8.50 (7.66-9.29)	9.76 (8.73-10.7)	11.2 (9.86-12.2)	13.2 (11.5-14.6)	14.9 (12.8-16.5)
3-day	3.45 (3.16-3.78)	4.18 (3.83-4.58)	5.32 (4.87-5.82)	6.27 (5.72-6.85)	7.65 (6.95-8.35)	8.81 (7.96-9.62)	10.1 (9.03-11.0)	11.5 (10.2-12.5)	13.5 (11.8-14.8)	15.1 (13.1-16.7)
4-day	3.64 (3.34-3.98)	4.40 (4.04-4.82)	5.58 (5.12-6.10)	6.55 (5.99-7.16)	7.96 (7.24-8.68)	9.13 (8.26-9.96)	10.4 (9.33-11.3)	11.8 (10.5-12.9)	13.7 (12.0-15.1)	15.4 (13.3-17.0)
7-day	4.28 (3.96-4.63)	5.13 (4.75-5.56)	6.38 (5.90-6.92)	7.42 (6.83-8.04)	8.90 (8.15-9.64)	10.1 (9.22-11.0)	11.4 (10.3-12.4)	12.8 (11.5-14.0)	14.8 (13.1-16.3)	16.5 (14.4-18.1)
10-day	4.87 (4.52-5.25)	5.82 (5.41-6.27)	7.13 (6.62-7.68)	8.20 (7.59-8.84)	9.72 (8.96-10.5)	11.0 (10.0-11.8)	12.3 (11.2-13.3)	13.7 (12.3-14.8)	15.6 (13.9-17.1)	17.2 (15.2-18.9)
20-day	6.56 (6.16-7.00)	7.79 (7.31-8.31)	9.30 (8.71-9.91)	10.5 (9.81-11.2)	12.1 (11.3-12.9)	13.3 (12.4-14.3)	14.6 (13.5-15.6)	15.9 (14.6-17.0)	17.6 (16.0-18.9)	18.9 (17.1-20.5)
30-day	8.18 (7.74-8.66)	9.67 (9.14-10.2)	11.3 (10.7-11.9)	12.6 (11.8-13.3)	14.2 (13.3-15.0)	15.4 (14.5-16.3)	16.6 (15.6-17.6)	17.8 (16.6-18.9)	19.3 (17.9-20.6)	20.4 (18.8-21.9)
45-day	10.4 (9.87-11.0)	12.2 (11.6-12.9)	14.1 (13.4-14.9)	15.5 (14.7-16.4)	17.4 (16.4-18.3)	18.7 (17.7-19.8)	20.1 (18.9-21.2)	21.3 (20.0-22.6)	22.9 (21.3-24.4)	24.1 (22.3-25.7)
60-day	12.5 (11.9-13.1)	14.6 (13.9-15.4)	16.7 (15.9-17.6)	18.3 (17.3-19.2)	20.2 (19.2-21.2)	21.6 (20.5-22.8)	22.9 (21.7-24.2)	24.2 (22.8-25.5)	25.7 (24.1-27.2)	26.7 (25.0-28.4)

25 Year 24 Hours Event

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

C. Flood Mitigation Strategies and Measures

There are a variety of flood mitigation measures and strategies that are available to help communities reduce the impact of flooding and achieve the resilience. These measures fall into broad categories usually based on the sources of flood waters and the level of protection needed by the community.

Accordingly, 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 also to facilitate the selection of flood mitigation measures for these communities, see Figure 10 below.

The Rutgers University Flood Mitigation Study Team also developed a menu of flood risk-reduction functions and their associated measures. Figure 11 is a schematic showing the application of various flood mitigation measures and Table 3 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), 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.

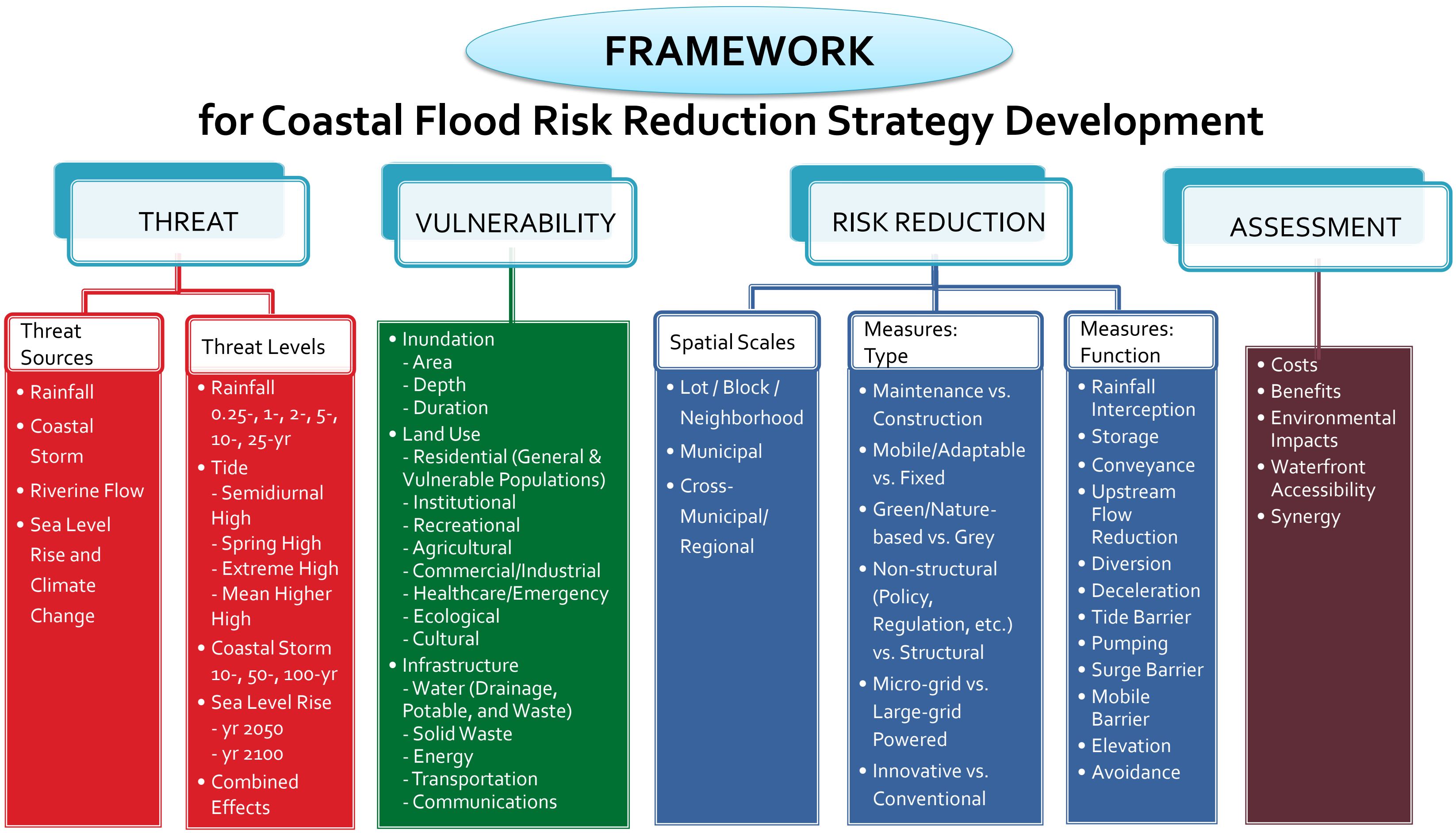

Figure 10-Framework for Flood Risk Reduction Strategy Development

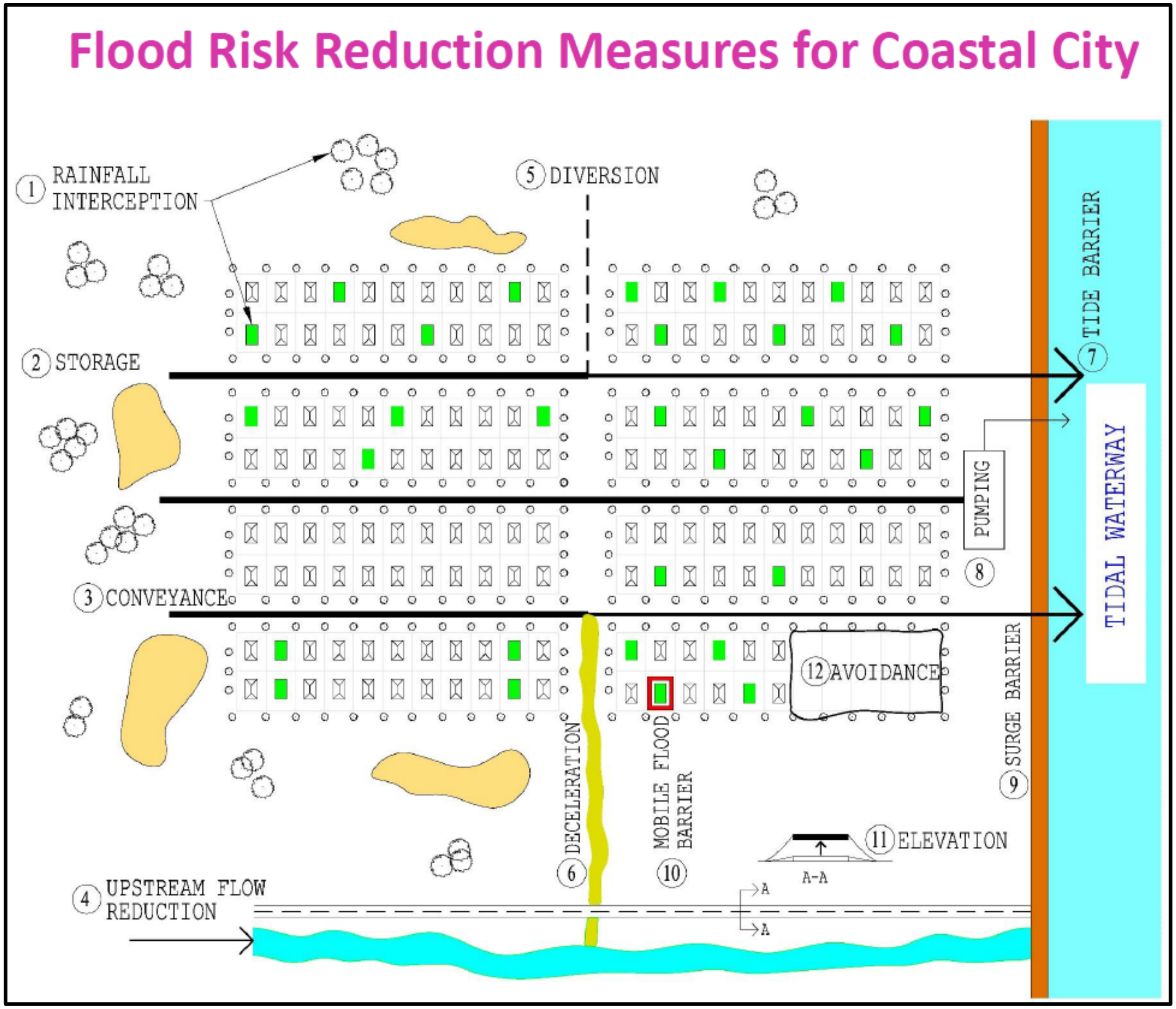

Figure 11-Flood Risk Reduction Measures

Table 3-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	ELEVAT-ION	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 MANAGE-MENT	BYPASS FORCE MAIN*	ARTIFICIAL WETLANDS	SLUICE GATE	EMERGENCY POWER	SEAWALL	FLOOD GATE	ELEVATED ROAD	EVACUA-TION
BIOSWALE	INFILTRA-TION	DREDGING				HEADWALL	WIND PUMP	TEMPORARY SEAWALL	INFLAT-ABLE BARRIER		WARNING
VEGETATED FILTER STRIP	EXPANSION	COMBINED SEWER SEPARATION					RAIN PUMP*	ELEVATING LEVEE			RISK EDUCATION
POROUS PAVING	CONSTRUCTE D 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		STRAIGHTEN-ING						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.

III. Arthur Kill Region

A. Regional Flooding Issues Overview

The Arthur Kill Study Area flooding issues can be broadly categorized by the source of the flood waters as either coastal or stormwater-related flooding. Although coastal flooding issues within the study area largely impact the banks of the Arthur Kill River, there are many flooding impacts resulting from surge water pushing upriver from the Arthur Kill up into the Elizabeth, Rahway and Woodbridge Rivers and up the many creeks that are tributary to the Arthur Kill and Rahway Rivers. The flooding issues that result inland surges range from levee overtopping in extreme cases, to impairment of combined and stormwater sewer outfall discharges on a more regular basis, under high tide conditions.

To evaluate the vulnerability of the Arthur Kill Study Area to coastal flooding, the FEMA Flood Insurance Rate Map (FIRM) was superimposed on the aerial photograph of the study area to determine the extent to which the 100 year flood (1% risk of occurring annually) would impact the area. When the extent of flooding in the study area from this event is reviewed from the regional perspective (see Figure 12 and Figure 13 below), the following clear risk patterns emerge:

- Locations along the Arthur Kill's banks are impacted by wave velocity risk
- With the exception of Elizabeth, only commercial entities exist in these flood zones.
- The NJ Turnpike largely parallels the Arthur Kill within the Study Area and acts as a surge barrier in the areas where it is elevated higher than the 100 year flood elevation, thereby preventing flood waters from inundating areas further west, see Figure 13 below.
- Mean Higher High Water (MHHW) tides do not impact this study area significantly, see Figure 14 below.

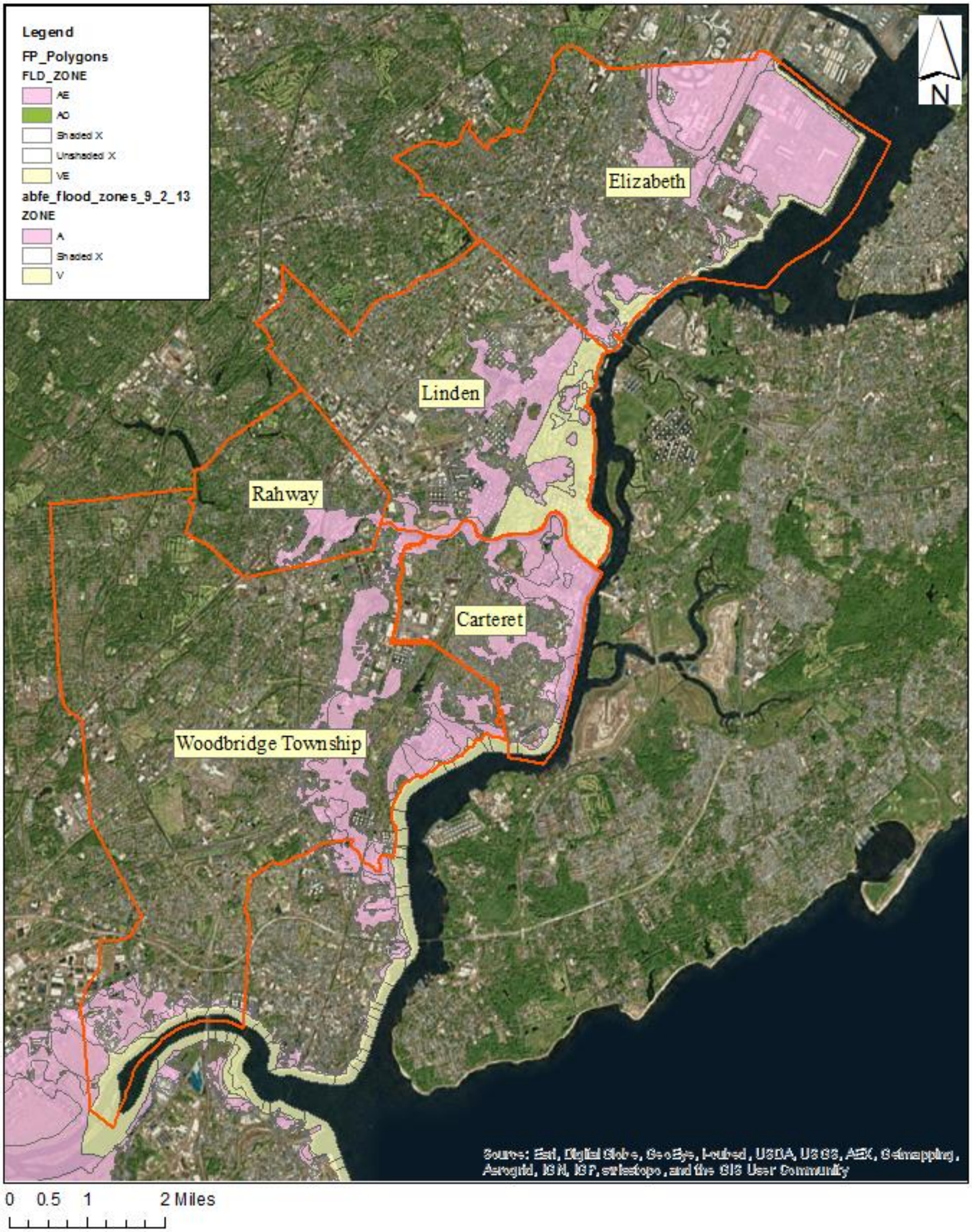

Figure 12-FEMA 100 Year Flood Overlaid on Arthur Kill Map (FEMA Prelim. FIRM, 2013), (FEMA ABFE, 2013)

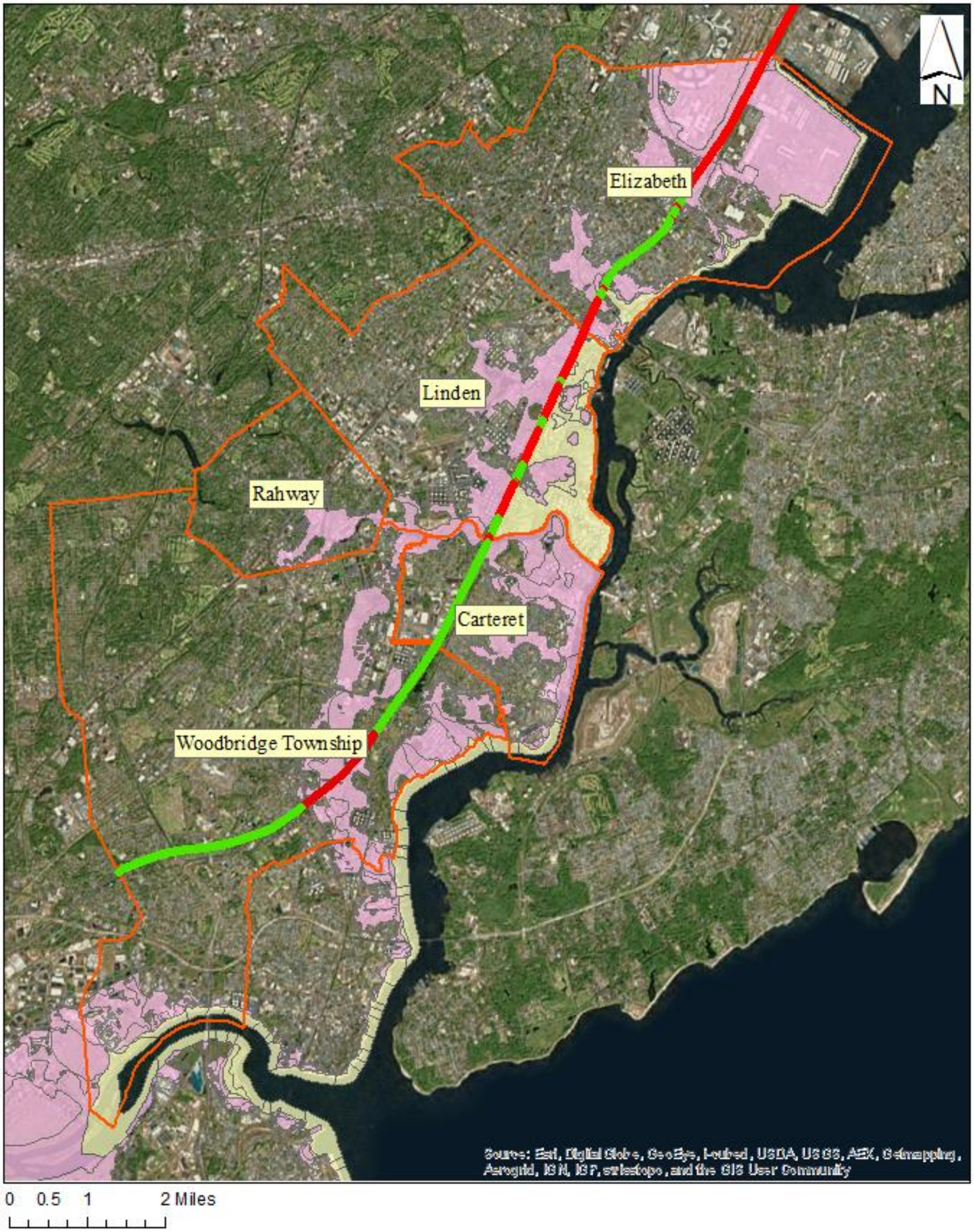

Figure 13-Arthur Kill Study Area Showing NJ Turnpike (Red indicates location below 100 Year Flood Zone-Requires Elevation; Green indicates location higher than the 100 Year Flood Zone-No elevation required).

Figure 14-Arthur Kill Study Area overlaid with Mean Higher High Water Layer ((NOAA), (NOS), & (CSC), 2012)

B. Regional Flood Mitigation

1. Mitigating 100 Year Coastal Storm Event

Based on the pattern of flooding in the Arthur Kill Study area, there are two regional flooding measures that can be implemented to mitigate coastal storm inundation. The flood mitigation measures that will best protect the region are:

1. Flood Wall from Elizabeth to Woodbridge as shown in Figure 15 (15 miles long).
2. Using the NJ Turnpike as a surge barrier by elevating the portions that need elevation (approximately 6 miles) to protect from the 100 year event, see Figure 16 below.

Both of these options will require in-water channel closures where they intersect with waterways. The locations and overall cost for the in-water channel closures are shown below in Table 4.

Table 4-In-water Closures

RIVER CROSSING	CLOSURE LENGTH (FT)	ESTIMATED COST ($)
Elizabeth River	160	$21M
Morses Creek	120	$11M
Rahway River	350	$62M
Noes Creek	150	$11M
Woodbridge River	220	$30M
Total	1000	$135 M

Table 5-Elevating NJ Turnpike, Installing River Closures

DESCRIPTION	QUANTITY	COST
Elevate Turnpike	6 Miles	$72M
In Water Closure	850 Feet	$122M
Total		$194M

Table 6-Installing Floodwall & Installing River Closures

DESCRIPTION	QUANTITY	COST
Install Floodwall	15 Miles	$320M
In Water Closure	1000 Feet	$135M
Total		$455M

Based on the costs shown in Table 4 and Table 5, elevating the NJ Turnpike and installing the required channel closures will cost $194M in 2014 dollars.

Based on the costs shown in Table 4 and Table 6, installing the new floodwall and installing the required channel closures will cost $455M in 2014 dollars.

One concept for the floodwall involves the use of a telescoping structure that is retained unobtrusively below grade (or at some protection level, say 5 year coastal storm) then activated to the required height when needed by either hydraulic action (as in an automobile jack) or by using a screw mechanism (also like an automobile jack).

2. Mitigating Stormwater-related flooding

The Arthur Kill Study Area is a densely populated community in New Jersey and many areas within the study area are prone to stormwater drainage-related flooding due to the high percentage of precipitation that is converted to stormwater runoff. Each community within the study area requires a stormwater-related flood mitigation plan based on its own unique circumstances and vulnerabilities. However, from a regional perspective the implementation of green infrastructure solutions that will reduce conversion of rainfall into runoff, delay the time it takes for runoff to enter the storm drainage system, prevent runoff from ever reaching the storm drainage system by diversion or infiltration is recommended as a general mitigation measure for the study area, see Table 7 below.

Table 7-Regional Summary of Green Infrastructure Costs

DESCRIPTION	QUANTITY	COST
Green Infrastructure	Sum of All Cities	$655M
Total		$655M

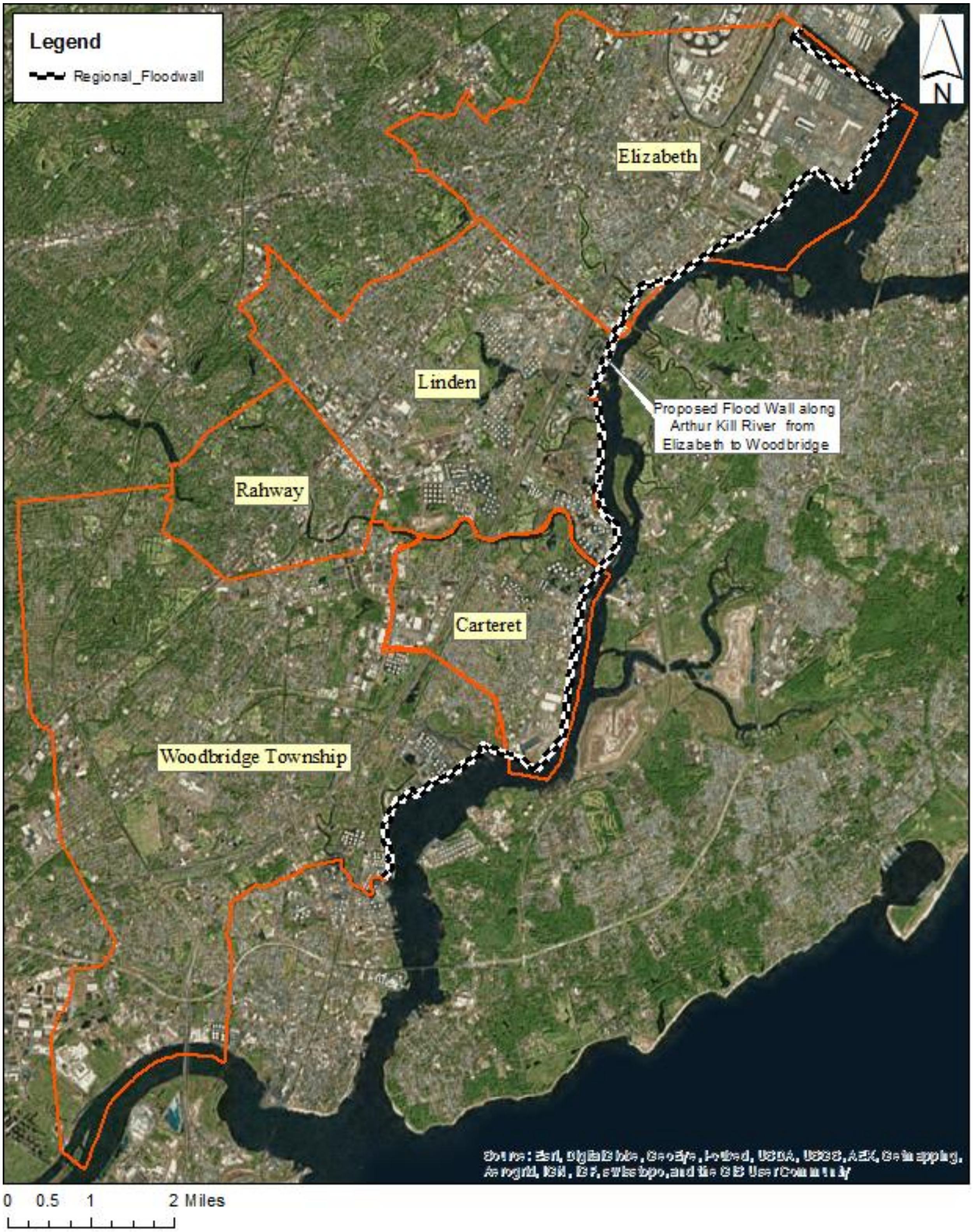

Figure 15-Proposed Regional Seawall along the Arthur Kill River

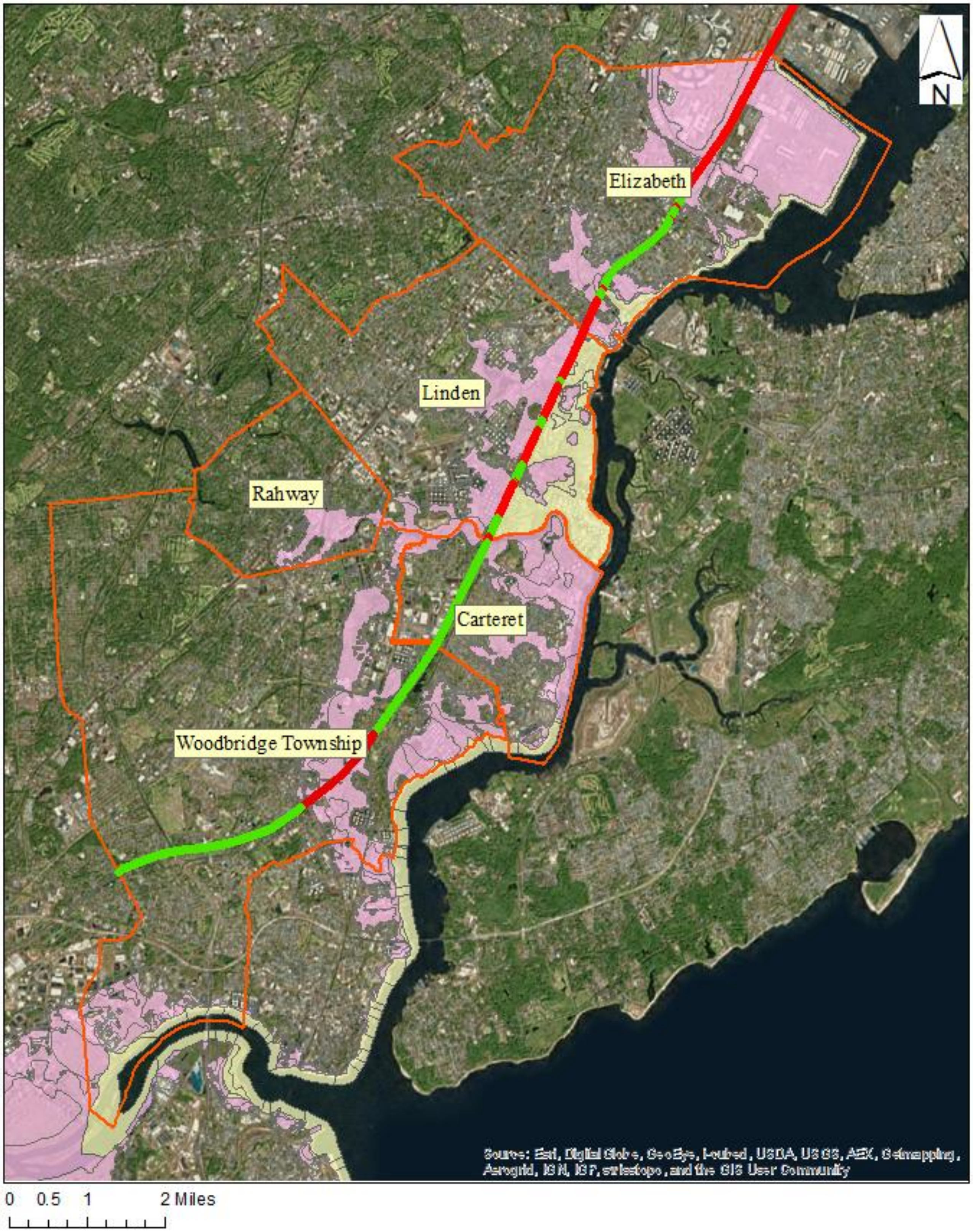

Figure 16-Proposed Locations to Elevate Along NJ Turnpike (Shown In Red)

C. Conclusion

Based on an assessment of the flooding risks from coastal storm events facing the communities in the Arthur Kill Study Area, it has been determined that the best regional mitigation measure is to prevent any anticipated surge from reaching the communities.

To prevent coastal storm surge from reaching all areas with the communities in the Arthur Kill Study Area, the flood wall along with river with the accompanying river closures devices is recommended. Although elevating the NJ Turnpike and installing required river closure devices will cost less than the flood wall option, this option will not protect communities east of the roadway and will result in severe traffic disruption on this heavily trafficked roadway.

After the benefits and costs of each option, installing a flood wall along the river bank will be the most practical and implementable. This wall will comprise of sections that are permanent and with others that are removable. The in-water river closure devices will be open on most occasions and only closed when there is the threat of coastal surge.

IV. City of Elizabeth

A. Background

The City of Elizabeth has a population of 125,000 (US 2010 Census) and is located on the west bank of both the Arthur Kill and Newark Bay waterways, see Figure 17 below.

There are two main sources of flood water that threaten the City of Elizabeth; coastal storm surge and stormwater runoff. Therefore, determination of level of threat from each source of flooding is necessary in assessing the community's vulnerability to flooding.

It is equally important to assess the existing level of flood protection in the community i.e. determine the community's flooding risk based on its location relative to the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) demarcated zones that map areas impacted by the 100 year coastal storm. On the stormwater-related risk assessment side, it is also necessary to determine what rainfall event can be withstood under existing conditions.

Based on the determination of the potential sources of flood waters and the existing level of flood protection available to the community, it must then be decided what level of protection should be recommended. Once the desired level of protection is determined, then it is necessary to determine the correct flood mitigation strategy and measures that will provide this protection.

Investigating the causes of flooding, the sources of flood waters and appropriate flood mitigation techniques are site specific. Therefore, to effectively investigate and recommend mitigation measures for flooding alleviation, it is necessary to target specific locations within the community according to their vulnerability. This targeting of specific areas is possible by using available FIRM mapping data and elevation data obtained from LIDAR.

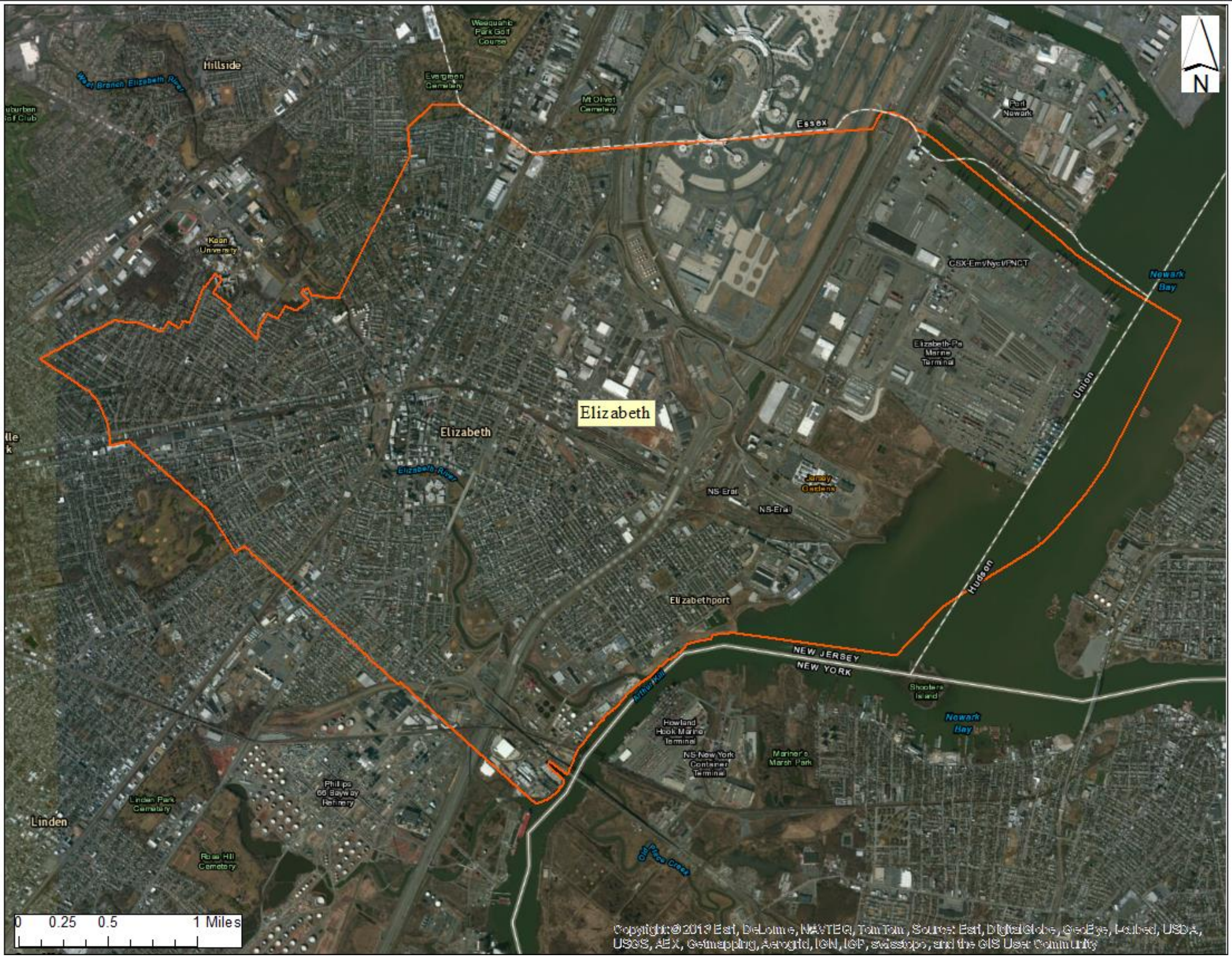

Figure 17-Aerial Photograph of the City of Elizabeth New Jersey

B. Flood Threat Assessment

1. Flood Threat Overview

The coastal flooding threat faced by the City of Elizabeth is related to its location on the western side of Newark Bay and the proximity of the Elizabeth River to low lying areas in the south eastern quadrant of the city.

The stormwater-related flooding threat faced by the city is mainly due to the fact that it's combined sewage system and stormwater drainage system receives a very large amount of stormwater runoff due to the city's high level of impervious cover and low ground gradient, which cannot be readily discharged during periods of elevated tide.

2. Coastal Storm Vulnerability

The FEMA FIRM map was overlaid over the community to determine the extent of flooding by the 100 year flood, see Figure 18 below. From this overlay it can be seen that a large portion will be inundated by the 100 year coastal storm event. Specifically, it can be seen that locations along the Newark Bay waterfront are vulnerable along with areas inland of these locations. Also, areas along the Elizabeth River are vulnerable if the levee is overtopped as it was during Hurricane Sandy.

In addition to the inundation threat from the 100 year coastal storm, locations along the shoreline of both Newark bay and the Arthur Kill face the threat of wave velocity action hazard as designated in the map shown in Figure 18 as the V-Zone.

Figure 18-City of Elizabeth with FEMA Advisory Base Flood Elevation (ABFE) Overlay (FEMA ABFE, 2013)

3. Stormwater Runoff Vulnerability

Due to the population density of the community and the resulting high percentage of impervious cover from houses, roadways and sidewalks, there is a significant amount of runoff that is generated from even small rainfall events. This generated runoff cannot be readily discharged from the drainage system when the water level in the discharging water bodies are elevated, see Figure 20 for map showing overlay of Mean Higher High Water levels in Elizabeth.

The inability of the combined sewer and stormwater drainage systems to discharge freely during elevated tide conditions results in sewer backwater conditions that then lead to sewer and manhole surcharging with resulting local flooding. See Figure 19 below for Combines Sewer Overflow (CSO) discharge locations in Elizabeth.

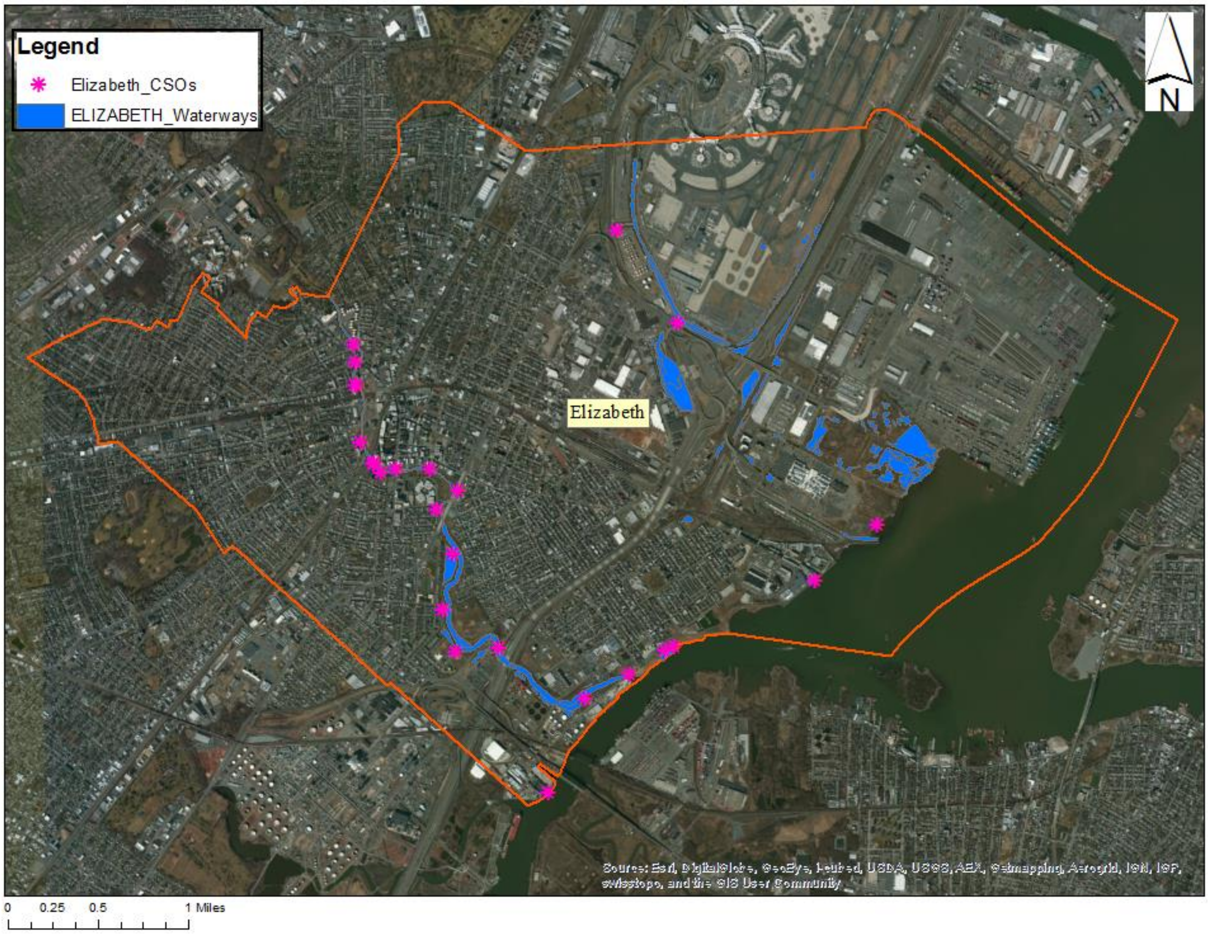

Figure 19-Combined Sewage Overflow Locations in Elizabeth ((NJDEP, 2012)

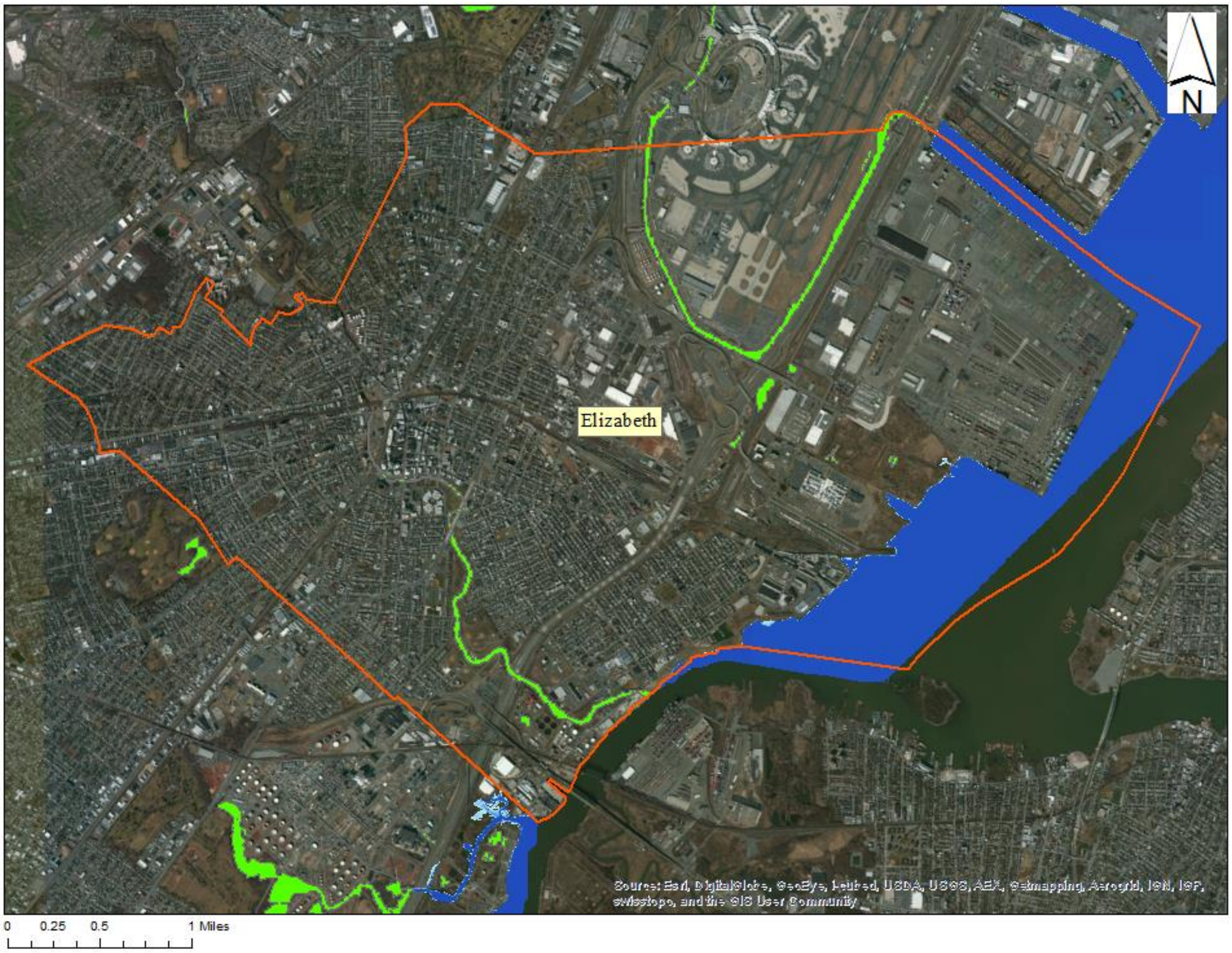

Figure 20-City of Elizabeth with Mean Higher High Water Overlay ((NOAA), (NOS), & (CSC), 2012)

From Table 2 above it can be seen that for the City of Elizabeth (Newark Airport weather station) the 24 hours duration/ 25 year return period precipitation event delivers 6.38 inches of rain. Although, further hydrological study is needed to determine the peak discharge flow that will result from this event given the high percentage of impervious cover in this community it can be expected that a significant percentage of rainfall will be converted into stormwater runoff.

C. Flood Mitigation

1. Coastal Storm Flooding Mitigation

a) Flood Mitigation Projects Provided by City Officials

The City of Elizabeth has been proactive in seeking solutions to their coastal flooding problems. The City provided Rutgers with a list of 18 proposed and ongoing flood mitigation projects; including both coastal storm and stormwater drainage-related projects. The proposed coastal flood mitigation projects are focused on maintaining the Elizabeth River Levee and on protecting commercial interest at the northern end of the Newark Bay coastline in the City. These projects are listed below and mapped in Figure 21.

1. ELIZABETH RIVER FLOOD CONTROL PROJECT

   This project generally consists of the modifications and improvements to the existing flood control facilities and drainage structures along the Elizabeth River from Trotters Lane to Trenton Avenue. Work includes maintenance on earthen levees, demolition, removal and construction of new concrete headwalls, sluice gates, inlet/outlet pipes, control manholes, tide gate valves, flexible check valves, flood gate structures and other drainage structures.

2. FAIRMOUNT AVENUE SEWER PROJECT

   This project generally consists of the construction of a dedicated storm sewer and other stormwater improvements along Fairmount Avenue between Spring Street (US Routes 1 & 9) and Division Street.

3. GREAT DITCH DREDGING PROJECT

   This project generally consists of the dredging of the Great Ditch to provide improved drainage area along a highly industrial section of the City of Elizabeth near Dowd Avenue, Newark Liberty International Airport (EWR) and Interchange 13A of the New Jersey Turnpike.

4. HARDING ROAD COMBINED SEWER PROJECT

This project generally consists of improvements to the existing combined sewer, construction of a new 36" diameter combined sewer and other drainage improvements on Harding Road between Browning Avenue and Park Avenue.

5. MIDTOWN INFRASTRUCTURE IMPROVEMENT CSO ABATEMENT

   This project will construct and/or reconstruct the storm and sanitary sewer system including sewer separation within the Midtown area on portions of the following streets: Murray Street, Sterling Place, Price Street, Union Street, West Grand Street, Crane Street, Julian Place, Harrison Street, West Jersey Street and Westfield Avenue.

6. NORTH AVENUE FLOOD CONTROL PROJECT

   This project consists of drainage improvements for the low area of North Avenue beneath the railroad bridge between Pennsylvania Avenue and Jefferson Avenue. The installation of drainage pipe will extend along Madison Avenue to Fanny Street.

7. PARK AVENUE SEWER FLOW METERING

   The scope of services will provide for the installation of three (3) flow velocity meters along Park Avenue in the existing 48 inch brick sewer for a period of four (4) weeks. The meters will be installed near the intersections of Palisade Road, Harding Road and Galloping Hill Road. The objective of this project is to gauge the flow upstream of the recently completed Park Avenue / Westfield Avenue sewer project as well as potential inflow and infiltration from Roselle Park storm sewer.

8. REMEDIATION OF COMBINED SEWER OVERFLOW (CSO) POINT 002

   The CSO regulator number 002 located at the intersection of Division Street and Fairmount Avenue has been blocked in an effort to redirect flow to another CSO discharge point to address frequent flooding in the area. This configuration has been deemed unacceptable by the NJDEP and requires remediation. The City will evaluate the feasibility of creating an express sewer from Regulator 002 to the netting chamber, separating the storm and sanitary flows and modifying or rehabilitating the chamber. This scope of services will also include utilizing existing topographic survey data, meeting with property owners to discuss flooding of their properties, visual inspection of CSO 002 and the Great Ditch outfall, verifying existing utilities, utilizing modeling software to analyze the existing conditions, evaluation of the feasibility of creating sewer easements through private property, determining the required permits and preparation of a preliminary report discussing the findings of the investigation.

9. SOUTH STREET FLOOD CONTROL PROJECT

   This project consists of the design of drainage improvements for the low area of South Street beneath the railroad bridge between Rahway Avenue and Burnett Street. The sewer would originate at the low point of South Street and proceed along South Street to Burnett Street and discharge to the Elizabeth River.

10. SOUTH STREET VICINTIY FLOOD RELIEF PROJECT

    This project consists of repairs, renovations, and upgrades to the South Street Stormwater Pump Station, restoration of the ponding storage areas and outlet structures, and repairs to sewers and drainage structures located in the study area. Work within the pump station includes replacement and upgrades to the pumps and motors, stand-by emergency generator, sluice gates, flap gates, sump pump, electric controls and instrumentation. The study will alleviate storm related flooding that occurs in the vicinity of South Street, Fourth Avenue and South Spring Street during heavy rainfall events.

11. SUMMER STREET STORM DRAINAGE SYSTEM IMPROVEMENTS

    Project consists of construction of approximately 50 LF of 42”, 1,590 LF of 30”, 170 LF of 16” and 240 LF of 10” storm sewers to alleviate flooding along Summer Street.

12. THIRD AVENUE FLOOD CONTROL PROJECT

    This project consists of the replacement of sections of trunk sewer on Third Avenue between Lt. Glenn Zamorski Drive and South First Street, with a larger sewer as well as modifications to the emergency overflow swale, Flushing Module 12, Storage Module 14 and Regulator 035.

13. TRUMBULL STREET FLOOD CONTROL FEASIBILITY STUDY

The scope of work includes a site survey of the Trumbull Street sewer from Sixth Street to the Newark Bay, installation of six (6) flow meters to collect data for three (3) months, creation of a hydraulic model of the existing sewer area and development of four (4) alternatives to address the flooding issue.

14. VERONA AVENUE / GEBHARDT AVENUE STORM SEWER IMPROVEMENT PROJECT

This project generally consists of the construction of a stormwater collection system, pump station and other drainage improvements to alleviate localized flooding in the area of Verona Avenue and Gebhardt Avenue near the City Line with Union Township/Kean University.

15. WESTERN INTERCEPTOR PROJECT

This project will increase the conveyance capacity of the Western Interceptor through the Mid-Town area with the design of replacement sewers as well as correction of hydraulic restrictions at the Bridge Street Siphon and along Elizabeth Avenue, Pear Street, South Pearl Street and Clarkson Avenue. This project will also increase sewer flow to the Trenton Avenue pump station and reduce CSO overflows in the Midtown Area and is necessary to ensure adequate capacity for the anticipated development within of the midtown redevelopment area. The City is awaiting a final permit from the Army Corps of Engineers and will then bid the project.

16. WESTFIELD AVENUE COMBINED SEWER IMPROVEMENTS

The scope of work included the replacement of approximately 2,500 linear feet of brick combined sewer with 54" and 48" diameter fiberglass reinforced sewer along Westfield Avenue, Park Avenue and through McPherson Park. Work in the intersection of Westfield Avenue and Elmora Avenue included open cut excavation and support of an active 100 year old 42" brick interceptor sewer owned by Joint Meeting of Essex and Union Counties. Approximately 262 linear feet of the 42" brick sewer received a cured in place structural liner. Additional work included drainage improvements on Park Avenue and Bellwood Place.

17. ATALANTA SEA WALL FLOOD CONTROL PROJECT

This project generally consists of the construction of a new sea wall and associated stormwater improvements to assist in mitigating and minimizing coastal flooding from the Arthur Kill/Newark Bay for commercial and industrial properties situated along Atalanta Place, Slater Drive and Puleo Plaza. Currently, this project has no funding and has not been designed.

18. DOWD AVENUE PUMP STATION PROJECT

This project generally consists of the construction of a stormwater pump station and other associated surface drainage improvements in an industrialized area of Dowd Avenue near North Avenue East and Interchange 13A of the New Jersey Turnpike that is consistently affected by localized flooding during heavy rain events. The stormwater pump station will connect to an existing 84” diameter reinforced concrete pipe that connects to an outfall located on the Peripheral Ditch situated in Newark Liberty International Airport (EWR). Currently, this project has no funding and has not been designed.

Note from Rutgers University Flood Study Team regarding projects provided by the City of Elizabeth [Projects shown underlined above will address stormwater-related flooding vulnerabilities and the projects not shown underlined are slated to address flooding from coastal storm surge].

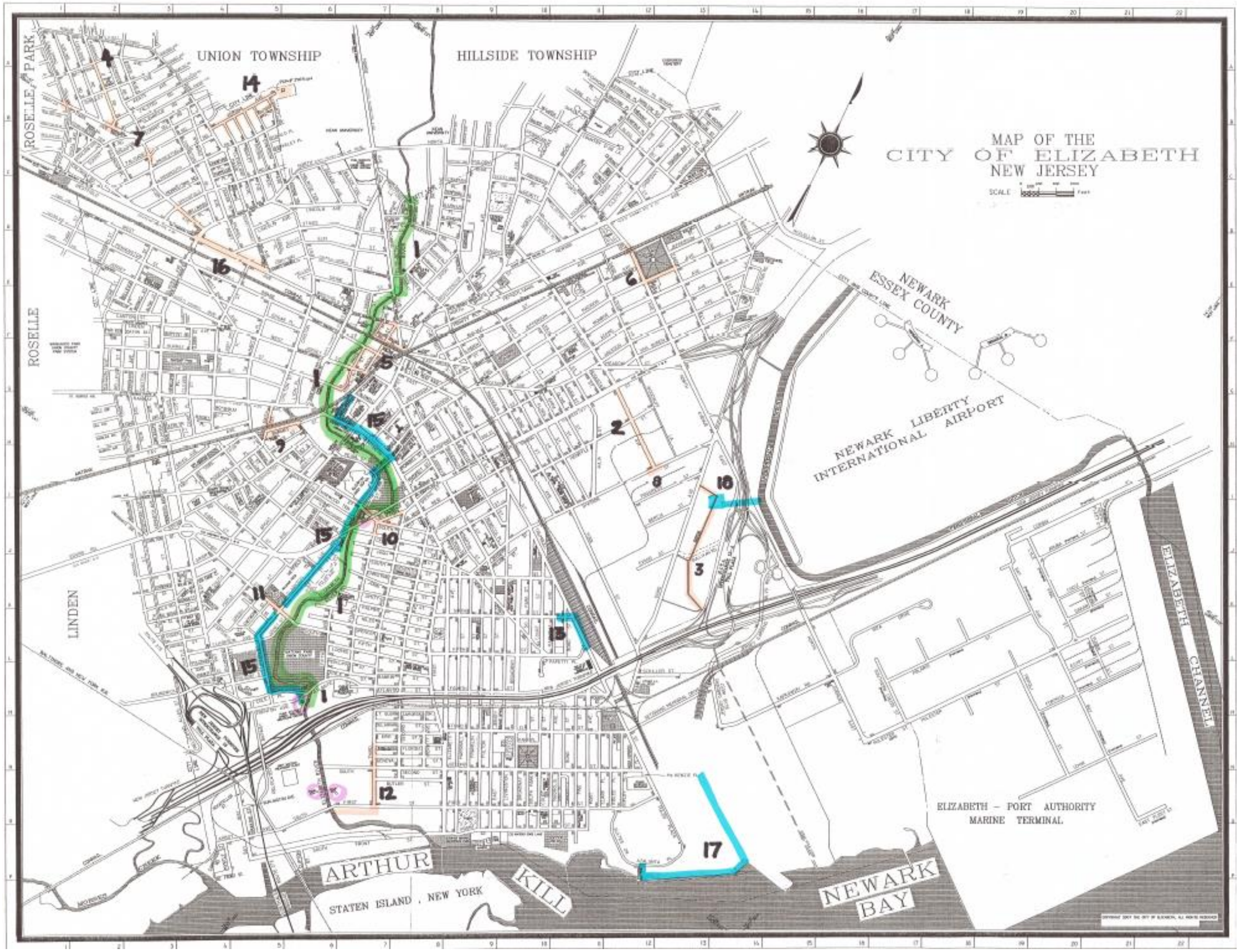

Figure 21-Map Showing City of Elizabeth Flood Mitigation Projects Locations (Provided by City of Elizabeth Officials)

2. Flood Mitigation Projects proposed by Rutgers University Team

The flood mitigation solutions proposed by the Rutgers University Flood Study Team for the coastal storm take into consideration the flooding projected by FEMA in the FIRM map for the City. After review of various options, such as elevating the NJ Turnpike to serve as a surge barrier, it is clear that the most effective way to protect this City from coastal flooding would be to install a seawall from the Elizabeth Channel to Morses Creek along the Newark Bay coastline and to install channel closure structures at the entrance of the Elizabeth River, see Figure 22 below. The proposed seawall will be a mixture of permanent and semi-permanent seawalls sections with the ability to extend higher to address future sea level rise and other contingencies. The proposed coastal flood mitigation measures will preclude the need for the projects proposed by the City for coastal storm protection (Projects not underlined above).

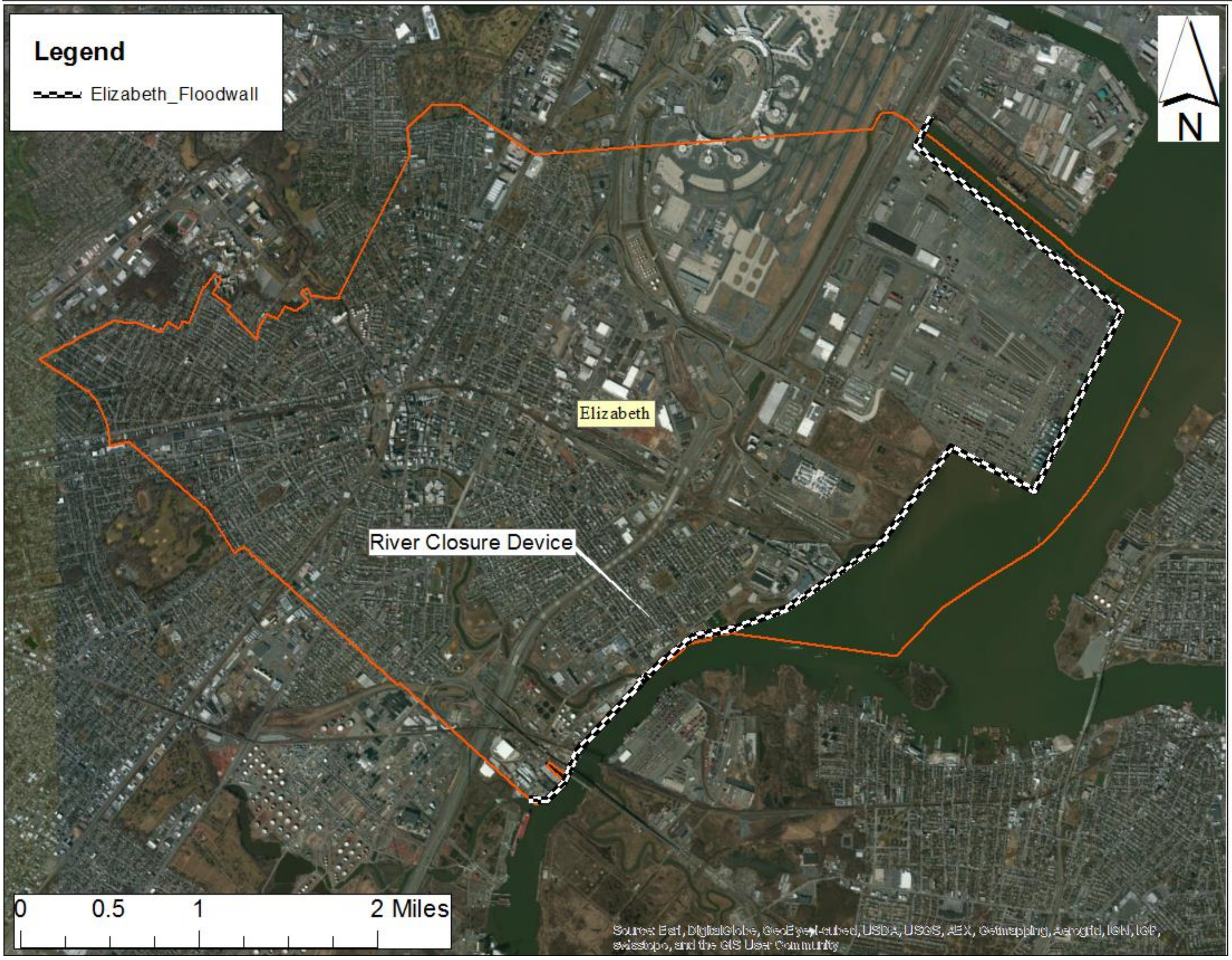

Figure 22-Proposed Seawall & River Closure Location

3. Stormwater-related flooding Mitigation

The City of Elizabeth has been proactive in seeking solutions to their rainfall related flooding problems. As mentioned above, the City has provided Rutgers with a list of 18 proposed and ongoing flood mitigation projects; including both coastal storm (4) and stormwater-related projects (14). The proposed stormwater-related flood mitigation projects are focused largely on improving the conveyance capacity of the system, separating combined sewers, removing system bottlenecks and increased in-sewer flow monitoring.

The proposed stormwater-related flood mitigation recommendations for the City are based largely on information obtained from City officials regarding past flooding events and current know system deficiencies. In general the sewers should have adequate capacity to handle the design storm peak flow. The best way to accomplish this objective is to develop and calibrate a hydraulic/hydrologic model of the City and its watershed (Elizabeth River) then use this model to assess current system performance and identify deficiencies. Once the assessment phase is complete the model should be used to simulate scenarios that will lead to a determination of appropriate conveyance sizing.

To address flooding resulting from the inability of combined sewer overflows and stormwater sewers to discharge freely under elevated tidal conditions, it is recommended that the sewers that drain to the Elizabeth River be converted from combined to separated sewers. Once separated, above ground stormwater storage will be increased along the Elizabeth River levees which will be served by pumping stations that will discharge excess stormwater into the river.

In addition to the sewer conversion, increased storage and pumping proposals it is also important to implement green infrastructure measures that can reduce the amount of precipitation that is converted to runoff and reduce the amount of runoff that gets into the drainage system either by diversion or delay. Besides the flood mitigation benefits, green infrastructure implementation will also reduce the number and volume of the combined sewer overflow (CSO). Rutgers University developed tools to optimize the selection of green infrastructure measures based on the characteristics of the community being considered (Appendix 1-Stormwater Green Infrastructure Methodology).

4. Green Infrastructure Measures

The Rutgers University Flood Study Team has developed a software package that optimizes the implementation of green infrastructure measures for a given study area. Table 8 and Table 9 below provide the software output for the City of Elizabeth.

Table 8: 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	3861615	5393412
Swales	1078682	1078682
Planter box	50338	50338
Vegetated filter strips	1078682	1078682
Permeable sidewalk	826989	826989
Permeable driveway	855659	855659
Permeable parking	355965	355965
Rain garden	201352	201352
Total cost ($) – 10 year	116324878	
Total cost ($) – 50 year	130204133	

Table 9: Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	88082976	0.75
50 year	111525939	0.85

Finally, it is recommended that the projects proposed by the City (shown underlined above) and developed based on field observation of flooding, be studied in greater detail and considered for implementation to deal with stormwater-related flooding issues.

D. Flood Mitigation Cost

The cost to implement the measures needed to mitigate flooding caused by the 100 year coastal storm in the City of Elizabeth is estimated at $171M in 2014 dollars as shown below in Table 10.

Table 10-Flood Mitigation Cost for 100 Year Coastal Storm

DESCRIPTION	QUANTITY	COST
New Floodwall	7 Miles	$150M
In Water Closure	300 Feet	$21M
Total		$171M

The cost to implement the measures recommended to mitigate stormwater-related flooding in the City of Elizabeth is estimated at $321M in 2014 dollars as shown below in Table 11.

Table 11-Flood Mitigation Cost for Stormwater-related flooding

DESCRIPTION	QUANTITY	COST
Sewer Conversion-Combined to Separated	35 Miles	$100M
Proposed City of Elizabeth Projects	Lump Sum	$70M
Green Infrastructure (50 year)	Lump Sum	$130M
Estimated Storage	70,000 CY	$20M
Estimated Pumping	10 MGD	$1M[1]
Total		$321M

1. Pumping cost based on USACE pumping station cost shown in Appendix B for stormwater pumping stations; in City of Elizabeth stormwater water runoff can be mixed with raw sewage in the combined sewer system in which case pumping station cost could be as high as that for the sewage pumping station which would be $5M to $12.5M for a 10 MGD pumping capacity.

E. Conclusion

The City of Elizabeth, New Jersey is located in an area that makes it vulnerable to both coastal flooding from Newark Bay and stormwater-related flooding from Elizabeth River due to the high conversation rate of precipitation to stormwater runoff.

After reviewing a number of different measures it became clear that the best way to mitigate flooding from coastal flooding is to build a seawall along the city's interface with Newark Bay and install a river closure device at the entrance of the Elizabeth River to prevent surge water from bypassing the seawall. The river closure will only be engaged to combat surge from a major coastal event and will remain open at all other times. This measure reduces the need for a piecemeal approach of levee elevation along the river that would be less effective than the proposed measure in any case.

Then on the stormwater-related side, the separation of combined sewers that drain to the tidal Elizabeth River into separate sanitary and stormwater sewers will allow for the above ground storage of stormwater runoff. Additional storage coupled with properly designed pumping capacity will allow for the discharge of excess stormwater runoff that may occur during periods of elevated water level.

Then last but not least, the implementation of green infrastructure will be especially beneficial in this community given its high percentage of impervious cover and associate high stormwater runoff generation. Although expensive, green infrastructure will result in savings from decreased amounts of stormwater runoff that need to be managed as well as other significant benefits.

V. City of Linden

A. Background

City of Linden has a population of 41,000 (US 2010 Census) and is located on the west bank of both the Arthur Kill, see Figure 23 below.

Two main sources of flood water threaten City of Linden; coastal storm surge and stormwater runoff. Therefore, determination of level of threat from each source of flooding is necessary to assess the community's vulnerability to flooding.

It is equally important to assess the existing level of flood protection in the community i.e. determine the community's flooding risk based on its location relative to the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) demarcated zones that map areas impacted by the 100 year coastal storm. On the stormwater-related risk assessment side, it is also necessary to determine what rainfall event can be experienced without flooding under existing conditions.

Based on the determination of the potential sources of flood waters and the existing level of flood protection available to the community, it must then be decided what level of protection should be recommended. Once the desired level of protection is determined, then it is necessary to determine the correct flood mitigation strategy and measures that will provide this protection.

Investigating the causes of flooding, the sources of flood waters and appropriate flood mitigation techniques are site specific. Therefore, to effectively investigate and recommend mitigation measures for flooding alleviation, it is necessary to target specific locations within the community according to their vulnerability. This targeting of specific areas is possible by using available FIRM mapping data and elevation data obtained from LIDAR.

Figure 23-Aerial Photograph of City of Linden New Jersey

B. Flood Threat Assessment

1. Flood Threat Overview

The eastern region of the City between Route 1&9 and the Arthur Kill River is vulnerable to coastal storm flooding as seen in Figure 35 below. This area is largely industrial, with the exception of Tremley Point which is located just west of the NJ Turnpike.

In addition to the 100 year coastal flood threat, the City also experiences frequent flooding at various locations as shown in Figure 24 below. In some of these vulnerable areas flooding is a result of inadequate conveyance capacity in the downstream channels and in some cases the flooding is a result of inadequate conveyance capacity due to coastal hydrology that creates backwater conditions in downstream channels.

The stormwater-related flooding threat faced by the city is mainly due to fact that many creeks within the City drain to tidal waterway does not have sufficient capacity to convey stormwater runoff in sufficient time even when the tide is not elevated. Combined with the highly urbanized nature of the City and its associated high stormwater runoff generation, heavy rainfall usually causes flooding.

After meeting with City officials, the Rutgers Flood Study Team was provided with a map of frequently flooded areas in the City of Linden shown in Figure 24 below:

1. Location#1-Pennsylvania Avenue and Cranford Avenue where Peach Orchard Brook crosses under the Amtrak Railway line (Stormwater-related flooding).
2. Location#2-Emma Place adjacent to West Brook on the southern boundary of the Rose Hill Cemetery (Coastal flooding).
3. Location#3-Community of Tremley Point situated just west where Marshes Creek crosses under the NJ Turnpike (Coastal flooding).

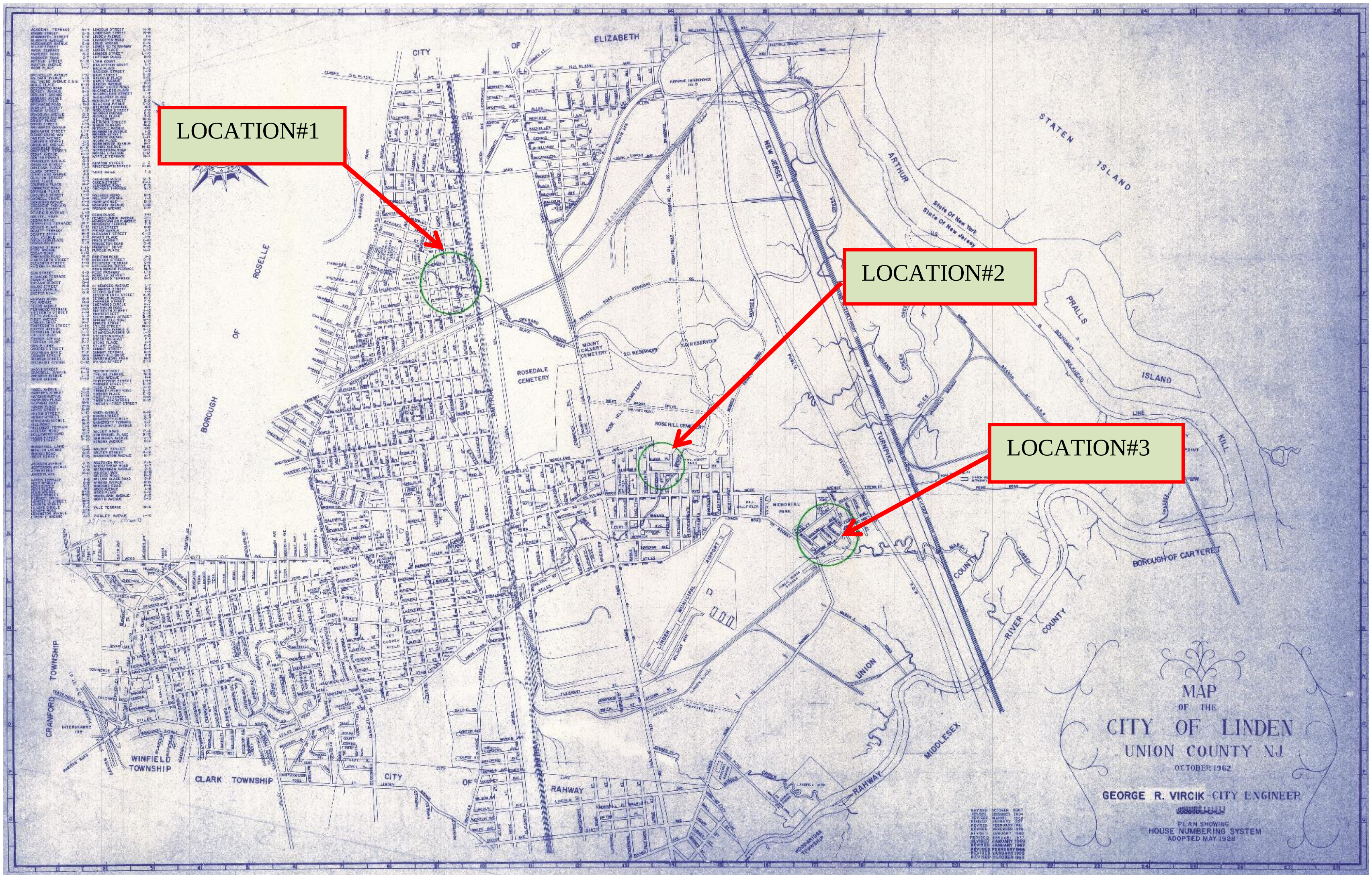

Figure 24-City of Linden Frequent Flooding Locations (Provided by City of Linden Officials)

At Location#1, where Peach Orchard Brook crosses under the Amtrak Railway line (Figure 25 and Figure 26) and at other locations downstream of Railway line, it is clear that conveyance is restricted by debris and sedimentation combined with an undersized culvert under the railway line. Further downstream, just south of Route 1&9 the stream flows into the S.O. Reservoir which is almost completely filled with sediment further restricting flow (Figure 27).

Figure 25-Peach Orchard Brook Crossing at Amtrak Railway Line

Figure 26-Peach Orchard Brook Just Downstream Of Amtrak Railway Line

Figure 27-Peach Orchard Brook Enter Heavily Sedimented S.O. Reservoir

At Location#2, houses situated on the southern boundary of the Rose Hill Cemetery adjacent to West Brook experience frequent flooding. At this location West Brook enters the S.O. Reservoir where heavily silted channel restricts the conveyance capacity of the stream, see Figure 28 & Figure 29.

Figure 28-West Brook Just Upstream of S.O. Reservoir

Figure 29-Elevated Home Adjoining West Brook Upstream of S.O. Reservoir

At Location#3, Tremley Point adjacent to the upper reaches of Marshes and just west of the NJ Turnpike experiences frequent flooding due to both coastal storms and rainfall. The upper reach of Marshes Creek is a heavily sedimented waterway that meanders westward towards the Rahway River. En-route to the Rahway River, the creek crosses under the NJ Turnpike and under a commercial railway line that parallels the Turnpike.

The residences in Tremley Point that are situated on the edges of the Marshes Creek flood plain are prone to flooding for a number of reasons, namely:

- Conveyance in Marshes Creek is impeded by excessive sedimentation, see Figure 30 below.
- Conveyance in Marshes Creek is also impeded at a choke point where it crosses under the railway track see Figure 31, Figure 32 & Figure 33.
- Runoff from rainfall events are not conveyed away from the area at a sufficient rate to prevent flooding during elevated tidal conditions
- Coastal storm surge reaches the community via the Arthur Kill, Rahway River then Marshes Creek route, inundating its low lying areas, see Figure 34.

Figure 30-Marshes Creek Adjoining Tremley Point (South)

Figure 31-Marshes Creek Crossing Under NJ Turnpike

Figure 32-Marshes Creek Upstream Crossing of Railway Line

Figure 33-Marshes Creek Downstream of Railway Line

Figure 34-Tremley Point Showing 100 Year Flood Overlay (FEMA ABFE, 2013)

2. Coastal Storm Vulnerability

The FEMA FIRM 100 year flood map was overlaid over a map of the City to determine the extent of flooding by this event, see Figure 35 below. From this overlay it can be seen that large sections of the City between Route 1&9 and the Arthur Kill will be inundated by these coastal storm events. Specifically, it can be seen that locations along the Arthur Kill waterfront are vulnerable to velocity wave action as well as inundation. Also, vulnerable are low lying inland areas adjacent to the Rahway River and its tributaries such as Marshes Creek.

Figure 35-City of Linden with FEMA ABFE Overlay (FEMA ABFE, 2013)

3. Stormwater Runoff Vulnerability

Due to the population density of the community and the resulting high percentage of impervious cover from houses, roadways and sidewalks, there is a significant amount of rainfall runoff that is generated from even small rainfall events. This generated runoff cannot be readily discharged from the drainage system when the water level in the discharging water bodies are elevated, see Figure 36 for map showing overlay of Mean Higher High Water levels in Linden.

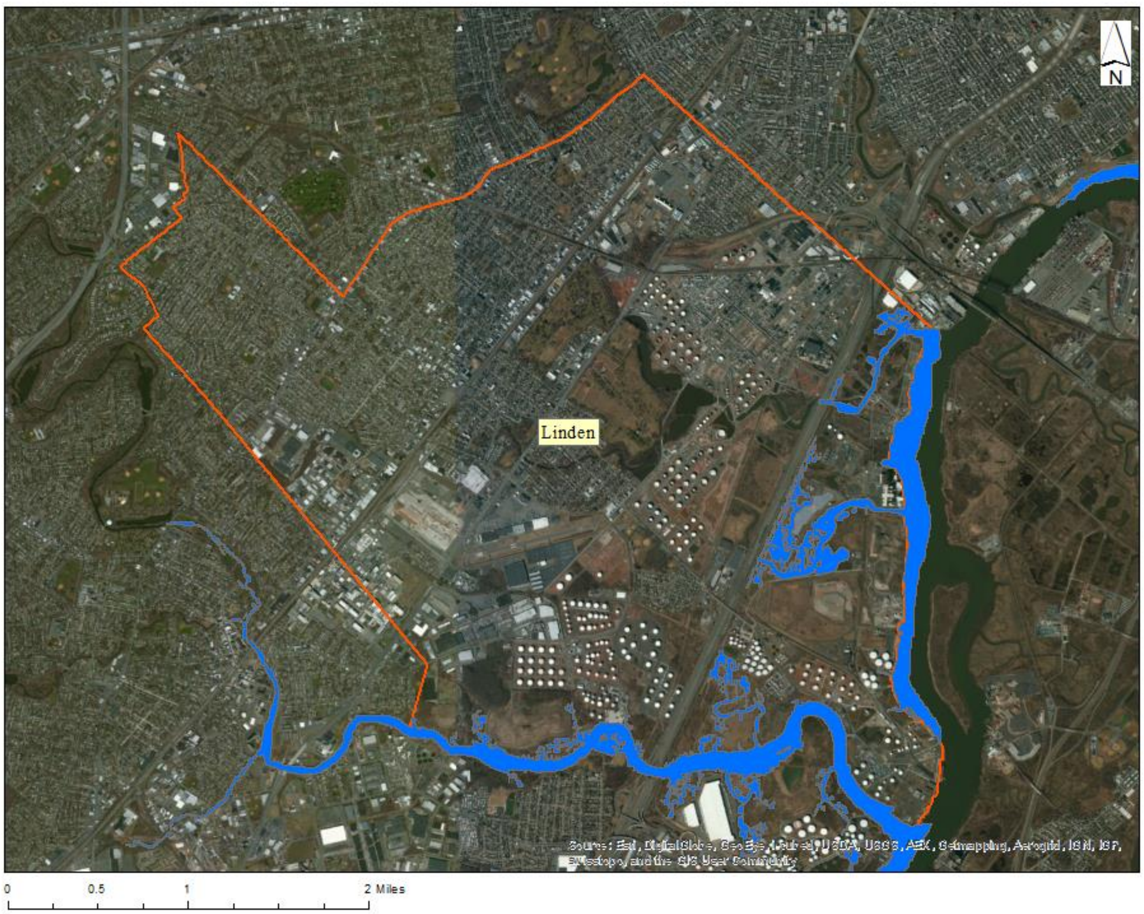

Figure 36-City of Linden with Mean Higher High Water Overlay ((NOAA), (NOS), & (CSC), 2012)

From Figure 36 it is clear that the low lying areas adjacent to Rahway River and its tributaries are flooded during the mean higher high tide and these same areas are vulnerable to stormwater drainage-related flooding even during low tide.

From Table 2 above it can also be seen that for the City of Linden (Newark Airport weather station) the 24 hours duration/ 25 year return period precipitation event delivers 6.38 inches of rain. Although, further hydrological study is needed to determine the peak discharge flow that will result from this event given the high percentage of impervious cover in this community it can be expected that a significant percentage of rainfall will be converted into stormwater runoff.

C. Flood Mitigation

1. Flood Mitigation Projects proposed by Rutgers University Team

The flood mitigation solutions proposed by the Rutgers University Flood Study Team for the coastal storm take into consideration the flooding projected by FEMA in the FIRM map for the City. After reviewing various options, such as elevating the NJ Turnpike to serve as a surge barrier, it is clear that the most effective way to protect this City from coastal flooding would be to install a seawall from the Morses Creek in the north to the Rahway River in the south and to install channel closure structures at the confluence of the latter and the Arthur Kill. The proposed seawall will be a mixture of permanent and semi-permanent seawalls sections with the ability to extend higher to address future sea level rise and other contingencies see Figure 37 below. In-water closure devices will also be required at the Arthur Kill confluences of Morses Creek and Piles Creek.

Figure 37-Proposed City of Linden Floodwall

2. Stormwater-related flooding Mitigation

The proposed stormwater-related flood mitigation recommendation for the City of Linden is based largely on information obtained from City officials regarding past flooding events and current know system deficiencies. In general the stormwater sewers and receiving streams should have adequate capacity to handle the design storm peak flow. The best way to accomplish this objective is to develop and calibrate a hydraulic/hydrologic model of the City and its watershed (Rahway River) then use this model to assess current system performance and identify deficiencies. Once the assessment phase is complete the model should be used to simulate scenarios that will lead to a determination of appropriate conveyance sizing.

In addition to the appropriate sizing of stormwater conveyance infrastructure, increased storage can also play a role in reducing or delaying flow from entering the drainage system. Equally important is the role that green infrastructure measures can play to reduce the amount of precipitation that is converted to runoff and also to reduce the amount of runoff that gets into the drainage system either by diversion or delay. Rutgers University developed tools to optimize the selection of green infrastructure measures based on the characteristics of the community being considered (See Appendix 1-Stormwater Green Infrastructure Methodology).

One location that is especially vulnerable to stormwater-related flooding is Tremley Point where inadequate conveyance during all tidal conditions leads to flooding in the low lying areas. Accordingly, to alleviate the flooding at this location, the following measures are proposed:

1. Straighten Marshes Creek west of the NJ Turnpike from the current meandering route to a more direct route to the NJ Turnpike Crossing, see Figure 38 below.
2. Create storage on the banks of the rerouted Marshes Creek for runoff storage, see Figure 38 below.
3. Install new 8 foot diameter culvert underneath the railway track to remove current bottleneck, see Figure 39 below.
4. Install headwalls and tide gates on the existing and proposed culverts under the railway track, see Figure 39 below.
5. Install green infrastructure solutions to reduce runoff from Tremley Point.

Figure 38-Proposed Channelized Marshes Creek and Proposed Storage

Figure 39-Culvert and Headwall under Rail Way Track

3. Green Infrastructure Measures

The Rutgers University Flood Study Team has developed a software package that optimizes the implementation of green infrastructure measures for a given study area. Table 12 and Table 13 below provide the software output for the City of Linden.

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	9746083	11457949
Swales	286448	286448
Planter box	114579	114579
Vegetated filter strips	286448	286448
Permeable sidewalk	2148365	2148365
Permeable driveway	2506426	2506426
Permeable parking	930958	930958
Rain garden	458317	458317
Total cost ($) – 10 year	252392128	
Total cost ($) – 50 year	282550585	

Table 13 : Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	131406059	0.52
50 year	165381851	0.58

D. Flood Mitigation Cost

1. 100 Year Coastal Storm Flood Mitigation

The cost to implement the measures needed to mitigate flooding caused by the 100 year coastal storm in City of Linden is estimated at $158M in 2014 dollars as shown below in Table 14.

Table 14-Flood Mitigation Cost for 100 Year Coastal Storm

DESCRIPTION	QUANTITY	COST
New Floodwall	4 Miles	$85M
In Water Closure	500 Feet	$73M
Total		$158M

2. Stormwater-Related Flood Mitigation

The cost to implement the measures to mitigate stormwater-related flooding in City of Linden is estimated at $300M in 2014 dollars as shown below in Table 15.

Table 15-Flood Mitigation Cost for Stormwater-related flooding

DESCRIPTION	QUANTITY	COST
City of Linden	Lump Sum	$20M
Green Infrastructure (50 year)	Lump Sum	$280M
Total		$300M

E. Conclusion

The City of Linden, New Jersey is located in an area that makes it vulnerable to both coastal flooding from the Arthur Kill River and stormwater-related flooding caused by high stormwater runoff generated due to the City's high percentage of impervious cover coupled with inadequate conveyance capacity of the stormwater infrastructure.

After reviewing a number of different measures it became clear that the best way to mitigate flooding from coastal sources is to build a seawall along the City's interface with the Arthur Kill and to install river closure devices at the entrances of the Rahway River and Morses Creek to prevent surge water from entering these channels. The river closures will only be engaged to combat surge from major coastal events and will remain open at all other times.

Then on the stormwater-related flooding side, improving the conveyance capacity of the tidal Marshes Creek will allow for better conveyance during low tide conditions. Additional storage can also help mitigate flooding during low tide conditions.

Then last but not least, the implementation of green infrastructure will be especially beneficial in this community given its high percentage of impervious cover and associate high stormwater runoff generation. Although expensive, green infrastructure will result in savings from decreased amounts of stormwater runoff that need to be managed as well as other significant benefits.

VI. City of Rahway

A. Background

The City of Rahway has a population of 28,000 (US 2012 Census) and is located on the west bank of the Arthur Kill, see Figure 40 below.

Two main sources of flood water that threaten the City of Rahway are from coastal storm surge and stormwater runoff. Therefore, determination of level of threat from each source of flooding is necessary to assess the community's vulnerability to flooding.

It is equally important to assess the existing level of flood protection in the community i.e. determine the community's flooding risk based on its location relative to the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) demarcated zones that map areas impacted by the 100 year return period coastal storm. On the stormwater-related risk assessment side, it is necessary to determine what rainfall event can be experienced without flooding under existing conditions.

Based on the determination of the potential sources of flood waters and the existing level of flood protection available to the community, it must then be decided what level of protection should be recommended. Once the desired level of protection is determined, then it is necessary to determine the correct flood mitigation strategy and measures that will provide this protection.

Investigating the causes of flooding, the sources of flood waters and appropriate flood mitigation techniques are site specific. Therefore, to effectively investigate and recommend mitigation measures for flooding alleviation, it necessary to target specific locations within the community according to their vulnerability. This targeting of specific areas is possible by using available FIRM mapping data and elevation data obtained from LIDAR.

Figure 40-Aerial Photograph of City of Rahway New Jersey

B. Flood Threat Assessment

1. Flood Threat Overview

The City of Rahway experienced flooding during Hurricane Sandy when the river's levee was overtopped in downtown Rahway. The Rahway River levee also experiences overtopping from the 100 year coastal storm as shown in Figure 41 below.

The stormwater-related flooding threat faced by the city is mainly due to the fact that the highly urbanized nature of the City leads to high stormwater runoff generation so that heavy rainfall usually causes localized flooding.

2. Coastal Storm Vulnerability

The FEMA FIRM 100 year flood map was overlaid over a map of the City to determine the extent of flooding by this event, see Figure 41 below. From this overlay it can be seen that large sections of downtown Rahway is flooded by this coastal event along the river.

Figure 41-City of Rahway with FEMA ABFE (FEMA ABFE, 2013)

3. Stormwater Runoff Vulnerability

Due to the population density of the community and the resulting high percentage of impervious cover from houses, roadways and sidewalks, there is a significant amount of rainfall runoff that is generated from even small rainfall events. This generated runoff cannot be readily discharged from the drainage system when the water level in the discharging water bodies are elevated, see Figure 36 for map showing overlay of Mean Higher High Water levels in Rahway.

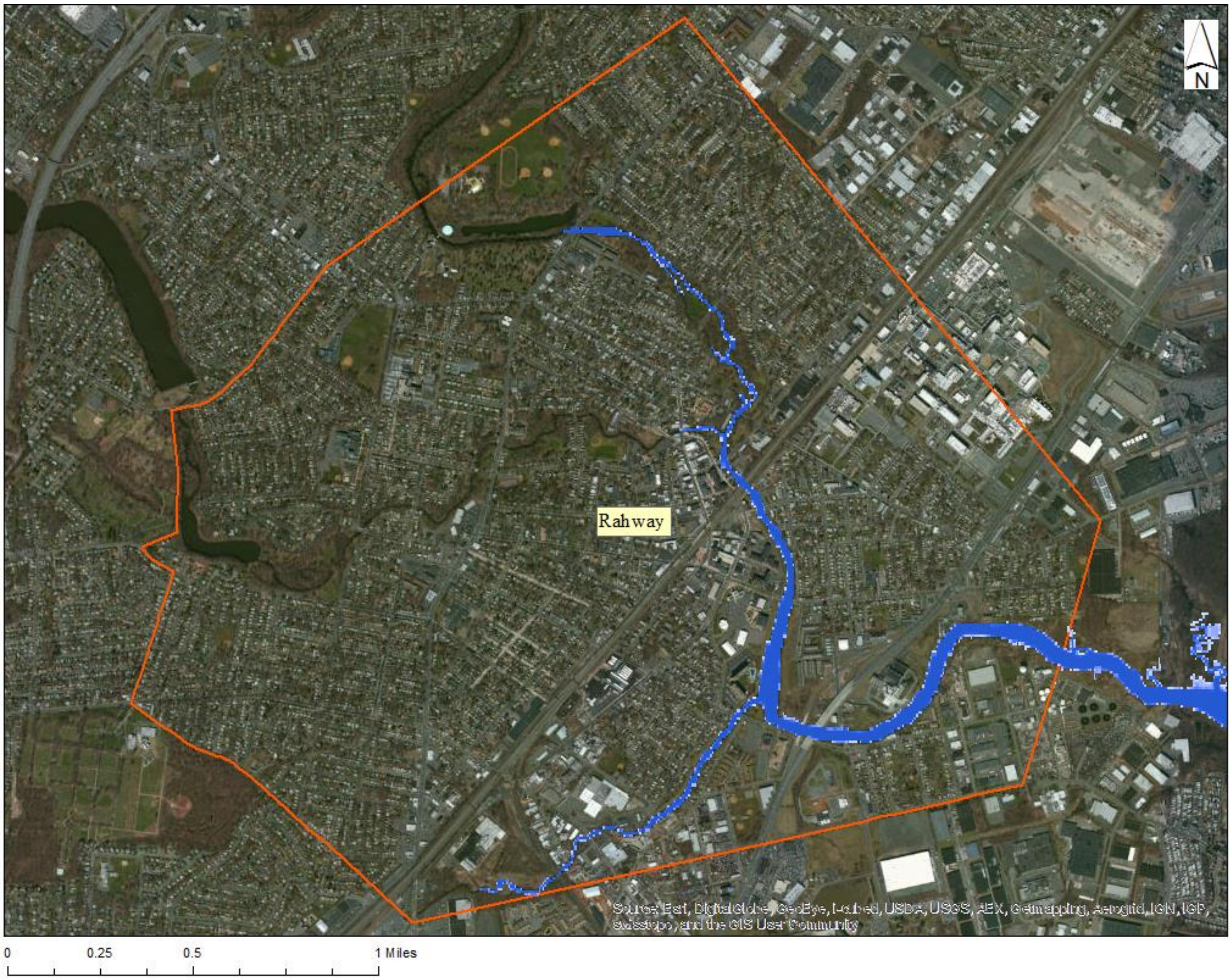

Figure 42-City of Rahway with Mean Higher High Water (MHHW) Overlay ((NOAA), (NOS), & (CSC), 2012)

From Figure 42 it is clear that the water level in the Rahway River is elevated during the MHHW which could lead to localized flooding when stormwater sewers are unable to discharge by gravity to this waterway. Further study is needed to determine exactly how vulnerable the stormwater system is to tidal elevation.

From Table 2 above it can also be seen that for the City of Rahway (Newark Airport weather station) the 24 hours duration/ 25 year return period precipitation event delivers 6.38 inches of rainfall. Although, further hydrological study is needed to determine the peak discharge flow that will result from this event given the high percentage of impervious cover in this community it can be expected that a significant percentage of rainfall will be converted into stormwater runoff.

C. Flood Mitigation

1. Flood Mitigation Projects proposed by Rutgers University Team

The flood mitigation solutions proposed by the Rutgers University Flood Study Team for the coastal storm take into consideration the flooding projected by FEMA in the FIRM map for the City. After reviewing various options, it is clear that the most effective way to protect this City from coastal flooding would be to install an in-water channel closure structures at the confluence of Rahway River and the Arthur Kill.

2. Stormwater-related flooding Mitigation

Concrete stormwater-related flood mitigation measures cannot be proposed this time before a full evaluation can be performed on the City's stormwater drainage system. Notwithstanding the lack of sufficient information, enough is known about the impervious nature of the City to recommend green infrastructure measures that can reduce the amount of precipitation that is converted to runoff and also to reduce the amount of runoff that gets into the drainage system either by diversion or delay. Rutgers University has developed tools to optimize the selection of green infrastructure measures based on the characteristics of the community being considered (Appendix 1-Stormwater Green Infrastructure Methodology).

3. Green Infrastructure Measures

The Rutgers University Flood Study Team has developed a software package that optimizes the implementation of green infrastructure measures for a given study area. Table 16 and Table 17 below provide the software output for the City of Rahway.

Table 16 : Optimal combination of green infrastructure and associated cost to remove 1 inch of runoff within 100-year flood zone

	Optimal area (ft^2) for 1 inch runoff removal	Maximum potential area (ft^2)
Green roof	993501	2126496
Swales	354416	354416
Planter box	21264	21264
Vegetated filter strips	354416	354416

Permeable sidewalk	330788	330788
Permeable driveway	413485	413485
Permeable parking	153580	153580
Rain garden	85056	85056
Total cost ($) – 10 year	34869099	
Total cost ($) – 50 year	39518962	

Table 17 : Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	33027462	0.94
50 year	38333393	0.97

D. Flood Mitigation Cost

1. 100 Year Coastal Storm Flood Mitigation

The cost to implement the measures needed to mitigate flooding caused by the 100 year coastal storm in City of Rahway is estimated at $62M in 2014 dollars as shown below in Table 18.

Table 18-Flood Mitigation Cost for 100 Year Coastal Storm

DESCRIPTION	QUANTITY	COST
In Water Closure	350 Feet	$62M
Total		$62M

2. Stormwater-Related Flood Mitigation

The cost to implement the measures to mitigate stormwater-related flooding in City of Rahway is estimated at $60M in 2014 dollars as shown below in Table 19. This figure includes an allocation of $20M that will be used to implement stormwater-related mitigation measures after vulnerabilities are identified by further study.

Table 19-Flood Mitigation Cost for Stormwater-related flooding

DESCRIPTION	QUANTITY	COST
Stormwater-related Projects Allocation	Lump Sum	$20M
Green Infrastructure (50 years)	Lump Sum	$40M
Total		$60M

E. Conclusion

The City of Rahway, New Jersey is vulnerable to coastal flooding if the Rahway River levee is overtopped. This levee was overtopped during Hurricane Sandy and will be overtopped by the 100 year coastal storm event.

After reviewing a number of different measures including elevating the existing Rahway River levee it is clear that the best way to protect the City of Rahway is to mitigate surge water from entering the channel by installing a river closures at the confluence of the Rahway River and the Arthur Kill. The river closure will only be engaged to combat surge from major coastal events and will remain open at all other times.

The cost to mitigation stormwater related mitigation is unknown at this time since further study is required to determine appropriate mitigation measures. Accordingly, it is suggested that $20M be set aside to implement future stormwater-related mitigation projects.

Then last but not least, the implementation of green infrastructure will be especially beneficial in this community given its high percentage of impervious cover and associate high stormwater runoff generation. Although expensive, green infrastructure will result in savings from decreased amounts of stormwater runoff that need to be managed and other significant benefits.

VII. Borough of Carteret

A. Background

Borough of Carteret has a population of 24,000 (US 2012 Census) and is located on the west bank of the Arthur Kill, see Figure 43 below.

Two main sources of flood water that threaten the Borough of Carteret are from coastal storm surge and stormwater runoff. Therefore, determination of level of threat from each source of flooding is necessary to assess the community's vulnerability to flooding.

It is equally important to assess the existing level of flood protection in the community i.e. determine the community's flooding risk based its location relative to the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) demarcated zones that map areas impacted by the 100 year return period coastal storm. On the stormwater-related risk assessment side, it is necessary to determine what rainfall event can be experienced without flooding under existing conditions.

Based on the determination of the potential sources of flood waters and the existing level of flood protection available to the community, it must then be decided what level of protection should be recommended. Once the desired level of protection is determined, then it is necessary to determine the correct flood mitigation strategy and measures that will provide this protection.

Investigating the causes of flooding, the sources of flood waters and appropriate flood mitigation techniques are site specific. Therefore, to effectively investigate and recommend mitigation measures for flooding alleviation, it necessary to target specific locations within the community according to their vulnerability. This targeting of specific areas is possible by using available FIRM mapping data and elevation data obtained from LIDAR.

Figure 43-Aerial Photograph of Borough of Carteret New Jersey

B. Flood Threat Assessment

1. Flood Threat Overview

The eastern region of the Borough alongside the Arthur Kill River and the areas alongside the Noes Creek are vulnerable to coastal storm flooding as seen in Figure 18 below. The northern areas of the Borough are vulnerable to flooding when the Rahway River overtops it banks, also as shown in Figure 18 below.

The stormwater-related flooding threat faced by the city is mainly due to fact that the Borough is highly urbanized which leads to the generation of large stormwater runoff that can overcome the available conveyance in the surrounding waterways.

2. Coastal Storm Vulnerability

The FEMA FIRM 100 year flood map was overlaid over a map of the Borough to determine the extent of flooding by this event, (Figure 44). From this overlay it can be seen that large sections of the City along the Arthur Kill, Rahway River and Noes Creek will be inundated by this coastal storm. Specifically, it can be seen that some locations along the Arthur Kill waterfront are also vulnerable to wave action velocity as well as inundation.

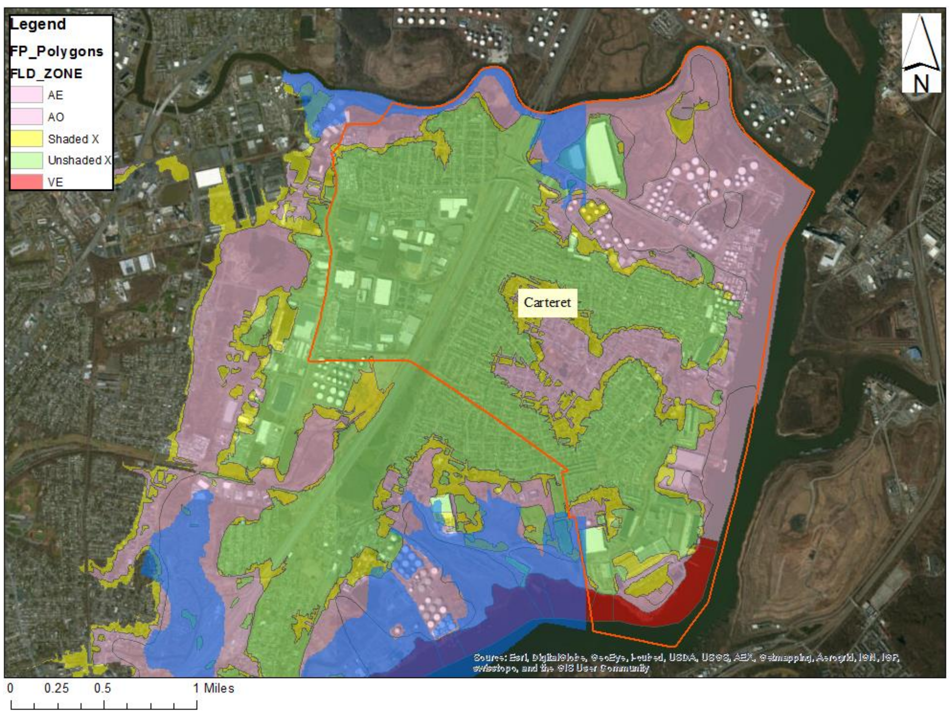

Figure 44-Borough of Carteret with FEMA Preliminary FIRM Overlay (FEMA Prelim. FIRM, 2013)

3. Stormwater Runoff Vulnerability

Due to the population density of the community and the resulting high percentage of impervious cover from houses, roadways and sidewalks, there is a significant amount of rainfall runoff that is generated from even small rainfall events. This generated runoff cannot be readily discharged from the drainage system when the water level in the discharging water bodies are elevated, see Figure 36 for map showing overlay of Mean Higher High Water levels in Carteret.

Figure 45-Borough of Carteret with Mean Higher High Water Overlay ((NOAA), (NOS), & (CSC), 2012)

From Figure 36 it is clear that the low lying areas adjacent to Rahway River are flooded during the mean higher high tide and these same areas are vulnerable to stormwater-related flooding if sufficient precipitation coincides with elevated tidal conditions.

From Table 2 above it can be seen that for the Borough of Carteret (Newark Airport weather station) the 24 hours duration/ 25 year return period precipitation event delivers 6.38 inches of rain. Although, further hydrological study is needed to determine the peak discharge flow that will result from this event given the high percentage of impervious cover in this community, it can be expected that a significant percentage of rainfall will be converted into stormwater runoff.

C. Flood Mitigation

1. Flood Mitigation Projects proposed by Rutgers University Team

The flood mitigation solutions proposed by the Rutgers University Flood Study Team for the coastal storm take into consideration the flooding projected by FEMA in the FIRM map for the Borough. After reviewing various options, it is clear that the most effective way to protect this location from coastal flooding would be to install a seawall from the Rahway River in the north along the Arthur Kill adjacent to Carteret in conjunction with channel closure structures at the confluences of the Rahway River/Arthur Kill and Noes Creek/Arthur Kill. The proposed seawall will be a mixture of permanent and semi-permanent seawalls sections with the ability to extend higher to address future sea level rise and other contingencies see Figure 38 below.

Figure 46-Proposed Seawall along the Arthur Kill in Carteret

2. Stormwater-related flooding Mitigation

The best way to determine appropriate stormwater-related flood mitigation strategies for the Borough of Carteret is to develop, calibrate then utilize a hydraulic/hydrologic model for the Borough and its watershed, first to assess the current stormwater conveyance system capacity and performance then to simulate various mitigation measures that may address identified deficiencies.

According to the Borough's website a flood mitigation study was conducted by an outside consultant (T&M, 2013) on areas that drain to Noes Creek (Figure 47). The study found that the storm drainage system in this area is undersized and proposes improvements (at the cost of $8M) including installation of pumping capacity to provide flood mitigation. Rutgers has not been able to independently verify the findings of this study and will not be able to do so until previously mentioned hydrologic/hydraulic modeling is conducted.

Also important to stormwater-related flood mitigation is the role that green infrastructure measures can play to reduce the amount of precipitation that is converted to stormwater runoff and also to reduce the amount of runoff that gets into the drainage system either by diversion or delay. Rutgers University has developed tools to optimize the selection of green infrastructure measures based on the characteristics of the community being considered (See Appendix 1-Stormwater Green Infrastructure Methodology).

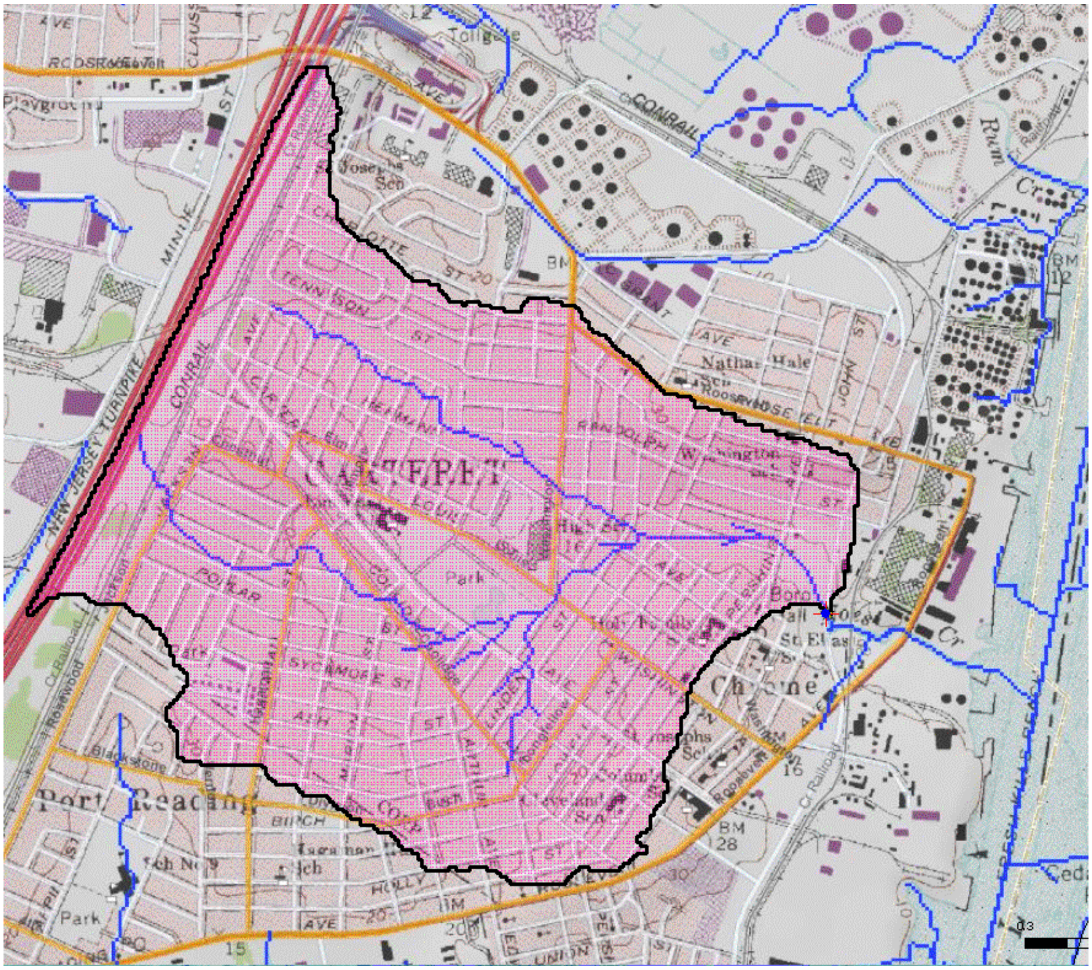

Figure 47-Noes Creek Watershed (USGS STREAMSTATS, 2014)

3. Green Infrastructure Measures

The Rutgers University Flood Study Team has developed a software package that optimizes the implementation of green infrastructure measures for a given study area. Table 20 and Table 21 below provide the software output for the Borough of Carteret.

Table 20- 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	927157	1505356
Swales	282267	282267
Planter box	15053	15053
Vegetated filter strips	282267	282267
Permeable sidewalk	262518	262518
Permeable driveway	319215	319215
Permeable parking	95924	95924
Rain garden	75265	75265
Total cost ($) – 10 year	30,250,655	
Total cost ($) – 50 year	34,130,483	

Table 21-Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	20442590	0.67
50 year	25596513	0.75

D. Flood Mitigation Cost

1. 100 Year Coastal Storm Flood Mitigation

The cost to implement the measures needed to mitigate flooding caused by the 100 year coastal storm in the Borough of Carteret is estimated at $143M in 2014 dollars as shown below in Table 22.

Table 22-Flood Mitigation Cost for 100 Year Coastal Storm

DESCRIPTION	QUANTITY	COST
New Floodwall	3 Miles	$70M
In Water Closure	400 Feet	$73M
Total		$143M

2. Stormwater-Related Flood Mitigation

The cost to implement the measures to mitigate stormwater-related flooding in Borough of Carteret is estimated at $85M in 2014 dollars as shown below in Table 23. This figure includes an allocation of $50M that will be used to implement stormwater-related mitigation measures after vulnerabilities are identified by further study.

Table 23-Flood Mitigation Cost for Stormwater-related flooding

DESCRIPTION	QUANTITY	COST
Stormwater-related Projects	Lump Sum	$50M
Green Infrastructure (50 years)	Lump Sum	$35M
Total		$85M

E. Conclusion

The Borough of Carteret, New Jersey is located in an area that makes it vulnerable to both coastal flooding from the Arthur Kill River and stormwater-related flooding caused by high stormwater runoff generated due to the City's high percentage of impervious cover coupled with inadequate conveyance capacity of the stormwater infrastructure.

After reviewing a number of different measures it became clear that the best way to mitigate flooding from coastal flooding is to build a seawall along the Borough's interface with the Arthur Kill and to install river closure devices at the entrances of the Rahway River and Noes Creek to prevent surge water from entering these channels. It is important to note that the river closure devices will only be engaged to combat surge from major coastal events and will remain open at all other times.

Then on the stormwater-related side, the implementation of green infrastructure will be especially beneficial in this community given its high percentage of impervious cover and associate high stormwater runoff generation particularly in the low lying areas that comprise the Noes Creek watershed. Although expensive, green infrastructure will result in savings from decreased amounts of stormwater runoff that need to be managed as well as other significant benefits.

The cost to mitigation stormwater related mitigation is unknown at this time since further study is required to determine appropriate mitigation measures. Accordingly, it is suggested that $50M be set aside to implement future stormwater-related mitigation projects.

Finally, it is of utmost importance that a full hydrologic/hydraulic study be performed to determine the existing performance and operation of the stormwater drainage system of the Borough and the overall Arthur Kill watershed that will allow for a holistic study that can identify deficiencies and simulate appropriate mitigation measures.

VIII. Woodbridge Township

A. Background

Woodbridge Township has a population of 97,000 (US 2010 Census) and is located on the west bank of both the Arthur Kill, see Figure 48 below.

Two main sources of flood water threaten Woodbridge Township; coastal storm surge and stormwater runoff. Therefore, determination of level of threat from each source of flooding is necessary to assess the community's vulnerability to flooding.

It is equally important to assess the existing level of flood protection in the community i.e. determine the community's flooding risk based on its location relative to the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) demarcated zones that map areas impacted by the 100 year coastal storm. On the stormwater-related risk assessment side, it is also necessary to determine what rainfall event can be experienced without flooding under existing conditions.

Based on the determination of the potential sources of flood waters and the existing level of flood protection available to the community, it must then be decided what level of protection should be recommended. Once the desired level of protection is determined, then it is necessary to determine the correct flood mitigation strategy and measures that will provide this protection.

Investigating the causes of flooding, the sources of flood waters and appropriate flood mitigation techniques are site specific. Therefore, to effectively investigate and recommend mitigation measures for flooding alleviation, it necessary to target specific locations within the community according to their vulnerability. This targeting of specific areas is possible by using available FIRM mapping data and elevation data obtained from LIDAR.

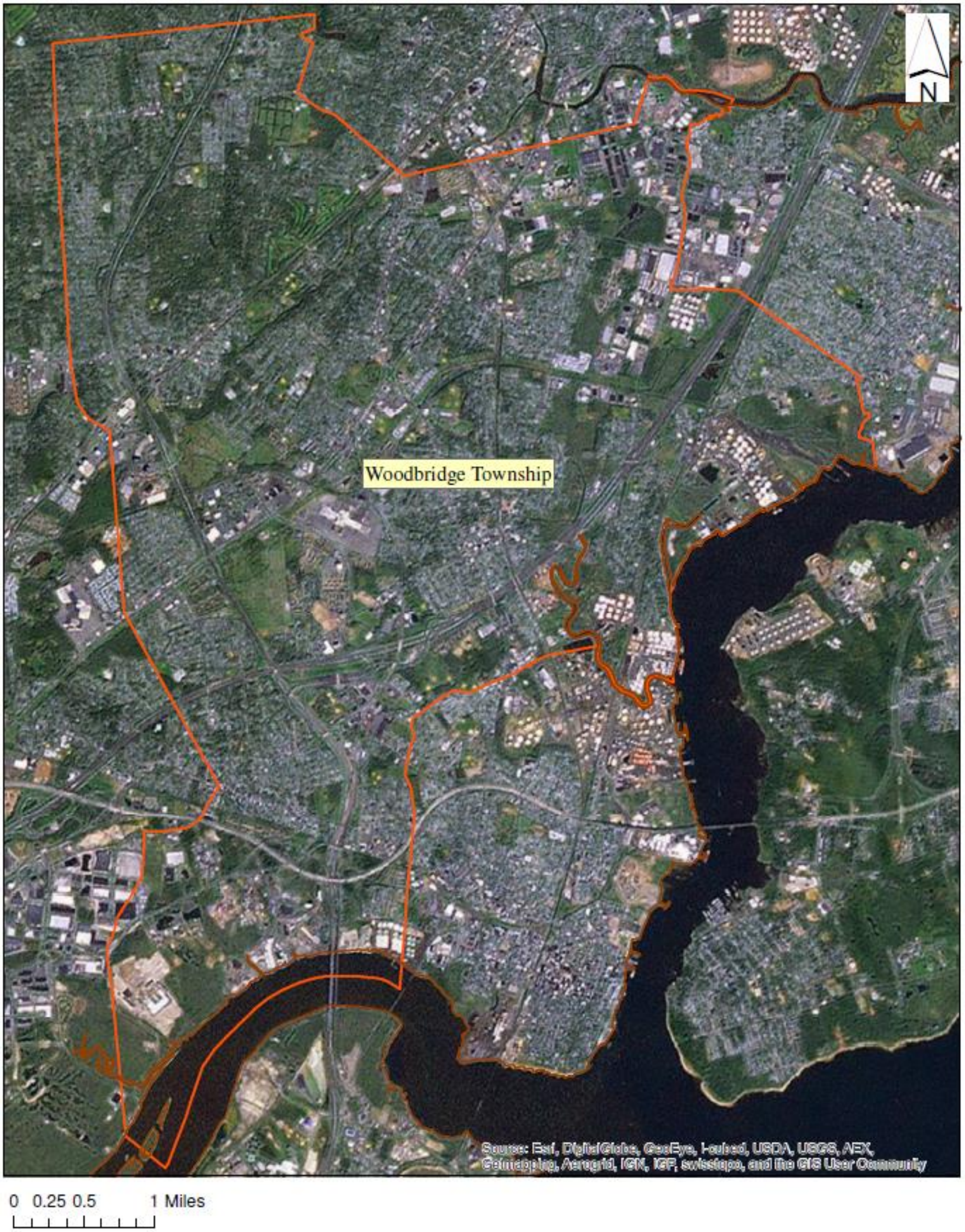

Figure 48-Aerial Photograph of Woodbridge Township New Jersey

B. Flood Threat Assessment

1. Flood Threat Overview

The coastal flooding threat faced by Woodbridge Township is related to its location on the Arthur Kill and the close proximity of the Woodbridge River to low lying communities along its banks.

The stormwater-related flooding threat faced by the city is mainly due to the fact that the Woodbridge River is a tidal waterway and does not have sufficient capacity to convey stormwater runoff in sufficient time even when the tide is not elevated. Combined with the highly urbanized nature of the Woodbridge River watershed and it associated high stormwater runoff generation, it is clear why this community is so vulnerable to stormwater-related flooding.

2. Coastal Storm Vulnerability

The FEMA FIRM 100, 50 and 10 year flood maps were overlaid over a map of the Township to determine the extent of flooding by these events, see Figure 49, Figure 50 and Figure 51 below. From these overlays it can be seen that large sections of the Township along the Arthur Kill, Woodbridge River and Rahway River will be inundated by these coastal storm events. Specifically, it can be seen that locations along the Arthur Kill waterfront are vulnerable along with areas inland of these locations. Also, vulnerable are low lying areas along the Woodbridge River and along the Rahway River.

In addition to the inundation threat from the 100 year coastal storm, locations along the shoreline of both Raritan Bay and the Arthur Kill face the threat of wave velocity action hazard as designated in the map shown in Figure 49 as the V-Zone.

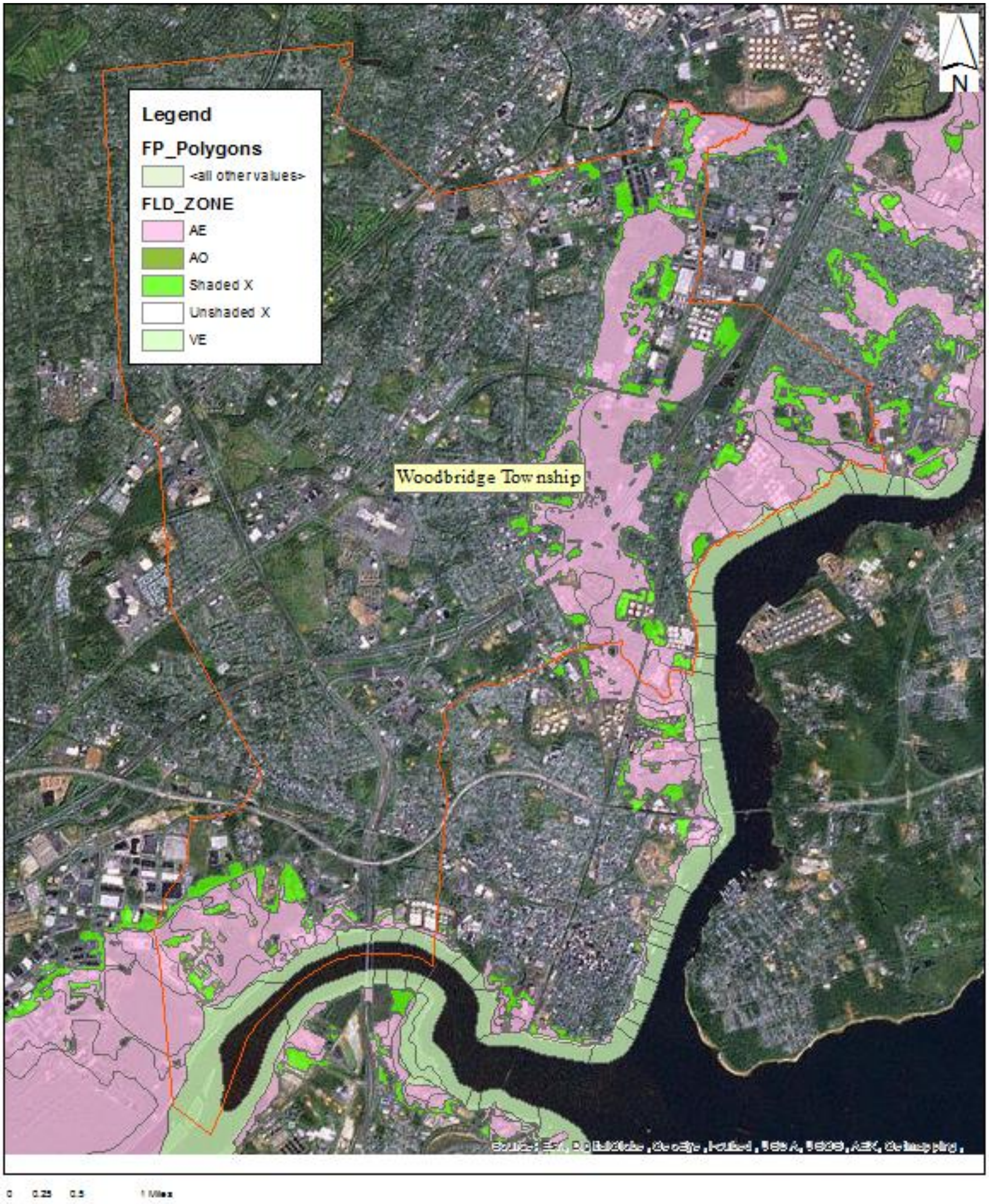

Figure 49-Woodbridge Township with FEMA Preliminary FIRM Overlay (FEMA Prelim. FIRM, 2013)

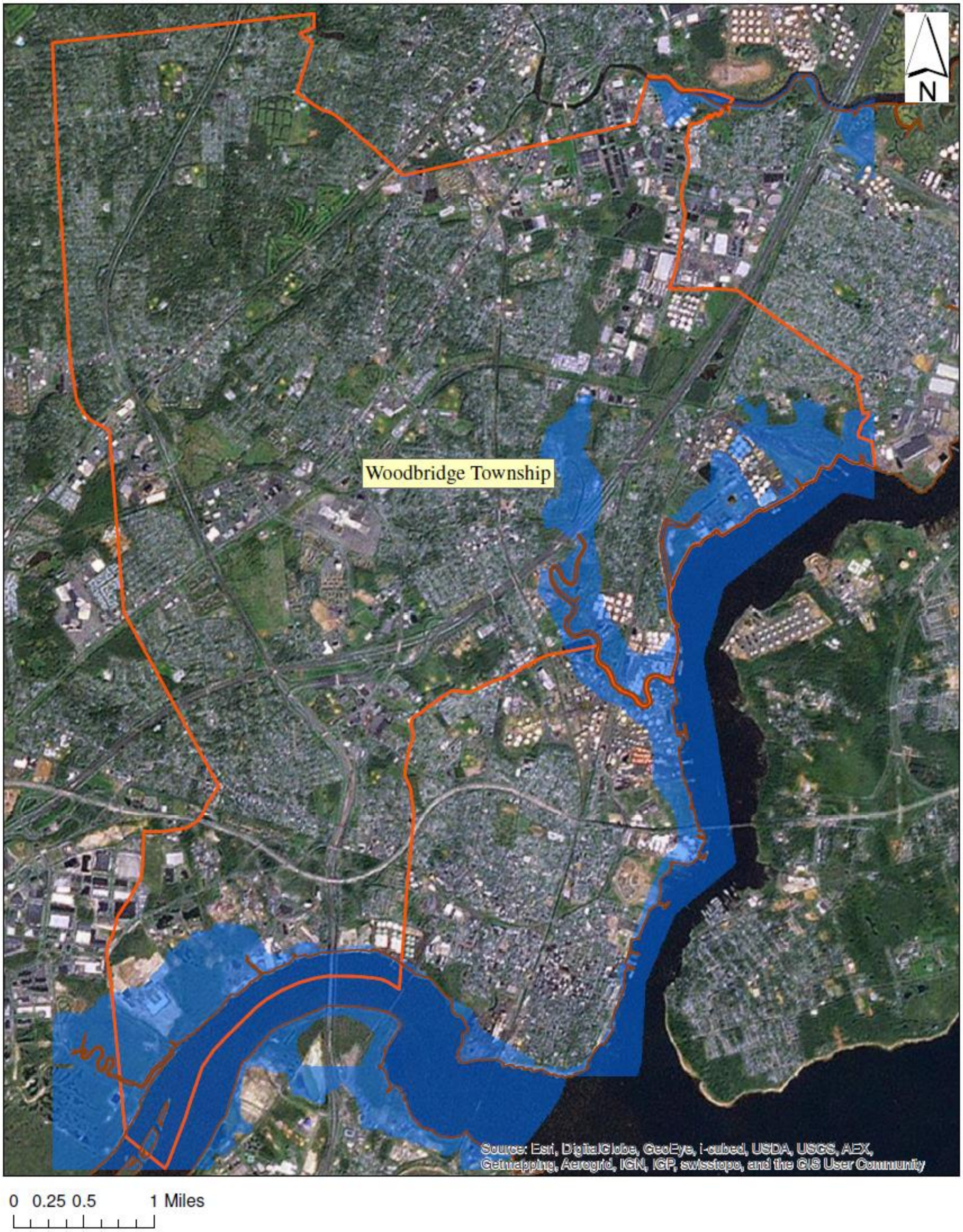

Figure 50-Woodbridge Township with 50 Year Flood Zone Overlay (FEMA, 2013)

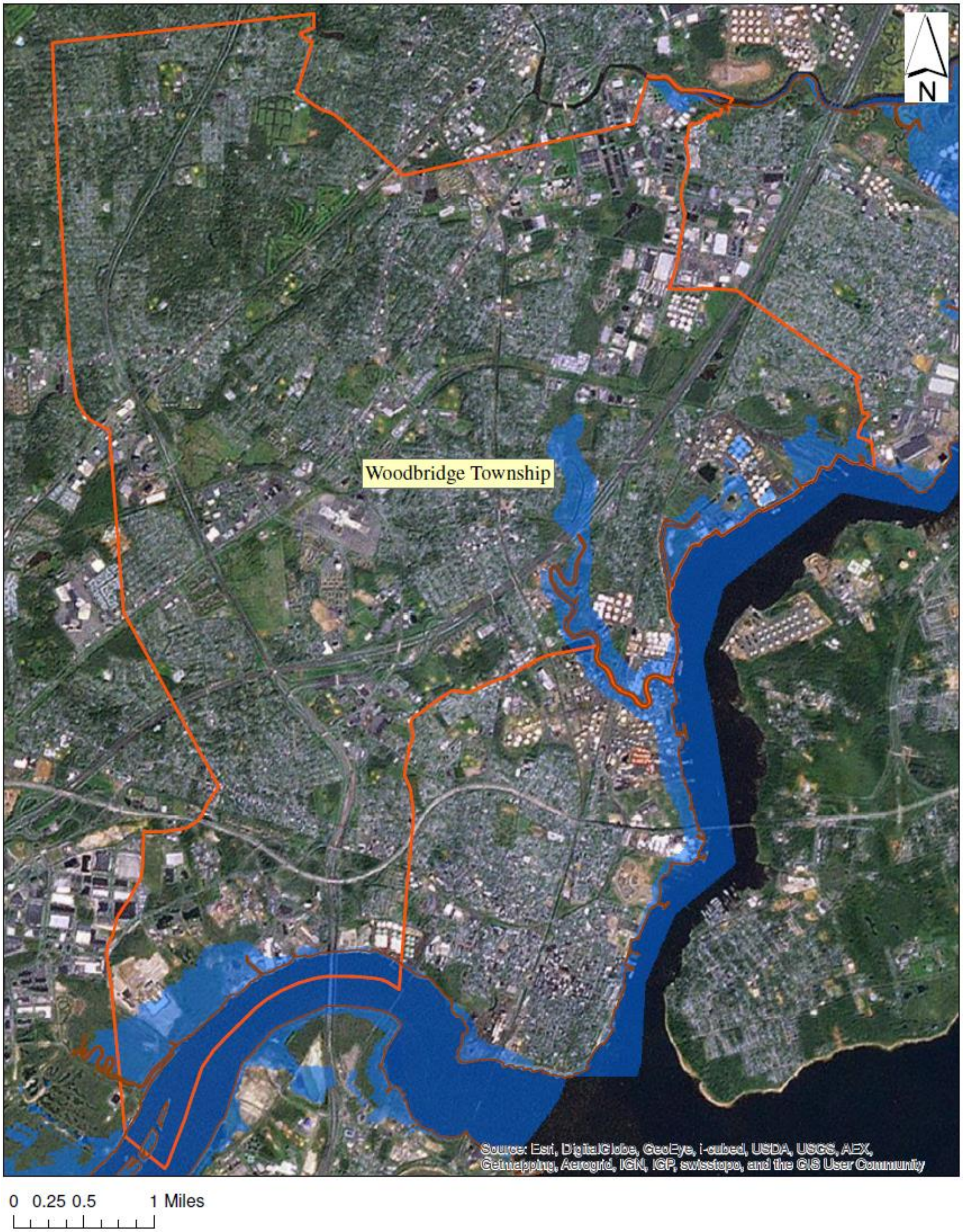

Figure 51-Woodbridge Township with 10 Year Flood Zone Overlay (FEMA, 2013)

3. Stormwater Runoff Vulnerability

Due to the population density of the community and the resulting high percentage of impervious cover from houses, roadways and sidewalks, there is a significant amount of rainfall runoff that is generated from even small rainfall events. This generated runoff cannot be readily discharged from the drainage system when the water level in the discharging water bodies are elevated, see Figure 52 for map showing overlay of Mean Higher High Water levels in Woodbridge.

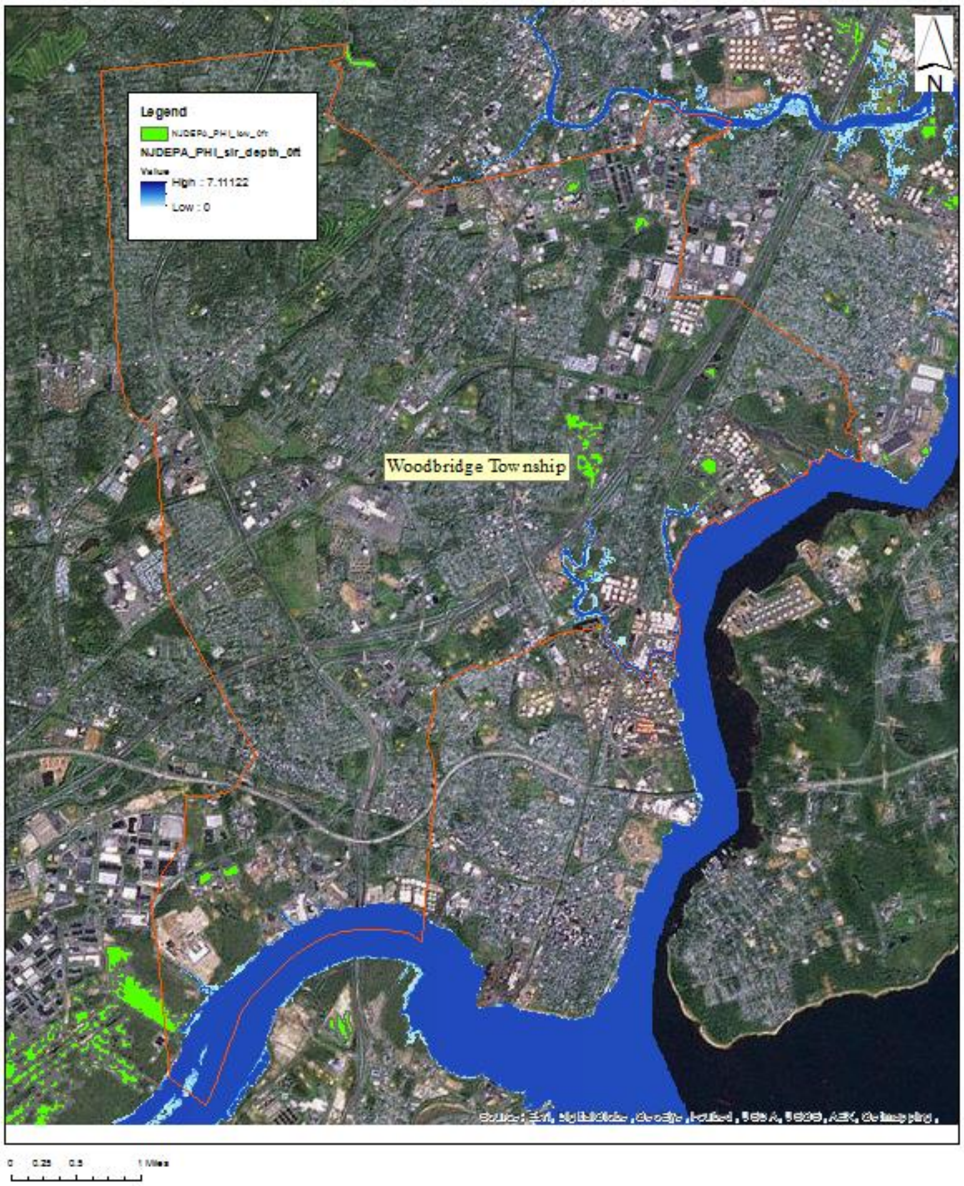

Figure 52-Woodbridge Township with Mean Higher High Water Overlay ((NOAA), (NOS), & (CSC), 2012)

From Figure 52 it is clear that the low lying areas adjacent to Woodbridge River are flooded during the mean higher high tide and these same areas are vulnerable to stormwater-related flooding even during low tide as conveyance along the upper reaches is severely limited by the meandering river channel.

From Table 2 above it can be seen that for Woodbridge Township (Newark Airport weather station) the 24 hours duration/ 25 year return period precipitation event delivers 6.38 inches of rain. Although, further hydrological study is needed to determine the peak discharge flow that will result from this event given the high percentage of impervious cover in this community it can be expected that a significant percentage of rainfall will be converted into stormwater runoff.

C. Flood Mitigation

1. Coastal Storm Flooding Mitigation

a) Flood Mitigation Projects proposed by Rutgers University Team

The flood mitigation solutions proposed by the Rutgers University Flood Study Team for the coastal storm take into consideration the flooding projected by FEMA in the FIRM map for the City. After reviewing various options, such as elevating the NJ Turnpike to serve as a surge barrier, it is clear that the most effective way to protect this Township from coastal flooding would be to install a seawall from the Woodbridge River in the south to the Rahway River in the north and to install channel closure structures at the confluences of both these rivers and the Arthur Kill. The proposed seawall will be a mixture of permanent and semi-permanent seawalls sections with the ability to extend higher to address future sea level rise and other contingencies see Figure 53 below.

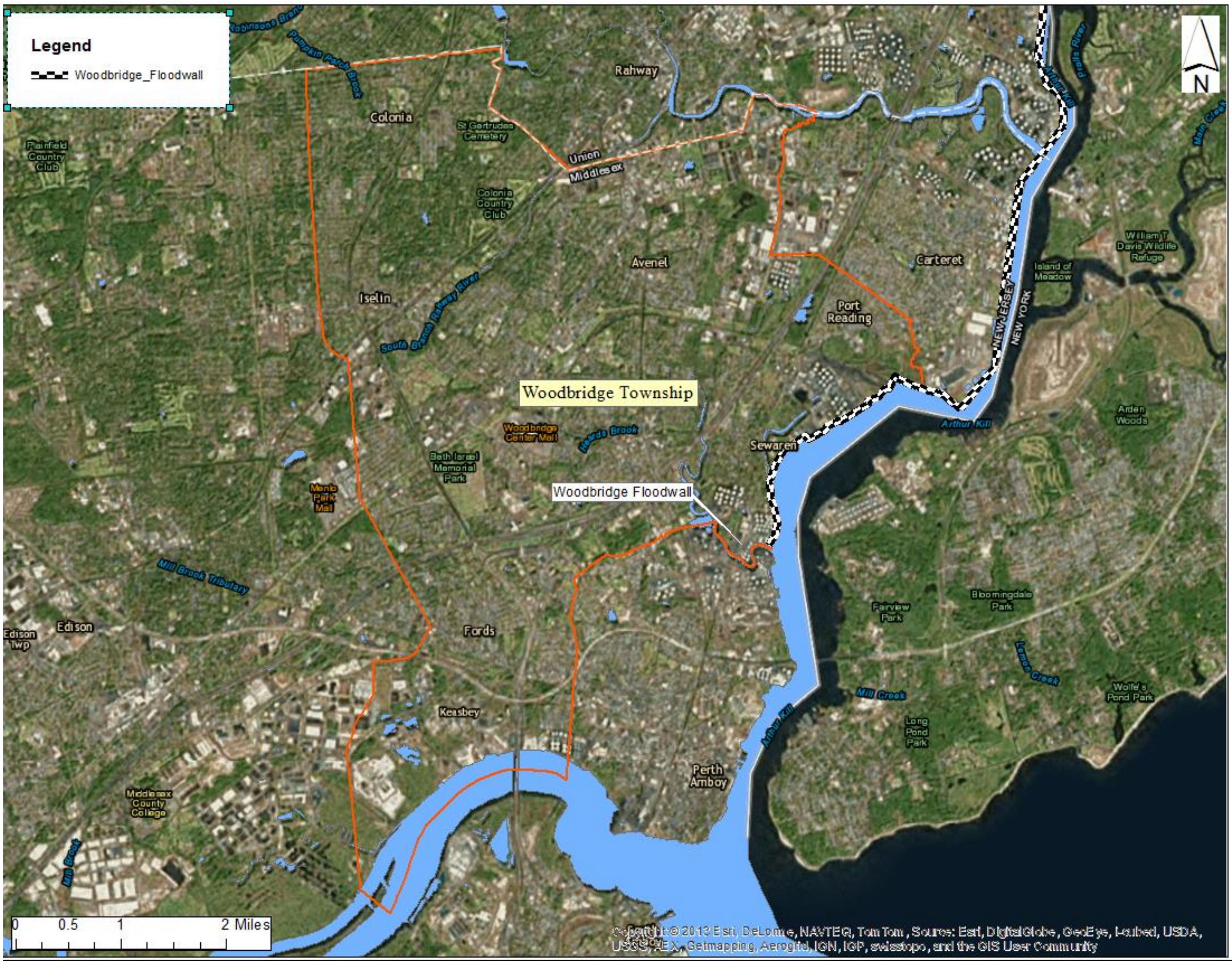

Figure 53-Proposed Woodbridge Township Seawall

2. Woodbridge Township Stormwater-related flooding Mitigation

The proposed stormwater-related flood mitigation recommendation for the Woodbridge Township is based largely on information obtained from City officials regarding past flooding events and current know system deficiencies. In general the stormwater sewers and receiving streams should have adequate capacity to handle the design storm peak flow. The best way to accomplish this objective is to develop and calibrate a hydraulic/hydrologic model of the City and its watershed (especially Woodbridge River) then use this model to assess current system performance and identify deficiencies. Once the assessment phase is complete the model should be used to simulate scenarios that will lead to a determination of appropriate conveyance sizing.

In addition to the appropriate sizing of stormwater conveyance infrastructure, increased storage can also play a role in reducing or delaying flow from entering the drainage system.

Also important to stormwater-related flood mitigation is the role that green infrastructure measures can play to reduce the amount of precipitation that is converted to stormwater runoff and also to reduce the amount of runoff that gets into the drainage system either by diversion or delay. Rutgers University has developed tools to optimize the selection of green infrastructure measures based on the characteristics of the community being considered (See Appendix 1-Stormwater Green Infrastructure Methodology).

3. Green Infrastructure Measures

The Rutgers University Flood Study Team has developed a software package that optimizes the implementation of green infrastructure measures for a given study area. Table 24 and Table 25 below provide the software output for the Woodbridge Township.

Table 24 : 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	4582964	7390666
Swales	1385749	1385749
Planter box	73906	73906
Vegetated filter strips	1385749	1385749
Permeable sidewalk	1292880	1292880
Permeable driveway	1570516	1570516
Permeable parking	472127	472127
Rain garden	369530	369530
Total cost ($) – 10 year	149,204,955	
Total cost ($) – 50 year	168,320,661	

Table 25 : Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	86052471	0.57
50 year	120151250	0.71

D. Flood Mitigation Cost

1. 100 Year Coastal Storm Flood Mitigation

The cost to implement the measures needed to mitigate flooding caused by the 100 year coastal storm in Woodbridge Township is estimated at $162M in 2014 dollars as shown below in Table 26.

Table 26-Flood Mitigation Cost for 100 Year Coastal Storm

DESCRIPTION	QUANTITY	COST
New Floodwall	3 Miles	$70M
In Water Closure	600 Feet	$92M
Total		$162M

2. 50 Year Coastal Storm Flood Mitigation

Based on how the coastal storm affects Woodbridge Township, the feasible options for flood mitigation would be to buy out the properties at the cost of $58M, as shown in Table 27 below.

Table 27-Flood Mitigation Cost for 50 Year Coastal Storm

NUMBER OF PROPERTIES AFFECTED	AVERAGE BUYOUT PRICE	TOTAL BUYOUT COST
250	230,000	$58M

3. 10 Year Coastal Storm Flood Mitigation

Based on how the coastal storm affects Woodbridge Township, the feasible options for flood mitigation would be to buy out the properties at the cost of approximately $27M, as shown in Table 28 below.

Table 28- Flood Mitigation 10 Year Coastal Storm

Number of Properties Affected	Average buyout Price	Total Buyout Cost
115	230,000	$27M

4. Stormwater-Related Flood Mitigation

The cost to implement the measures to mitigate stormwater-related flooding in Woodbridge Township is estimated at $220M in 2014 dollars as shown below in Table 29.

Table 29-Flood Mitigation Cost for Stormwater-related flooding

DESCRIPTION	**QUANTITY**	**COST**
Dredging Woodbridge River	Lump Sum	$10M
Woodbridge River Channelization	Lump Sum	$15M
Green Infrastructure (50 years)	Lump Sum	$170M
Storage	70,000 CY	$25M
Total		$220M

E. Conclusion

Woodbridge Township, New Jersey is located in an area that makes it vulnerable to both coastal from both Woodbridge and Rahway Rivers and from stormwater-related flooding from the Woodbridge River due to its lack of adequate capacity for conveyance of stormwater runoff.

After reviewing a number of different measures it became clear that the best way to prevent flooding from coastal flooding was to build a seawall along the Township interface with the Arthur Kill and to install river closure devices at the entrance of both the Woodbridge and Rahway Rivera to prevent surge water from entering these channels. The river closure will only be engaged to combat surge from major coastal events and will remain open at all other times.

Then on the stormwater-related side, improving the conveyance capacity of the tidal Woodbridge River will allow for better conveyance during low tide conditions but will not help mitigate flooding during elevated tides. Additional storage can also help mitigate flooding during low tide conditions. The most impactful riverine flood mitigation measure would be to install a levee on both sides of the river to protect the flood prone areas along its banks.

Then last but not least, the implementation of green infrastructure will be especially beneficial in this community given its high percentage of impervious cover and associate high stormwater runoff generation. Although expensive, green infrastructure will result in savings from decreased amounts of stormwater runoff that need to be managed as well as other significant benefits.

Summary of Costs

Table 30 below summarizes all cost for the regional and municipal projects that are recommended.

Table 30-Summary of Proposed Project Costs

Item#	Location	Stormwater-Related Flood Mitigation Costs	Green Infrastructure Costs	Coastal Flood Mitigation Cost	Total Location Cost
1	Arthur Kill Region	$ -	$ 655,000,000	$ 455,000,000	$ 1,110,000,000
2	City of Elizabeth	$ 191,000,000	$ 130,000,000	$ 171,000,000	$ 492,000,000
3	City of Linden	$ 20,000,000	$ 280,000,000	$ 158,000,000	$ 458,000,000
4	City of Rahway	$ 20,000,000	$ 40,000,000	$ 62,000,000	$ 122,000,000
5	Borough of Carteret	$ 50,000,000	$ 35,000,000	$ 143,000,000	$ 228,000,000
6	Woodbridge Township	$ 50,000,000	$ 170,000,000	$ 162,000,000	$ 382,000,000

Note that the cost for the regional measures proposed are primarily for mitigation of coastal flooding plus the sum of the green infrastructure cost for each municipality.

Note that the cost for the in-water closure for the Rahway River is reflected in the costs for coastal flood mitigation for the municipalities of Linden, Rahway, Woodbridge and Carteret since all these locations are exposed to flooding from this waterway.

Note that all unit prices used in this study are documented in Appendix 2-Unit Cost Tables.

IX. References

(NOAA), N. O., (NOS), N. O., & (CSC), C. S. (2012). *NOAA Coastal Services Center Sea Level Rise Data: Current Mean Higher High Water Inundation Extent.* Charleston, SC: NOAA's Ocean Service, Coastal Services Center (CSC).

FEMA. (2014). *Coastal Analysis and Mapping*. Retrieved 2014, from Mapping Basics: http://www.region2coastal.com/coastal-mapping-basics

FEMA ABFE. (2013). *Federal Emergency Management Agency ABFE MAP*. Retrieved from Coastal Analysis and Mapping: http://www.region2coastal.com/bestdata

FEMA Prelim. FIRM. (2013). *Preliminary FIRM Middlesex County*. Retrieved from Coastal Analysis and Mapping: http://www.region2coastal.com/preliminaryfirms

Guo, D. Q. (2013). Linden NJ Photos.

NASA. (2013). *Comparing the Winds of Sandy and Katrina*. Retrieved from Earth Observatory: http://earthobservatory.nasa.gov/IOTD/view.php?id=79626

National Oceanic and Atmospheric Agency. (2013). *NOAA Tides and Currents*. Retrieved from Tides and Currents: http://tidesandcurrents.noaa.gov/waterlevels.html?id=8531680

National Weather Service. (2013). *Hurricane Sandy*. Retrieved April 04/12/2014, 2014, from weather.gov: http://www.weather.gov/okx/HurricaneSandy

NJDEP. (2012). NJPDES Combined Sewer Overflow (CSO)- DRAFT Edition 201202. *NJPDES Combined Sewer Overflow (CSO)- DRAFT Edition 201202*. NJDEP.

NOAA. (2013). Retrieved from Hydrometeorological Design Studies Center: http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nj

T&M. (2013). *Noe Street Area Drainage Study, Summary of Findings.* T & M Consultants.

The City of New York. (2013). *A Stronger More Resilient New York.* New York.

United States Geological Service. (2014). *USGS Flood Information*. Retrieved from Water Resources of the United States: https://water.usgs.gov/floods/events/2012/sandy/sandymapper.html

University Corporation for Atmospheric Research. (2013). *UCAR Digital Image Library*. Retrieved from Dissecting Sandy's Battery Surge: http://www.fin.ucar.edu/netpub/server.np?find&catalog=catalog&template=detail.np&field=itemid&op=matches&value=4215&site=imagelibrary

USGS STREAMSTATS. (2014). *USGS STREAMSTATS New Jersey*. Retrieved from USGS STREAMSTATS: http://streamstatsags.cr.usgs.gov/nj_ss/default.aspx?stabbr=nj&dt=1402171670542

RELATED REPORTS AND PUBLICATIONS

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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, Qizhong, Robert Miskewitz, Eleni Athanasopoulou, Kaveh Gharyeh, Jun Zhao, 2014. Strategies for Flood Risk Reduction for Vulnerable Coastal Populations along Hudson River at Hoboken and Jersey City. 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.

X. 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.

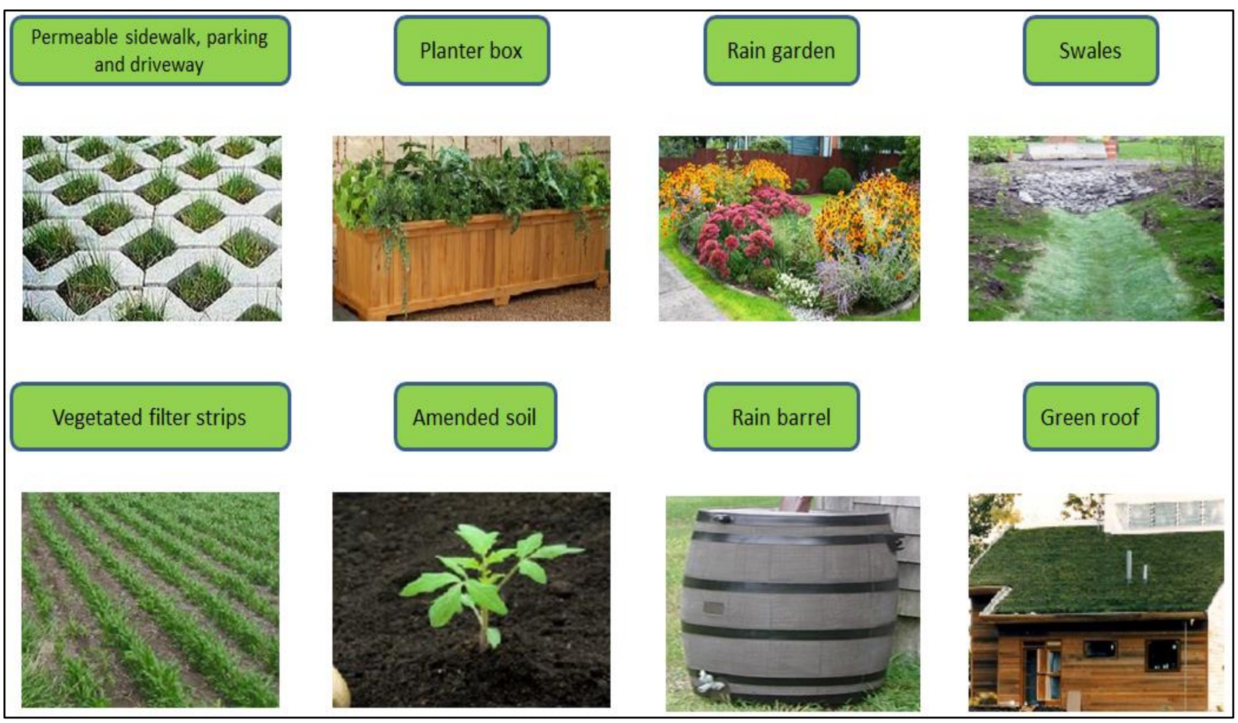

Figure 1: Green Infrastructure types

US Department of Environmental Protection (DEP) is conducting a comprehensive research to quantify non- 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 system by removing fraction of runoff. Table 1 summarizes the problem, our approach and source of floodwater.

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[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

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.

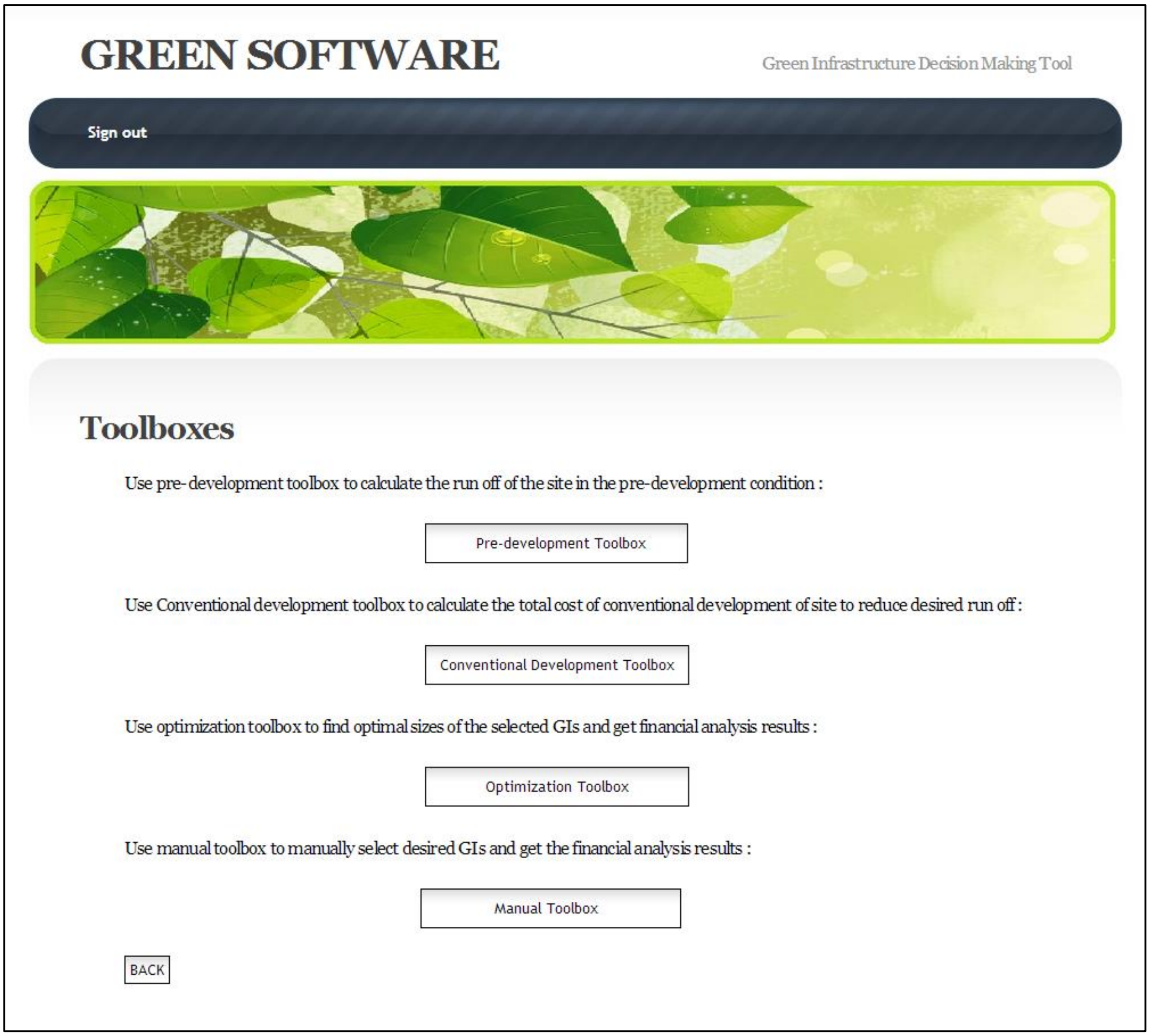

Figure 2: Snapshot of the Green Software

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.

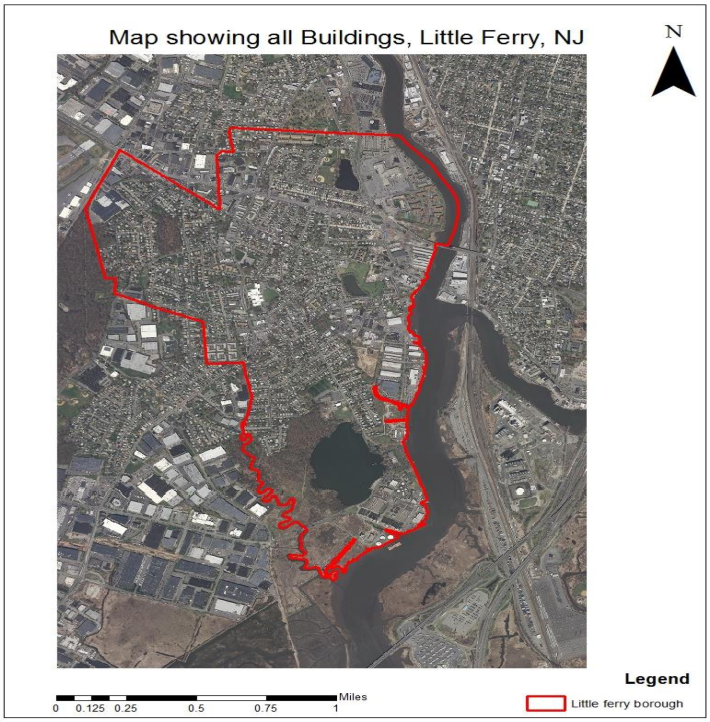

Figure 3: Sample layer of a municipality

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

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

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.

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) 1-foot raise: $37 1-to 3-foot raise: $120 Greater than 3-foot raise: $875 2) Levee raise by fill (unit cost per linear foot) 1-foot raise: $31 1-to 3-foot raise: $45 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 -4' Muscle Wall 99 $/LF excludes tax, installation, liner, sandbags, Muscle Wall accessories -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 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 Diameter: 3 ft : $4,500 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 Flap Gate for 8 Inch Pipe 1 EA 2,500 Flap Gate for 12 Inch Pipe 1 EA 3, 000 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: Flap gate: 24” cost: 2500 EA Flap gate: 30” cost: 3000 EA	http://www.hutchgov.com/egov/docs/13831420807713.pdf
Sluice gate	Sluice gates, cast iron Hydraulic structures, 18" x 18", HD, self cont with crank, sluice Detail $ 7,764.89 / EA Hydraulic structures, 24" x 24", HD, self cont with crank, sluice Detail $ 10,011.41 / EA Hydraulic structures, 30" x 30", HD, self cont with crank, sluice Detail $ 11,828.56 / EA Hydraulic structures, 36" x 36", HD, self cont with crank, sluice Detail $ 13,627.37 / EA Hydraulic structures, 42" x 42", HD, self cont with crank, sluice Detail $ 16,221.16 / EA Hydraulic structures, 48" x 48", HD, self cont with crank, sluice Detail $ 19,026.87 / EA Hydraulic structures, 54" x 54", HD, self cont with crank, sluice Detail $ 26,137.59 / EA Hydraulic structures, 60" x 60", HD, self cont with crank, sluice Detail $ 31,611.97 / EA Hydraulic structures, 66" x 66", HD, self cont with crank, sluice Detail $ 36,680.48 / EA Hydraulic structures, 72" x 72", HD, self cont with crank, sluice Detail $	http://www.allcostdata.info/browse.html/059110009

	43,605.95 / EA Hydraulic structures, 78" x 78", HD, self cont with crank, sluice Detail $ 48,429.74 / EA Hydraulic structures, 84" x 84", HD, self cont with crank, sluice Detail $ 64,999.97 / EA Hydraulic structures, 90" x 90", HD, self cont with crank, sluice Detail $ 60,630.76 / EA Hydraulic structures, 96" x 96", HD, self cont with crank, sluice Detail $ 67,440.10 / EA Hydraulic structures, 108" x 108", HD, self cont with crank, Detail $ 87,380.36 / EA Hydraulic structures, 120" x 120", HD, self cont with crank, Detail $ 117,696.03 / EA 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

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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 $ 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