Strategies for Flood Risk Reduction for Vulnerable Coastal Populations around Delaware Bay

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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August 2014

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I. Executive Summary

A. Regional

The Delaware Bay Study Area is comprised of seven small communities that are located throughout Cumberland County in New Jersey; Port Norris, Fortescue, Greenwich, Heislerville, Leesburg and Dorchester. During Superstorm Sandy these communities were flooded by the storm surge that was generated as the storm passed by the area. Notable damages to the communities include:

- Homes destroyed
- Bulkheads and levees overtopped
- Bulkheads and levees breached
- Beaches washed away
- Roads washed away
- Surge waters trapped behind breached levees
- Wetlands damaged
- Marinas destroyed

In light of the extensive damage caused to New Jersey communities by flooding from Superstorm Sandy, Rutgers University was tasked to determine the flood vulnerability of several communities across New Jersey, including the communities along Delaware Bay and to develop measures to mitigate against these vulnerabilities.

Accordingly, with Dr. Qizhong (George) Guo as the Principal Investigator, flood researchers embarked on the study of Delaware Bayshore communities in Cumberland County, NJ using data from multiple federal and state sources such as USGS, FEMA, NOAA, NJDEP etc. to assess flood vulnerabilities and propose appropriate mitigation measures to address the vulnerabilities that were identified.

Flood vulnerability assessment indicates that these communities are not prepared to withstand a 100 coastal storm event and they are also not prepared to withstand the mean higher high water (MHHW) tide plus anticipated future sea level rise. Assessment of the current flood protection levels determined that none of the existing levees or other mitigation structures could protect above a 10-year coastal storm event. Accordingly, a set of regional flood mitigation measures were developed to reduce risk to the most vulnerable parts of Cumberland County. Local flood mitigation measures were also developed for the seven communities to reduce risk from the 100 year coastal storm and future sea level rise.

In general the regional coastal flood mitigation measures involve installation of a regional causeway system equipped with operable flood barriers underneath, elevating existing levees so that they can reduce flooding risk from a 100-year event and the restoring wetlands that can be a valuable buffer to attenuate coastal surge and wave.

In addition to the elevation of existing levees and extension of the flood protection system using causeways, installation of in-water closure devices is also suggested to provide flood protection to communities upstream of the device locations (causeway system comes already equipped with in-water closure device). In-water river closure devices are recommended for consideration on the Maurice and the Cohansey Rivers.

In-water closure devices prevent flow from entering or leaving a waterway when they are closed. They can take the form of swinging or sliding gates or many more complicated constructions; all with the goal of stopping flow or surge from inundating communities that are to be protected.

If implemented as part of a comprehensive holistic approach, the proposed measures will mitigate the risk of flooding in communities across the county and may be implementable across state where coastal flood threat conditions are similar.

B. Port Norris

The community of Port Norris in Commercial Township is located within the 100-year flood zone and was flooded by the coastal storm surge produced by Superstorm Sandy in 2012.

The community is currently protected from flooding by a levee system that is not high enough to offer protection for coastal storms beyond the 10-year event. Accordingly, it is recommended for consideration that the existing Port Norris and Port Norris North levees that protect the community be elevated higher up to the level that will offer protection from the 100-year coastal storm and future sea level rise. It is also recommended for consideration to extend the existing levees laterally as well to eliminate surge water pathways that allow flood waters to bypass the levees.

If implemented, these flood mitigation measures will offer the community a better protection level than that which exists today for the 100-year coastal storm event and future sea level rise.

C. Fortescue

The community of Fortescue in Downe Township is located within the 100-year flood zone on the shore of Delaware Bay and was flooded by the coastal storm surge produced by Superstorm Sandy in 2012.

The community is currently protected from flooding by a bulkhead system along the Bayshore that is not high enough to offer protection for a 100-year coastal storm event. Accordingly, it is recommended for consideration that the existing bulkheads that protect the community on the Bayshore be elevated higher up to the level that will offer protection from the 100-year coastal storm and future sea level rise.

On the eastern side of the community, the level of protection offered by the higher bulkheads should be continued by the installation of a new levee and flood gates where the levee meets the bulkheads at Jersey Avenue in the south and Downe Avenue in the north

If implemented, these flood mitigation measures will offer the community a better protection level than that which exists today for the 100-year coastal storm event and future sea level rise.

D. Greenwich

The community of Greenwich in Greenwich Township is located within the 100-year flood zone and was flooded by the coastal storm surge produced by Superstorm Sandy in 2012.

The community is currently protected from flooding by a levee system that is not high enough to offer protection for coastal storms beyond the 10-year event. Accordingly, it is recommended for consideration that the existing Market Street levee that protects the community be elevated higher up to the level that will offer protection from the 100-year coastal storm and future sea level rise.

It is also recommended for consideration to extend the existing levees laterally as well to eliminate surge water pathways that allow flood waters to bypass the levees.

If implemented, these flood mitigation measures will offer the community a better protection level than that which exists today for the 100-year coastal storm event and future sea level rise.

E. Heislerville, Leesburg and Dorchester

The communities of Heislerville, Leesburg and Dorchester in Maurice Township are located within the 100-year flood zone and were flooded by the coastal storm surge produced by Superstorm Sandy in 2012.

The community is currently protected from flooding by a levee system on the Maurice River called the Heislerville impoundment that is not high enough or extensive enough to offer protection for coastal storms beyond the 10-year event. Accordingly, it is recommended for consideration that the existing Heislerville Impoundment and Thompson levees that protect the community be elevated higher up to the level that will offer protection from the 100-year coastal storm and future sea level rise.

It is also recommended for consideration to extend the existing levees laterally to the north along the Maurice River and north then east of the Thompson levee to eliminate surge water pathways that allow flood waters to bypass the levees and flood the communities.

If implemented, these flood mitigation measures will offer the community a better protection level than that which exists today for the 100-year coastal storm event and future sea level rise.

II. Introduction

A. The Delaware Bay Study Area

Cumberland County is characterized by rural communities, rich in tidal wetlands and open spaces, many of which are vulnerable to coastal flooding from the Delaware Bay either directly or through the many waterway that are tributary to the Bay. The Delaware Bay Study Area is focused on communities located both along the shore of Delaware Bay and along the tributaries of the bay such as; Port Norris, Fortescue, Greenwich, Leesburg, Dorchester and Heislerville, see Figure 1 below.

Figure 1 Delaware Bay Study Area

- Community boundaries are approximate
- Communities were selected to broadly represent flood affected communities

During Superstorm Sandy, the communities within the study area experienced severe coastal flooding from Superstorm Sandy's storm surge. Water levels monitored by National Oceanic and Atmospheric Administration (NOAA) gages in Delaware Bay (Figure 2) during Superstorm Sandy are shown in Figure 3, Figure 4 and Figure 5, respectively.

Figure 2 NOAA Water Level Gages in Vicinity of Delaware Bay (NOAA, 2013)

These graphs show that on October 29th when the region was impacted by Superstorm Sandy, water levels ranged from 3 to 8 feet above mean higher high water levels at these gages. This surge inundated the communities within the Delaware Study Area (Figure 6) and caused extensive damage to property and infrastructure.

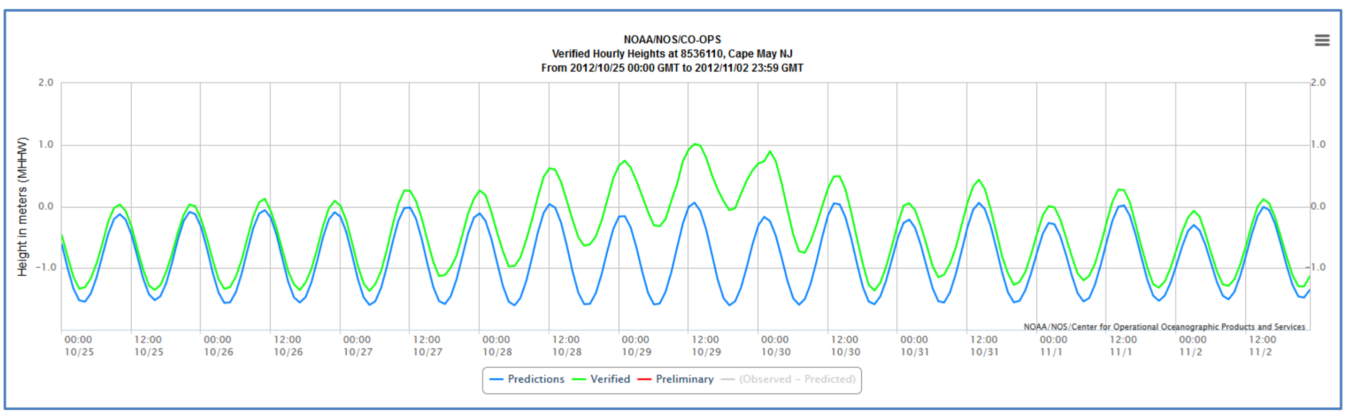

Figure 3 Water Levels at Cape May, NJ, Oct. 25 to Nov. 2, 2012. (NOAA, 2012)

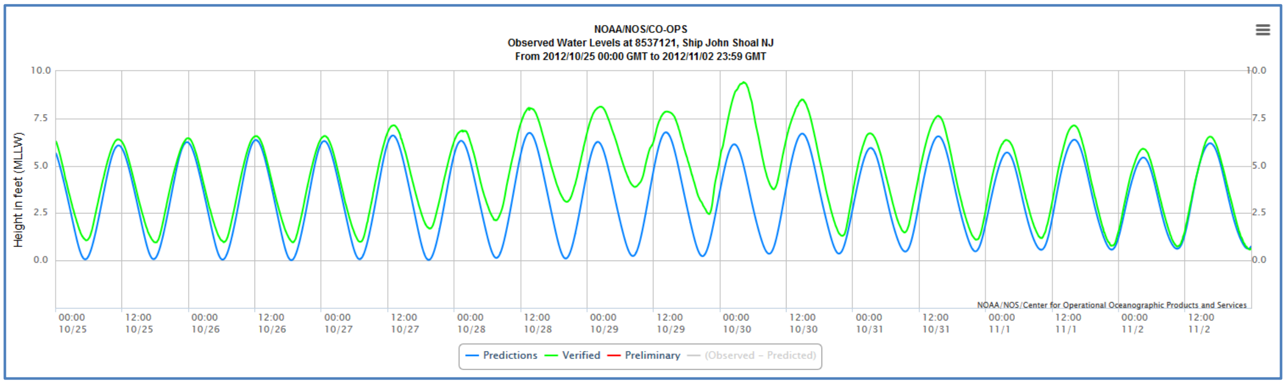

Figure 4 Water Levels at Ship John Shoal NJ, Oct. 25 to Nov. 2, 2012. (NOAA, 2012)

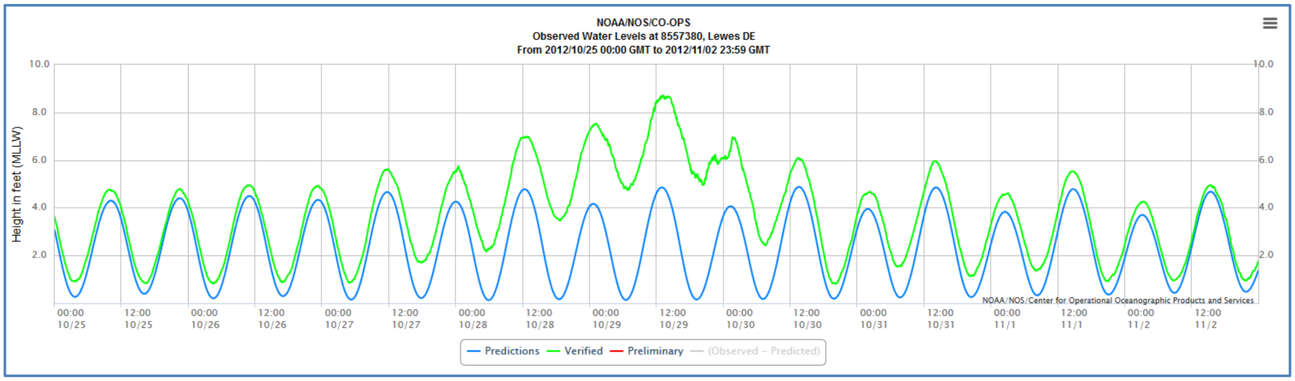

Figure 5 Water Levels at Lewes, DE, Oct. 25 to Nov. 2, 2012. (NOAA, 2012)

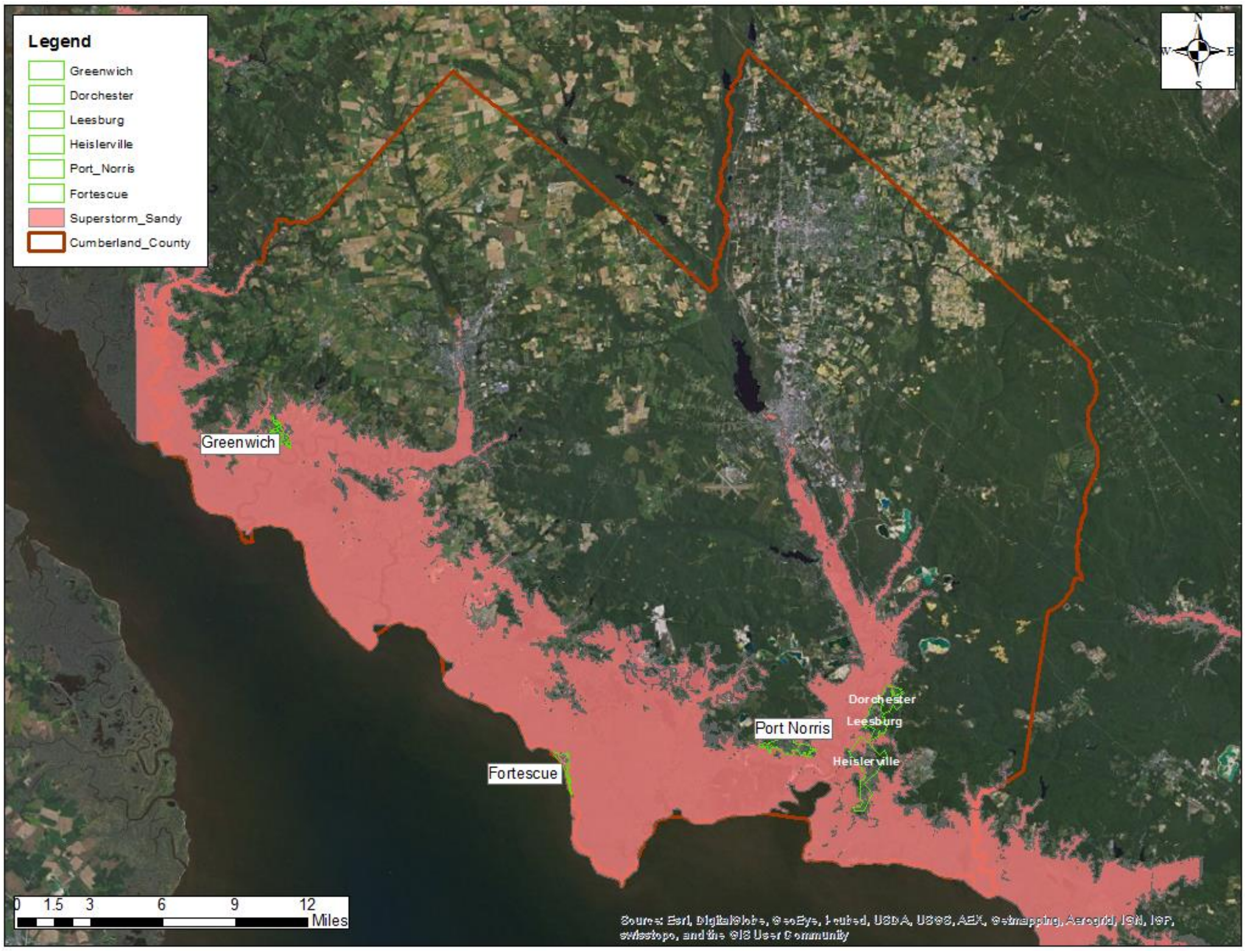

Figure 6-Superstorm Sandy-Flooded Areas along Delaware Bay (USGS, 2014)

B. Flood Study Objective

The objective of this research project was first to determine the subject communities' vulnerability to flooding and then to determine the current level of flood protection that exists in these communities. Once the communities' flood vulnerability and current level of flood protection was determined, flood mitigation measures were developed to enhance flood protection against future storms.

C. Flooding Study Approach

1. Procedure

The following procedure was used to study flooding in the Delaware Bay 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 PRELIMINARY FIRM mapping on the map of the community to determine what part of the community if any would be impacted by the 10-, 50- and 100-year recurrence intervals for coastal storm events and future sea level rise.
- Assess the stormwater runoff potential of the community to determine whether runoff generation would increase the risk of flooding.
- Determine the potential sources of floodwaters 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 PRELIMINARY FIRM Map

Within the FEMA 100 year flood zones both inundation and wave velocity action are identified. Figure 7 illustrates how these areas are designated.

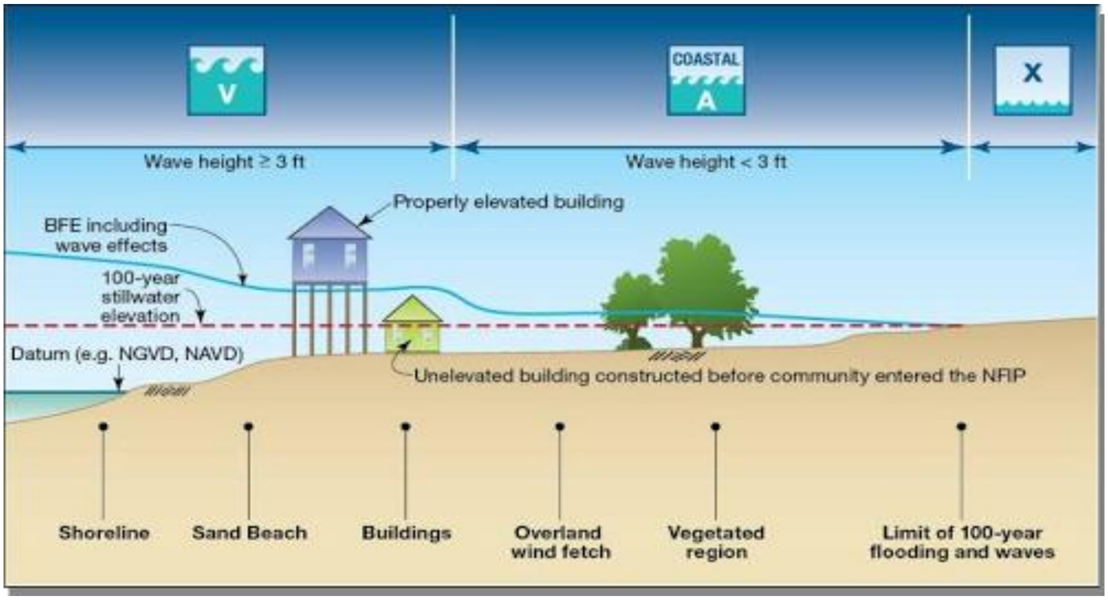

Figure 7-FEMA Flood Zone Mapping Methodology (Federal Emergency Management Agency, 2013)

3. Sea Level Rise

There are several predictions for future sea level rise in the region. For this study sea level rise is predicted to rise 45 cm (1.5 ft.) by 2050 and 106 cm (3.5 ft.) at Delaware Bay by 2100 (Miller, 2013)

4. Historical Rainfall Data

Table 1. Rainfall Data for Delaware Bay (NOAA, 2013)

NOAA Atlas 14, Volume 2, Version 3
Location name: Maurice River, New Jersey, US*
Latitude: 39.2545°, Longitude: -74.9527°
Elevation: 34 ft*
* source: Google Maps

POINT PRECIPITATION FREQUENCY ESTIMATES

G.M. Bonnin, D. Martin, B. Lin, T. Parzybok, M.Yekta, and D. Riley

NOAA, National Weather Service, Silver Spring, Maryland

PF_tabular | PF_graphical | Maps_&_aerials

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	0.347 (0.310-0.389)	0.404 (0.361-0.450)	0.460 (0.409-0.511)	0.533 (0.474-0.593)	0.600 (0.533-0.669)	0.662 (0.585-0.738)	0.715 (0.630-0.798)	0.765 (0.669-0.857)	0.820 (0.710-0.924)	0.876 (0.751-0.992)
10-min	0.555 (0.496-0.621)	0.646 (0.577-0.719)	0.736 (0.655-0.819)	0.852 (0.759-0.949)	0.956 (0.849-1.07)	1.05 (0.932-1.18)	1.14 (1.00-1.27)	1.21 (1.06-1.36)	1.30 (1.12-1.46)	1.38 (1.18-1.56)
15-min	0.694 (0.620-0.776)	0.812 (0.725-0.904)	0.931 (0.829-1.04)	1.08 (0.960-1.20)	1.21 (1.08-1.35)	1.33 (1.18-1.49)	1.44 (1.27-1.60)	1.53 (1.34-1.71)	1.63 (1.41-1.84)	1.73 (1.49-1.96)
30-min	0.951 (0.849-1.06)	1.12 (1.00-1.25)	1.32 (1.18-1.47)	1.56 (1.39-1.74)	1.80 (1.59-2.00)	2.01 (1.78-2.24)	2.20 (1.94-2.46)	2.38 (2.08-2.67)	2.60 (2.25-2.93)	2.80 (2.40-3.17)
60-min	1.19 (1.06-1.33)	1.41 (1.26-1.57)	1.70 (1.51-1.89)	2.03 (1.81-2.26)	2.39 (2.12-2.67)	2.72 (2.41-3.04)	3.03 (2.67-3.3[illegible])	3.34 [illegible]	3.73 [illegible]	4.09 [illegible]
2-hr	1.44 (1.27-1.64)	1.71 (1.51-1.93)	2.07 (1.82-2.34)	2.50 (2.20-2.83)	2.97 (2.59-3.36)	3.40 (2.96-3.85)	3.81 (3.31-[illegible])	[illegible]	[illegible]	[illegible]
3-hr	1.57 (1.39-1.79)	1.86 (1.65-2.11)	2.26 (1.99-2.55)	2.74 (2.40-3.10)	3.27 (2.85-3.70)	3.77 (3.27-4.27)	4.25 (3.67-4.83)	4.76 (4.07-5.42)	5.41 (4.56-6.19)	6.04 (5.03-6.94)
6-hr	1.95 (1.73-2.23)	2.30 (2.04-2.62)	2.77 (2.45-3.15)	3.36 (2.96-3.83)	4.05 (3.54-4.60)	4.72 (4.10-5.37)	5.38 (4.63-6.13)	6.09 (5.18-6.95)	7.03 (5.89-8.07)	7.96 (6.56-9.18)
12-hr	2.35 (2.08-2.69)	2.77 (2.46-3.15)	3.35 (2.96-3.81)	4.10 (3.62-4.66)	5.01 (4.39-5.69)	5.94 (5.16-6.74)	6.87 (5.90-7.82)	7.91 (6.69-9.03)	9.34 (7.72-10.7)	10.8 (8.74-12.5)
24-hr	2.70 (2.42-3.02)	3.28 (2.94-3.67)	4.26 (3.81-4.77)	5.10 (4.55-5.70)	6.39 (5.66-7.11)	7.52 (6.62-8.35)	8.80 (7.68-9.74)	10.2 (8.84-11.3)	12.4 (10.6-13.7)	14.3 (12.0-15.8)
2-day	3.09 (2.77-3.45)	3.77 (3.38-4.21)	4.89 (4.38-5.45)	5.85 (5.23-6.51)	7.31 (6.49-8.11)	8.58 (7.56-9.51)	10.0 (8.75-11.1)	11.6 (10.1-12.8)	14.0 (12.0-15.5)	16.1 (13.6-17.8)
3-day	3.25 (2.95-3.60)	3.96 (3.59-4.38)	5.12 (4.63-5.65)	6.10 (5.51-6.73)	7.59 (6.82-8.35)	8.88 (7.93-9.75)	10.3 (9.14-11.3)	11.9 (10.5-13.1)	14.3 (12.4-15.7)	16.4 (14.1-18.0)
4-day	3.42 (3.13-3.75)	4.15 (3.80-4.55)	5.34 (4.89-5.85)	6.36 (5.80-6.95)	7.88 (7.15-8.59)	9.19 (8.29-9.99)	10.6 (9.53-11.6)	12.3 (10.9-13.3)	14.7 (12.9-15.9)	16.7 (14.5-18.2)
7-day	3.96 (3.65-4.31)	4.77 (4.40-5.20)	6.04 (5.57-6.59)	7.12 (6.54-7.75)	8.72 (7.97-9.46)	10.1 (9.17-10.9)	11.6 (10.5-12.5)	13.2 (11.9-14.3)	15.7 (13.9-16.9)	17.7 (15.5-19.2)
10-day	4.43 (4.11-4.81)	5.32 (4.93-5.78)	6.63 (6.14-7.19)	7.72 (7.12-8.36)	9.29 (8.53-10.0)	10.6 (9.69-11.4)	12.0 (10.9-13.0)	13.5 (12.2-14.6)	15.8 (14.2-17.1)	17.8 (15.8-19.2)
20-day	5.97 (5.58-6.39)	7.10 (6.65-7.61)	8.59 (8.02-9.19)	9.79 (9.14-10.5)	11.5 (10.7-12.3)	12.8 (11.9-13.7)	14.2 (13.1-15.2)	15.7 (14.4-16.8)	17.7 (16.2-19.0)	19.3 (17.6-20.7)
30-day	7.43 (6.99-7.91)	8.81 (8.28-9.36)	10.5 (9.85-11.2)	11.8 (11.1-12.6)	13.7 (12.8-14.5)	15.1 (14.1-16.0)	16.6 (15.4-17.6)	18.1 (16.8-19.2)	20.1 (18.5-21.3)	21.7 (19.9-23.0)
45-day	9.43 (8.93-9.97)	11.1 (10.5-11.8)	13.0 (12.3-13.8)	14.5 (13.7-15.3)	16.4 (15.5-17.3)	17.9 (16.8-18.9)	19.3 (18.1-20.4)	20.7 (19.4-21.8)	22.5 (21.0-23.8)	23.8 (22.1-25.2)
60-day	11.3 (10.7-11.9)	13.3 (12.6-14.0)	15.3 (14.5-16.2)	16.9 (16.0-17.8)	18.9 (17.8-19.9)	20.3 (19.2-21.4)	21.7 (20.5-22.8)	23.0 (21.6-24.3)	24.7 (23.1-26.0)	25.8 (24.2-27.3)

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.

5. 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 8 below).

The Rutgers University Flood Mitigation Study Team also developed a menu of flood risk-reduction functions and their associated measures. Figure 9 is a schematic showing the application of various flood mitigation measures and provides a listing of each function and its associated measure.

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. Considerations for the various types of the strategies 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.

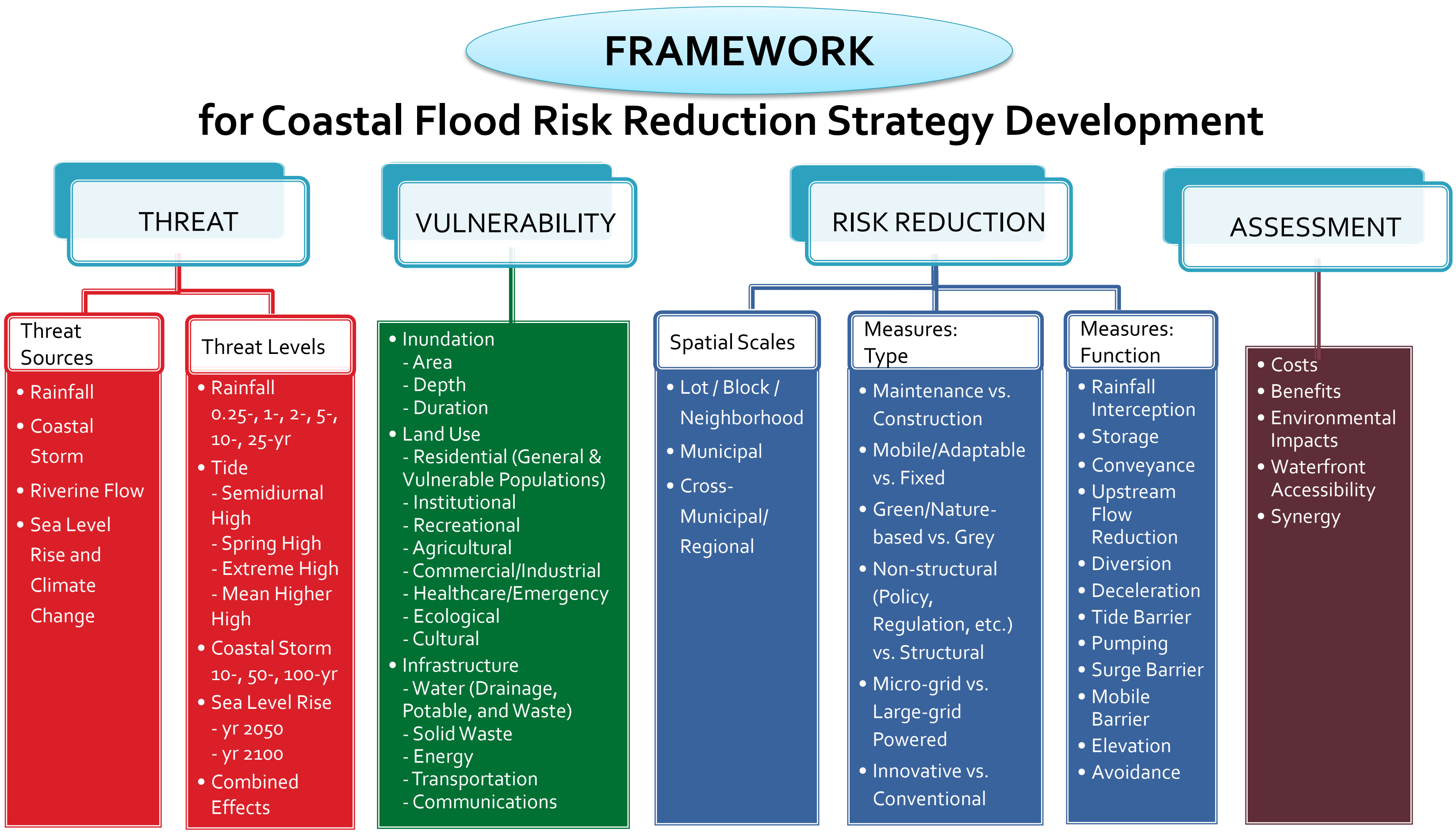

Figure 8. Framework for Flood Risk Reduction Strategy Development

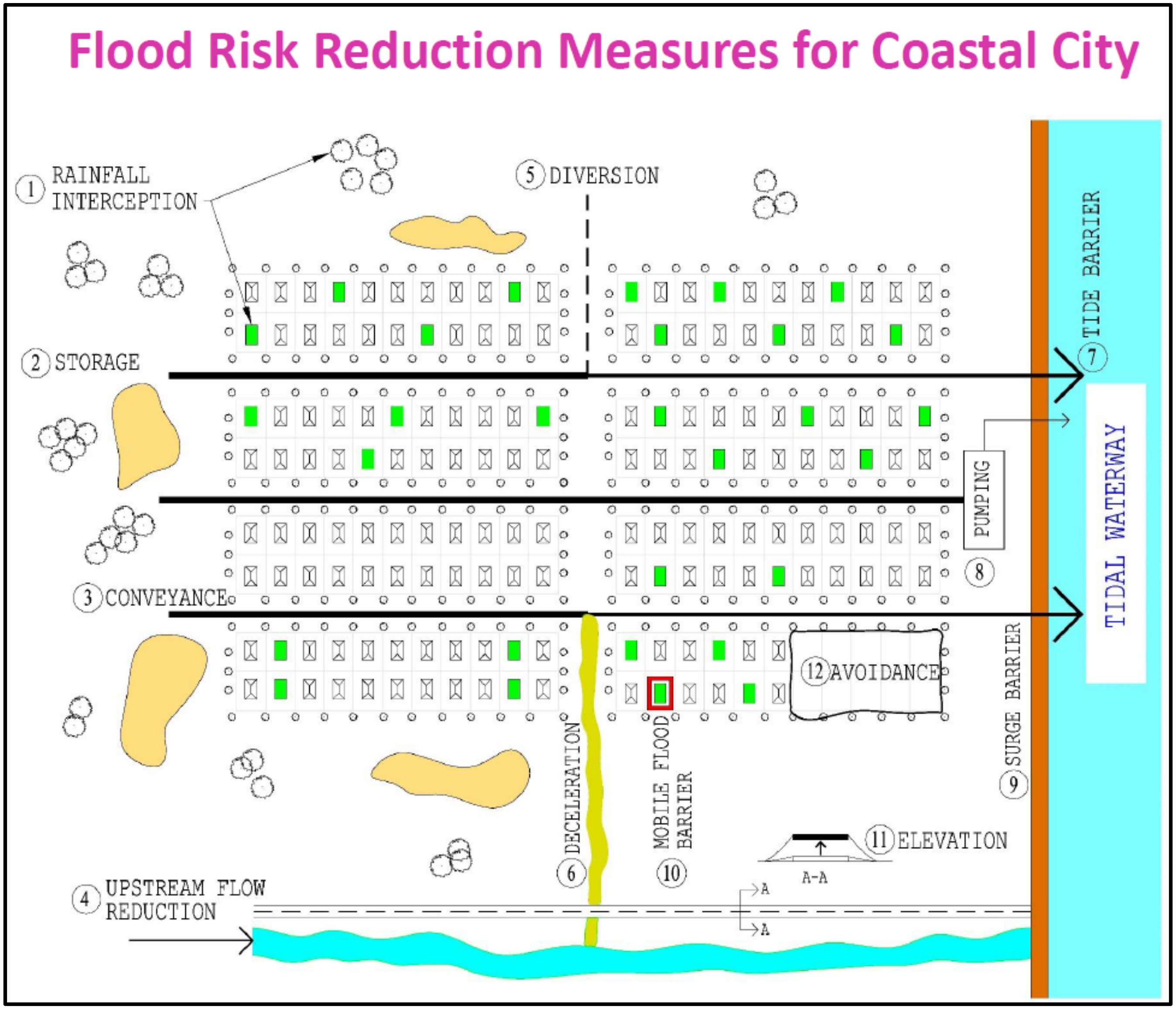

Figure 9 Flood Risk Reduction Measures

Table 2 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. Delaware Bay Region

A. Regional Flooding Overview

The Delaware Bay Study Area flooding issues can be broadly categorized by the source of the flood waters as either coastal storm surge or sea level rise. Many locations within the study area experience coastal flooding issues regularly during elevated tidal cycles (e.g., perigean spring tides, or simply spring tides in some locations). These coastal flooding issues are exacerbated by coastal storm events such as nor'easters and hurricanes, which was the case when Superstorm Sandy impacted the area. Higher water levels in Delaware Bay forced water upstream in tributaries such as the Maurice River and Cohansey River resulting in widespread flooding along the bayshore.

To evaluate the vulnerability of the Delaware Bay Study Area to coastal flooding, the Preliminary 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 10 below), the following clear risk patterns emerge:

- Locations along the Delaware Bay shoreline up to a half mile inland are impacted by wave velocity risk i.e. located in the FIRM Map VE Zone
- The 100 year flood zone extends approximately 7 miles inland from the Delaware Bay shoreline
- Coastal flood waters extend inland along the waterways that are tributary to the Bay
- Current Mean Higher High Water (MHHW) tides do not impact the residential communities in this study area significantly, see Figure 11 below.
- Future MHHW tides (6 feet higher than current) will impact this study area significantly, see Figure 16 below.

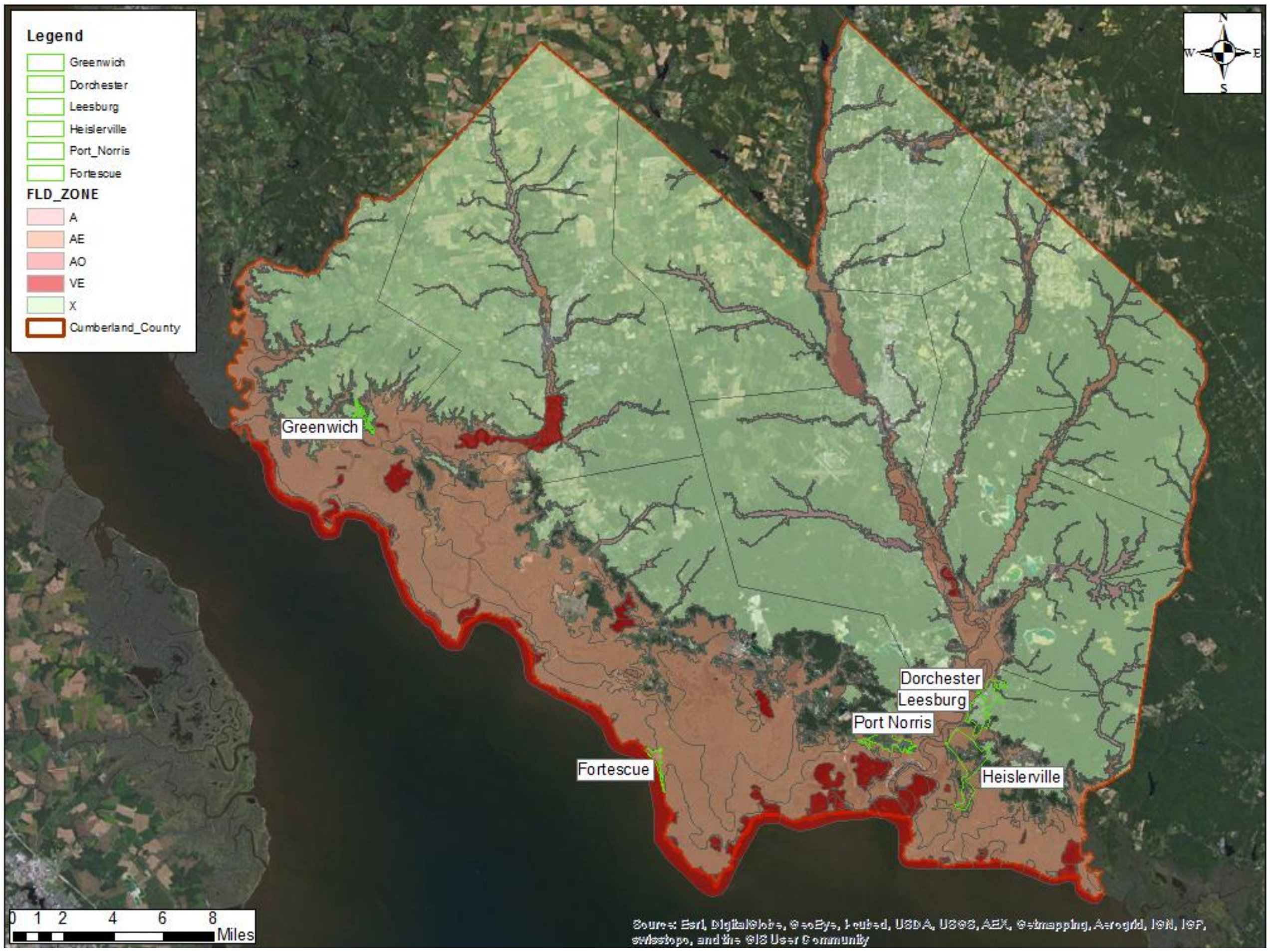

Figure 10-100 Year FEMA PRELIMINARY FIRM Overlaid on Map of Delaware Bay Study Area (FEMA, 2013)

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A map of the flooded areas during mean higher high water (MHHW) tides (Figure 11) was constructed using the data obtained from NOAA Coastal Services Center and shows shallow flooding occurring in low-lying coastal areas during these events.

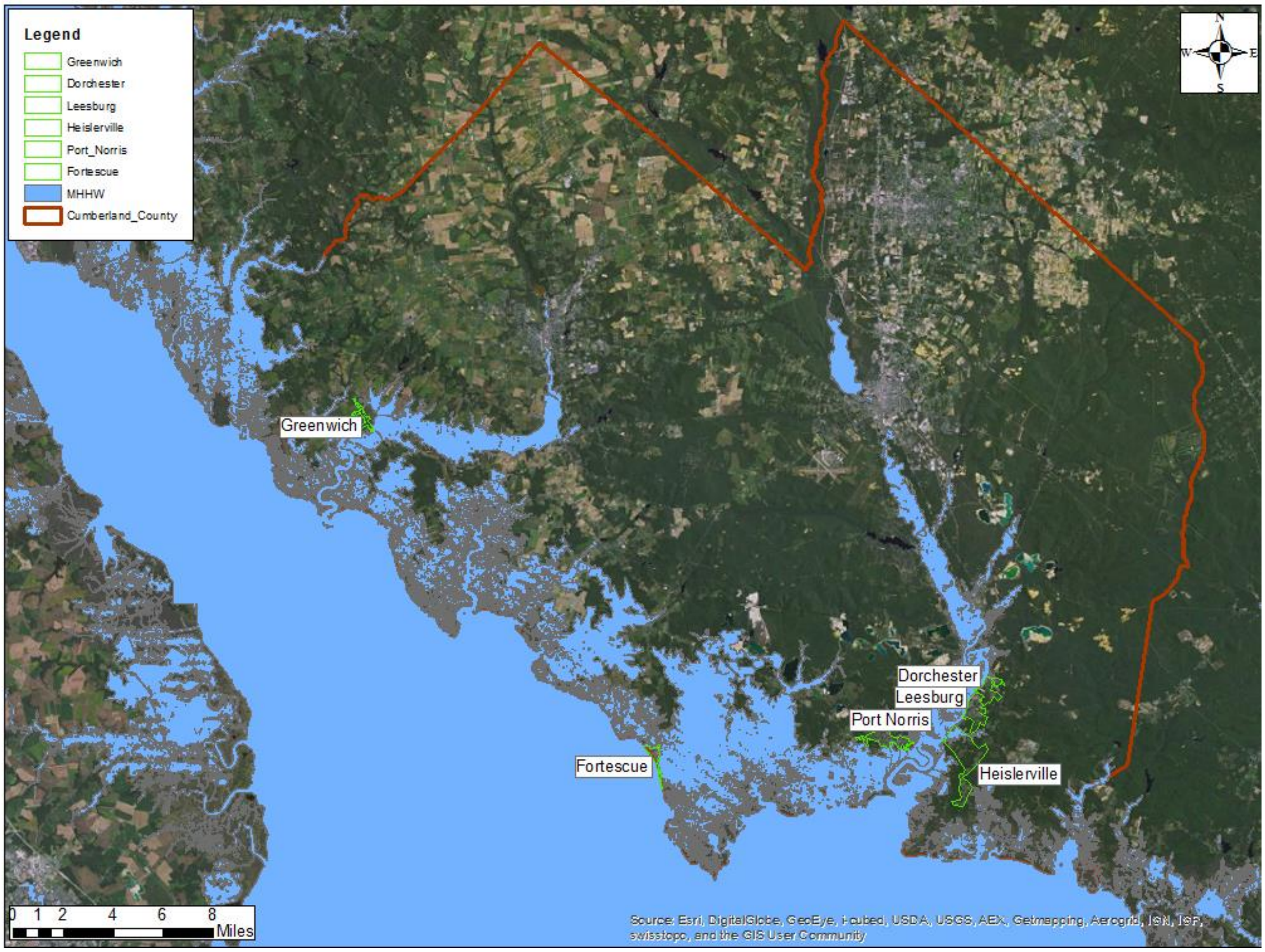

Figure 11 Flooded Areas during MHHW Tide in Cumberland County (NOAA, NOAA Coastal Services Center Sea Level Rise Data: Current Mean Higher High Water Inundation Extent, 2012)

Figure 12, Figure 13, Figure 14 and Figure 15 below show the flood prone areas in Cumberland County under the 10-, 50-, 100- and 500-year coastal storm according to data obtained from FEMA Region II Coastal Analysis and Mapping. The 10-, 50- and 100-year storm maps were used to perform flood risk vulnerability assessment and for developing coastal flood risk reduction strategies for locations identified as vulnerable.

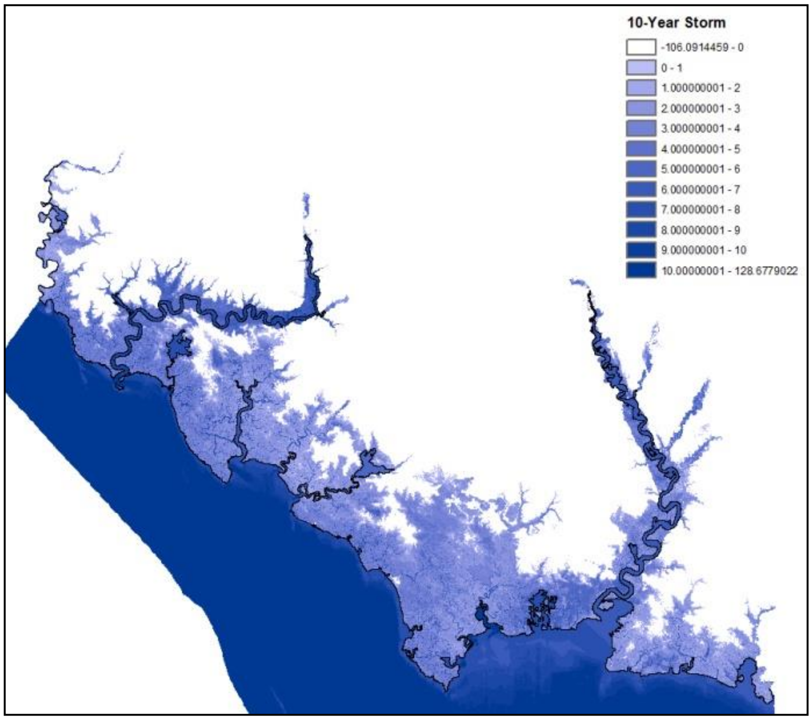

Figure 12-10 Year -Coastal Flood Depth Grid Derived from SWEL and DEM
(Source: http://content.femadata.com/Public/PreliminaryWorkMaps/NJ/Ocean/Coastal_Data/Storm_Surge/OceanNJ_Storm_Surge.zip)

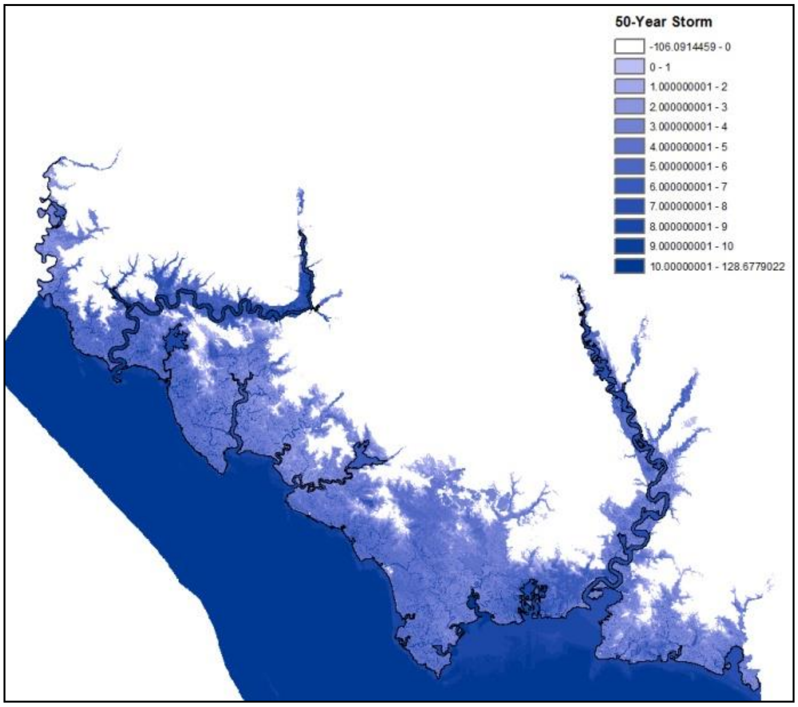

Figure 13-50 Year Coastal Flood Depth Grid Derived from SWEL and DEM
(Source: http://content.femadata.com/Public/PreliminaryWorkMaps/NJ/Ocean/Coastal_Data/Storm_Surge/OceanNJ_Storm_Surge.zip)

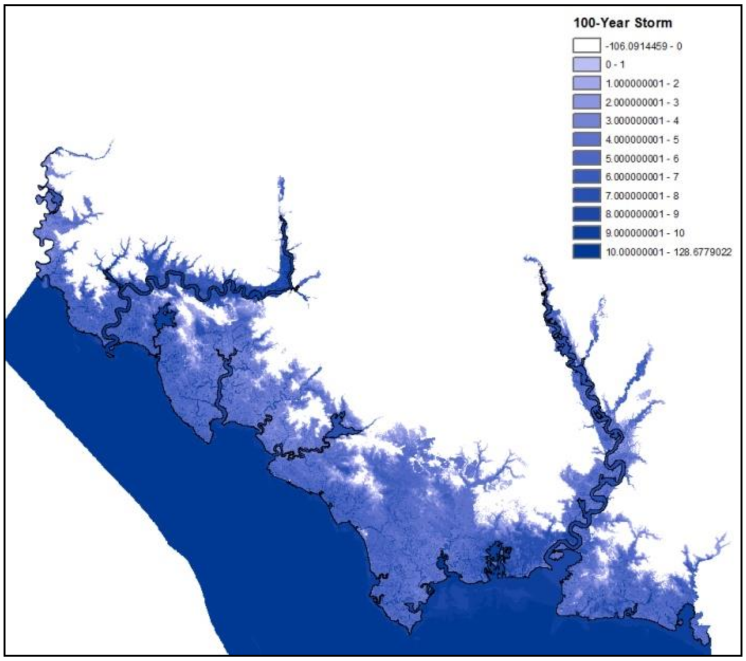

Figure 14-100 Year Coastal Flood Depth Grid Derived from SWEL and DEM

(Source: http://content.femadata.com/Public/PreliminaryWorkMaps/NJ/Ocean/Coastal_Data/Storm_Surge/OceanNJ_Storm_Surge.zip)

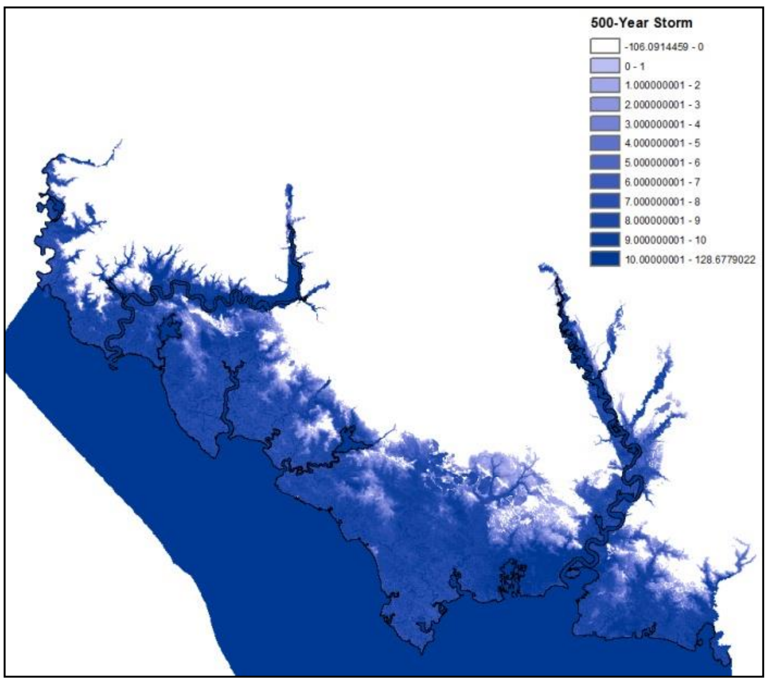

Figure 15-500 Year Coastal Flood Depth Grid Derived from SWEL and DEM

(Source: http://content.femadata.com/Public/PreliminaryWorkMaps/NJ/Ocean/Coastal_Data/Storm_Surge/OceanNJ_Storm_Surge.zip)

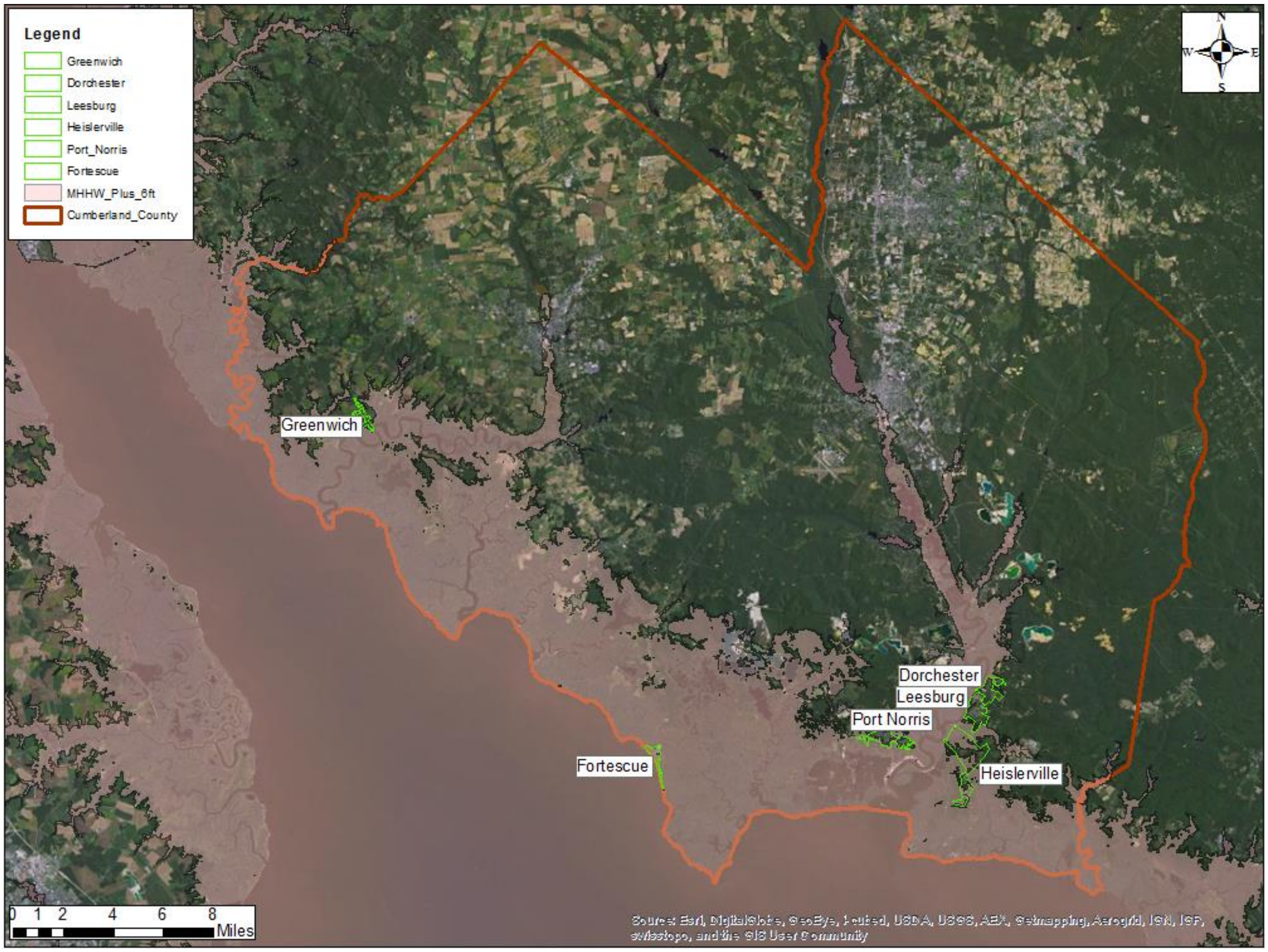

Figure 16-Sea Level Rise 6 Feet above current MHHW (NOAA, NOAA Coastal Services Center Sea Level Rise Data: Current Mean Higher High Water Inundation Extent, 2012)

A. Regional Flood Assessment

1. Coastal Flooding Assessment

After reviewing overlays of the various flood return frequency maps on aerial photographs of the study area, it is apparent that the communities of Delaware Bay are vulnerable to coastal storm surge and in some cases velocity wave hazard in addition to coastal storm surge. The risk of flooding is greatest at locations that are adjacent to Delaware Bay and its tributaries that are flooded when surge water is forced upstream into these channels.

2. Future Sea Level Rise Coastal Flooding Assessment

Many experts agree that the water levels in the world's oceans will rise over time. For the analyses of how sea level rise will affect the communities in the study area an overlay of a map developed by NOAA depicting the MHHW plus 6 feet was superimposed on top of a map of the study area and the areas of inundation were observed. After reviewing this overlay, it is apparent that in the future, communities of Delaware Bay will be at risk of flooding from the future MHHW which likely occurs once daily at close to the level of flood threat posed by the current 100 year coastal storm event. This is an important point since if these sea level rise predictions turn out to be accurate, then many of these communities will have to be abandoned unless measures are implemented in a timely manner to protect them from the coming inundation. Figure 17 and Figure 18 are photos that show the effects of past sea level rise on the region.

Figure 17-Effect of Past Sea Level Rise at Port Norris Marina in Shell Pile

Figure 18-Effect of past Sea Level Rise at the boathouse of Beaver Dam Rentals in Downe Township

3. Stormwater-Related Flooding Assessment

The risk of stormwater drainage-related flooding in the Delaware Bay Study Area is small and as is often the case is related both to impervious cover and the water levels in the waterways that convey stormwater runoff away from the region. Further analyses shows that large ditches adjacent to the communities provides more than adequate conveyance channels effectively diminishing any chance of flooding from stormwater runoff.

B. Current Regional Protection Level

The Delaware Bay Region is protected by a system of earthen levees that are designed to prevent coastal storm surge from inundating farmlands and population centers. These levees have been overtopped and bypassed in the past so it is necessary to determine what level of protection they currently provide. Table

3 below summarizes the level of protection provided by the existing levee system and was developed by the Rutgers University Team using LiDAR data to establish the top elevation of the existing levees and then comparing these elevations to various flood elevations. Figure 19 below shows the locations of the existing levees within the study area while Figure 20 and Figure 21 are close-up views of the levees showing their names.

Table 3 Table showing Existing Levees Elevations (extracted from LiDAR) and Current Level of Protection from Coastal Storm Events; Levee Information provided by Cumberland County.

Levee Name	Municipality	Length (ft)	Average Elevation (NAVD 88)	FEMA 100 Year (NAVD 88)	FEMA 50 Year (NAVD 88)	FEMA 10 Year (NAVD 88)	FEMA 100 Year + 2050 SLR (NAVD 88)	FEMA 100 Year + 2100 SLR (NAVD 88)	Current Protection Level
Port Norris	Commercial Twp.	21459	3.2	8.7	8	7	10.2	12.2	Less Than 10 Year
Port Norris North	Commercial Twp.	488	8.0	8.7	8	7	10.2	12.2	Equal 50 Year
Berrytown	Commercial Twp.	6798	4.8	8.7	8	7	10.2	12.2	Less Than 10 Year
Maple Street	Downe Twp.	2809	3.2	8.7	8	7	10.2	12.2	Less Than 10 Year
Sea Breeze Road	Fairfield Twp.	7014	5.7	8.7	8	7	10.2	12.2	Less Than 10 Year
Durham	Fairfield Twp.	8050	3.4	8.7	8	7	10.2	12.2	Less Than 10 Year
Back Neck 1	Fairfield Twp.	1443	4.8	8.7	8	7	10.2	12.2	Less Than 10 Year
Back Neck 2	Fairfield Twp.	4048	6.2	8.7	8	7	10.2	12.2	Less Than 10 Year
Rock Creek	Fairfield Twp.	1566	4.3	8.7	8	7	10.2	12.2	Less Than 10 Year
Pine Mount King	Greenwich Twp.	665	4.6	8.7	8	7	10.2	12.2	Less Than 10 Year
Pine Mount Bacons Neck Rd	Greenwich Twp.	2003	4.6	8.7	8	7	10.2	12.2	Less Than 10 Year
Market Street	Greenwich Twp.	856	4.5	8.7	8	7	10.2	12.2	Less Than 10 Year
Mill Creek (Union Bank)	Greenwich Twp.	4552	6.6	8.7	8	7	10.2	12.2	Less Than 10 Year
	/ Hopewell Twp.			8.7	8	7	10.2	12.2	Less Than 10 Year
Pease Road	Hopewell Twp.	900	4.2	8.7	8	7	10.2	12.2	Less Than 10 Year
Sheppard Davis North	Lawrence Twp.	5380	4.5	8.7	8	7	10.2	12.2	Less Than 10 Year
Sheppard Davis South	Lawrence Twp.	1979	5.5	8.7	8	7	10.2	12.2	Less Than 10 Year
Sheppard Davis Southeast	Lawrence Twp.	961	5.8	8.7	8	7	10.2	12.2	Less Than 10 Year
Sayres Neck North	Lawrence Twp.	4045	6.1	8.7	8	7	10.2	12.2	Less Than 10 Year
Sayres Neck South	Lawrence Twp.	12772	2.1	8.7	8	7	10.2	12.2	Less Than 10 Year
Sayres Neck Southeast	Lawrence Twp.	2169	3.3	8.7	8	7	10.2	12.2	Less Than 10 Year
Jones Island Road	Lawrence Twp.	5606	4.1	8.7	8	7	10.2	12.2	Less Than 10 Year
Bay Point Road	Lawrence Twp.	6273	6.2	8.7	8	7	10.2	12.2	Less Than 10 Year
Blizzard Neck Gut	Lawrence Twp.	9997	5.6	8.7	8	7	10.2	12.2	Less Than 10 Year
Bay Point Road South	Lawrence Twp.	2937	6.8	8.7	8	7	10.2	12.2	Less Than 10 Year
Nancy Gut	Lawrence Twp.	2431	5.3	8.7	8	7	10.2	12.2	Less Than 10 Year
Heislerville Impoundment	Maurice River Twp.	14984	5.9	8.7	8	7	10.2	12.2	Less Than 10 Year
Thompson	Maurice River Twp.	5537	7.0	8.7	8	7	10.2	12.2	Equal 10 Year
Burcham	Millville City	5915	5.0	8.7	8	7	10.2	12.2	Less Than 10 Year

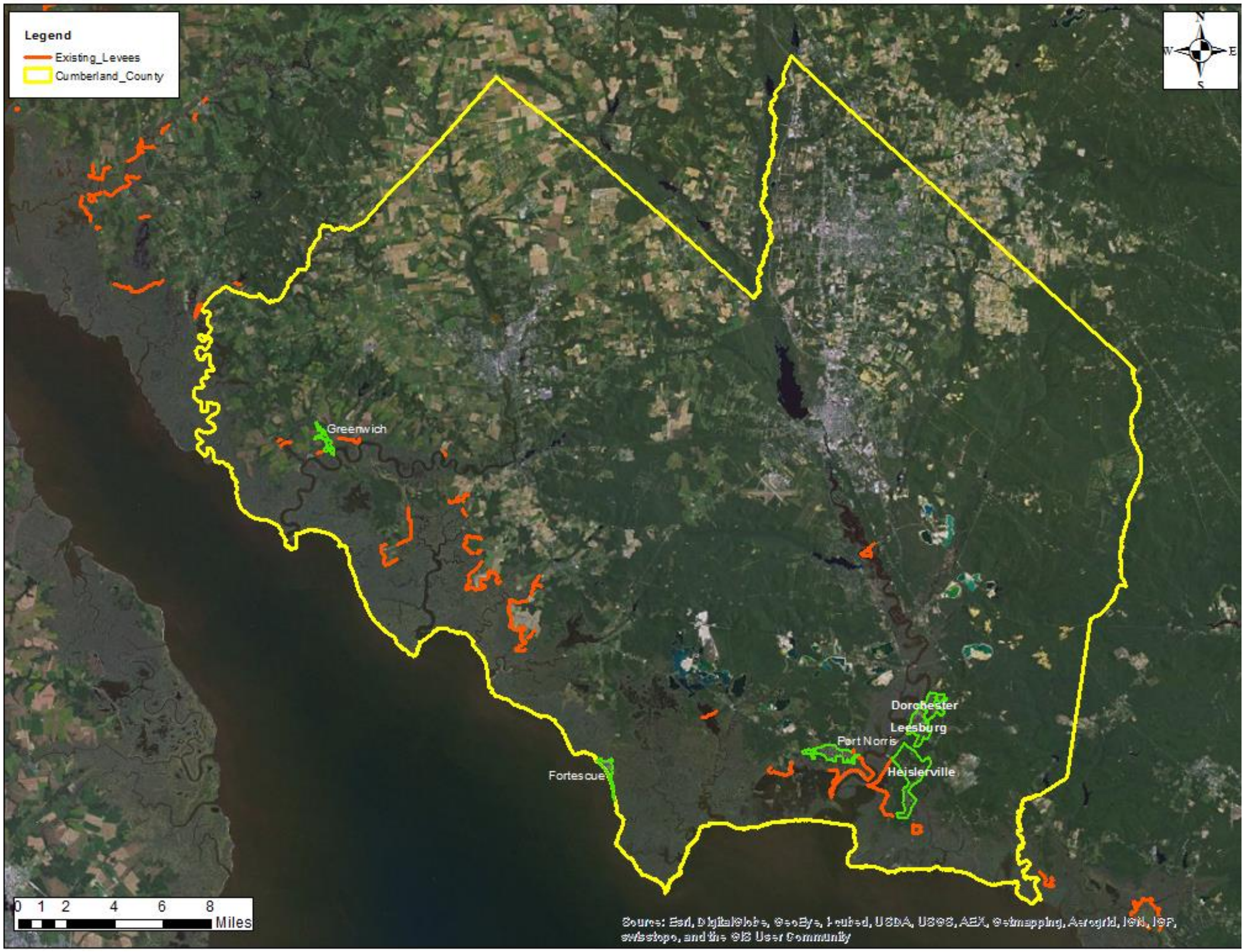

Figure 19- Map of Existing Levees within Study Area developed by Rutgers University Team using Levee Data from County (Cumberland_County, 2013)

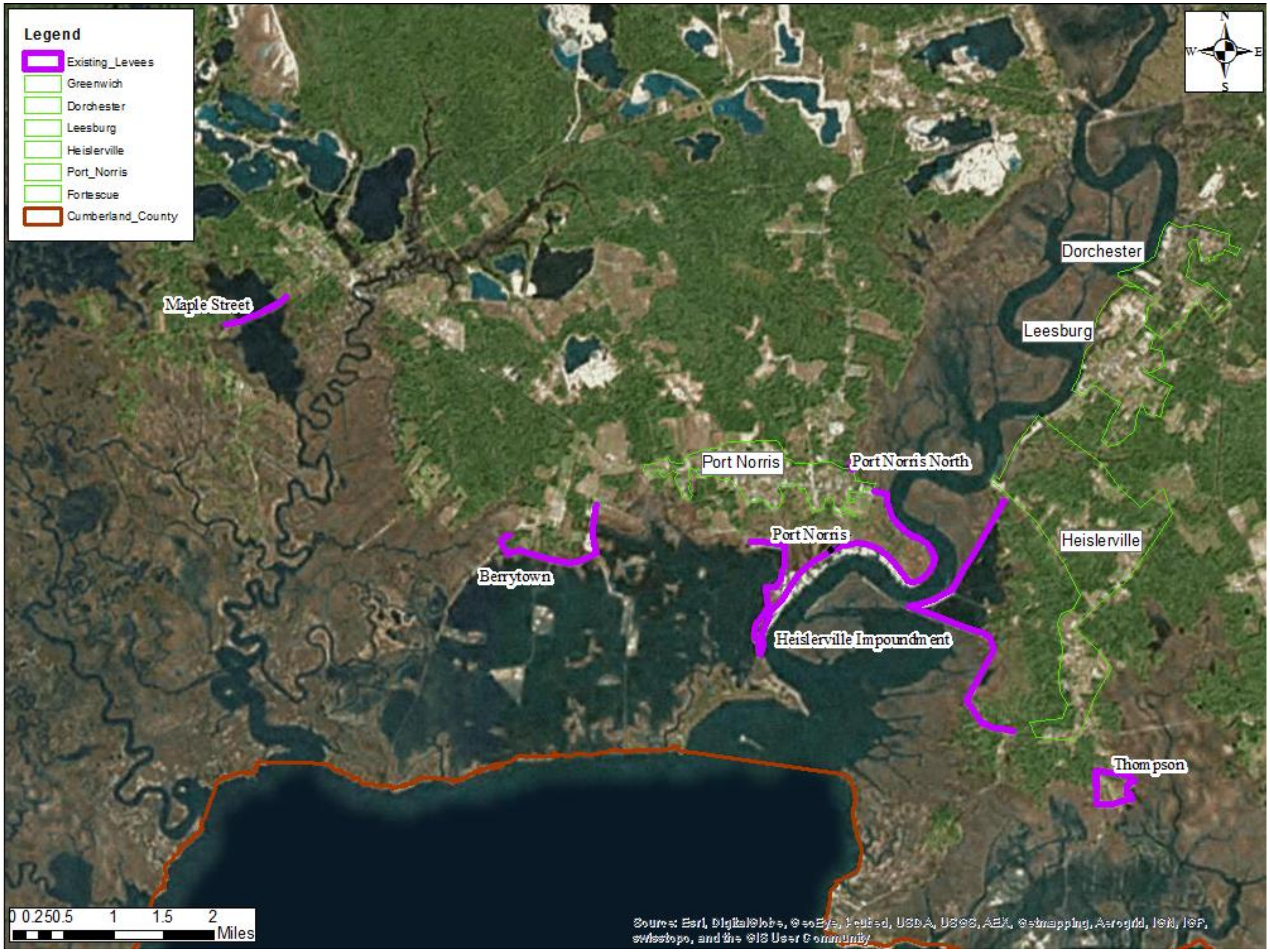

Figure 20-Map showing Existing Regional coastal storm barrier system on Eastern Section of Study Area developed by Rutgers University Team using Levee Data from County (Cumberland_County, 2013)

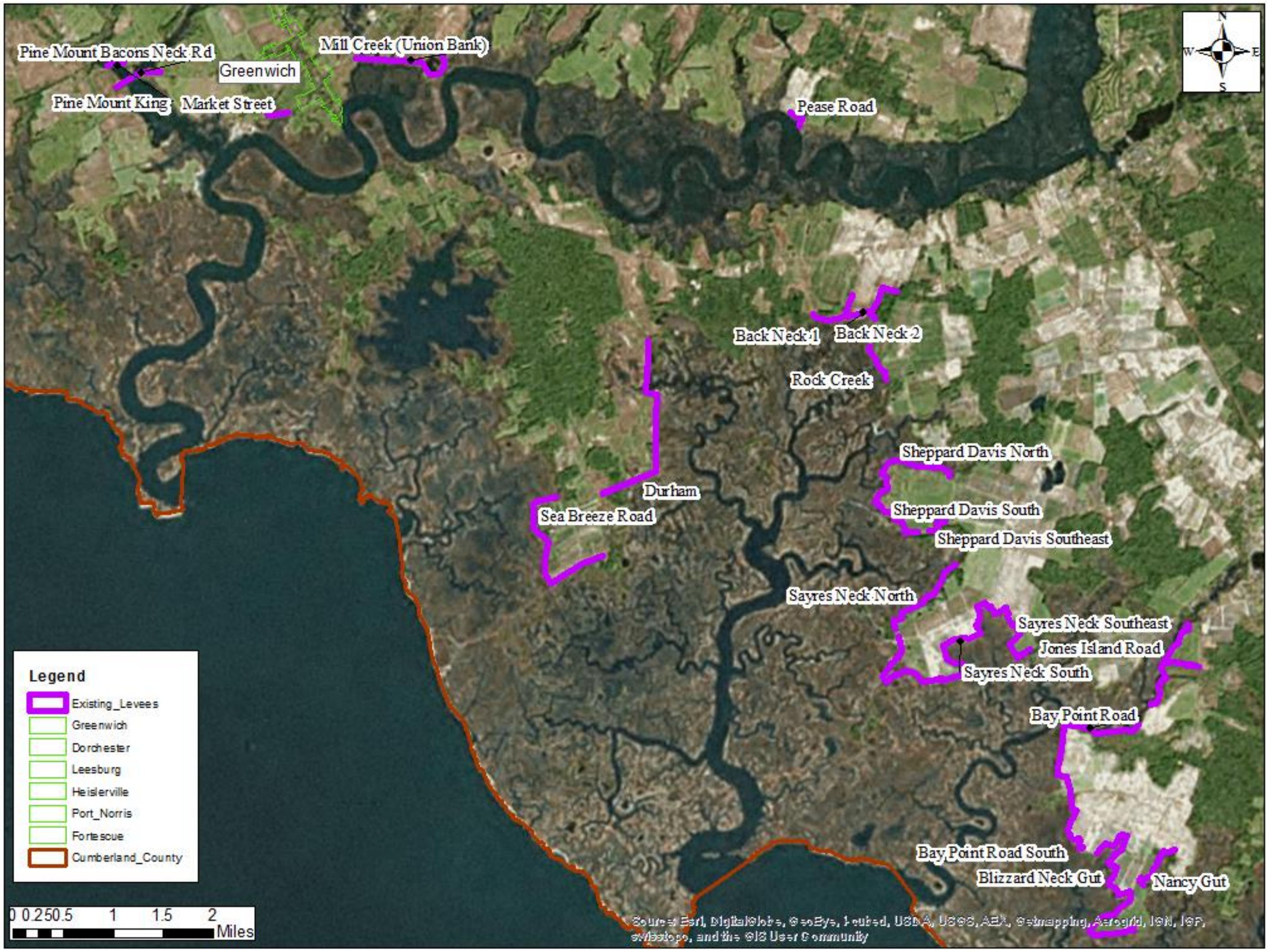

Figure 21 Map showing Existing Regional coastal storm barrier system on Western Section of Study Area developed by Rutgers University Team using Levee Data from County (Cumberland_County, 2013)

C. Regional Coastal Flood Mitigation Recommendations

1. Regional Causeway System

Based on the regional threat from flooding as represented by the FEMA PRELIMINARY FIRM map overlay of the study area, it is apparent that a regional approach to flood protection will be more effective than a localized piecemeal strategy. Accordingly, a regional coastal storm barrier system that allows the salt marshes along the banks of the Delaware Bay to flourish and act as a natural barrier to surge is likely to be effective in regional flood mitigation, see Figure 22. Such a system will require input from environmentalists and ecologist to ensure that the suggested alignment of the system is located as far upland as possible to sustain and proliferate the existing salt marshes while also providing protection from coastal storm surges to populations at risk.

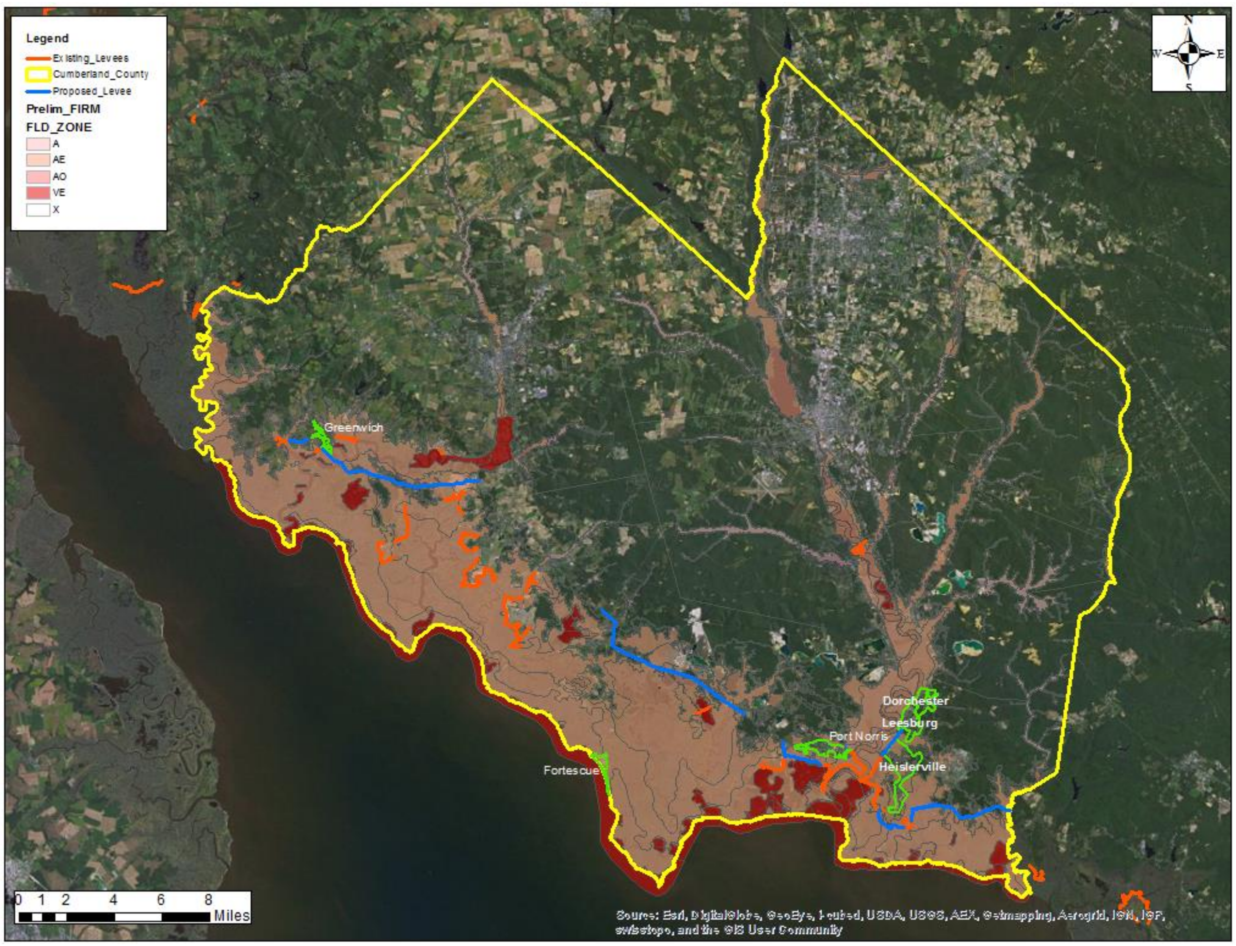

Figure 22- Suggested Regional Coastal Storm Barrier System Layout

- Proposed alignment is conceptual only; actual alignment will requirement input from wetlands experts

The regional coastal storm barrier system will utilize causeways equipped with operable flood gates that can be opened and closed mechanically. See Figure 23 below for example of the type of causeway suggested to be built for regional coastal flood barriers.

Figure 23-Bridge over Wetlands in Louisiana (Susan Poag, The Times-Picayune)

The strategy of using causeways equipped with operable flood barriers instead of installing earthen levees was developed to allow the existing salt marshes to migrate upland with sea level rise thereby increase the chance of survival of this vital ecosystem (Lathrop & Bognar, 2014). See causeway schematic below in Figure 24.

Also, the project seeks to utilize levee raising technologies to increase the flood protection level provided by existing levees by adding fill material (Figure 25) or by installing metal sheet piles in various configurations (Figure 26, Figure 27, and Figure 28).

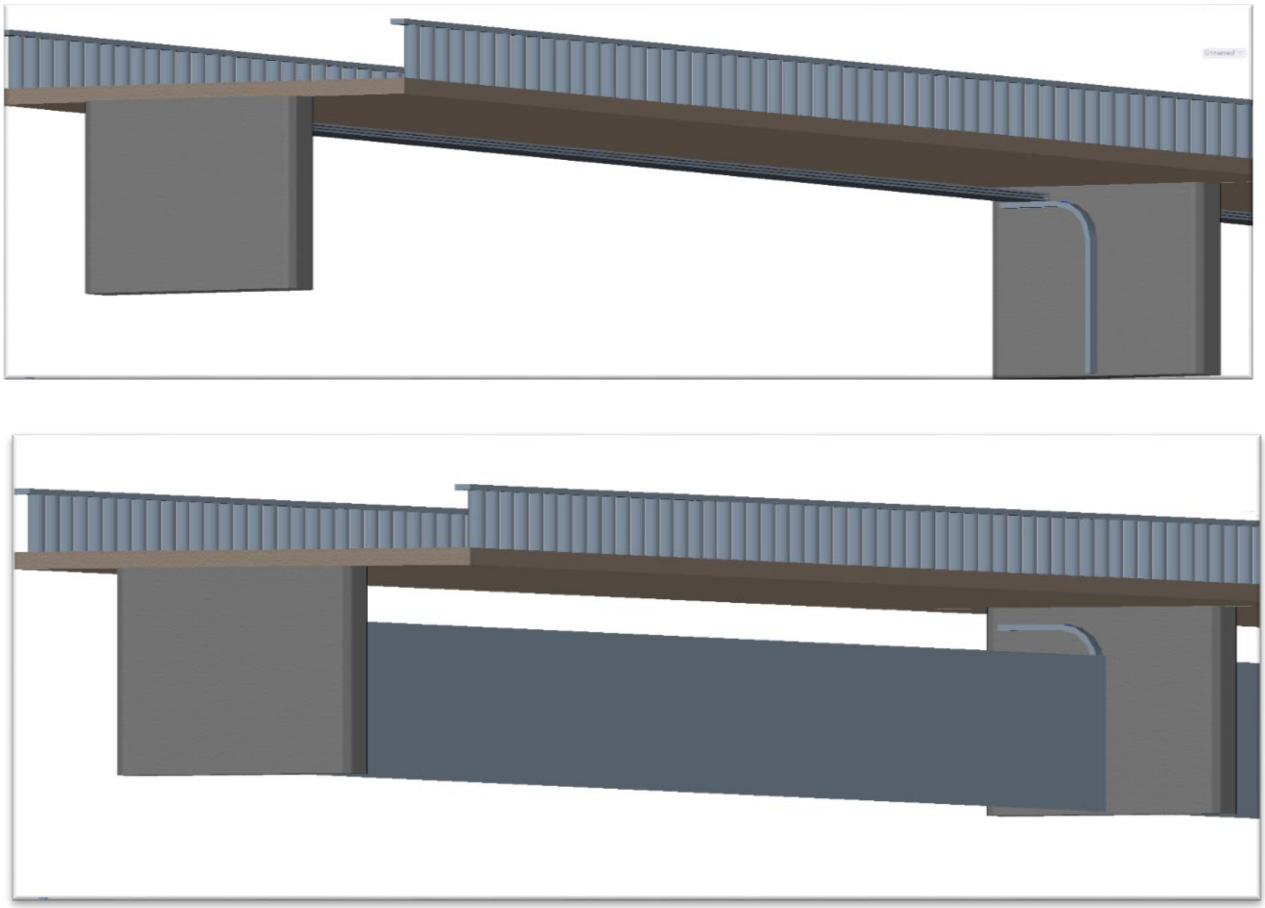

Figure 24-Causeway Schematic showing Flood Barrier Open (Top) and Closed (Bottom)

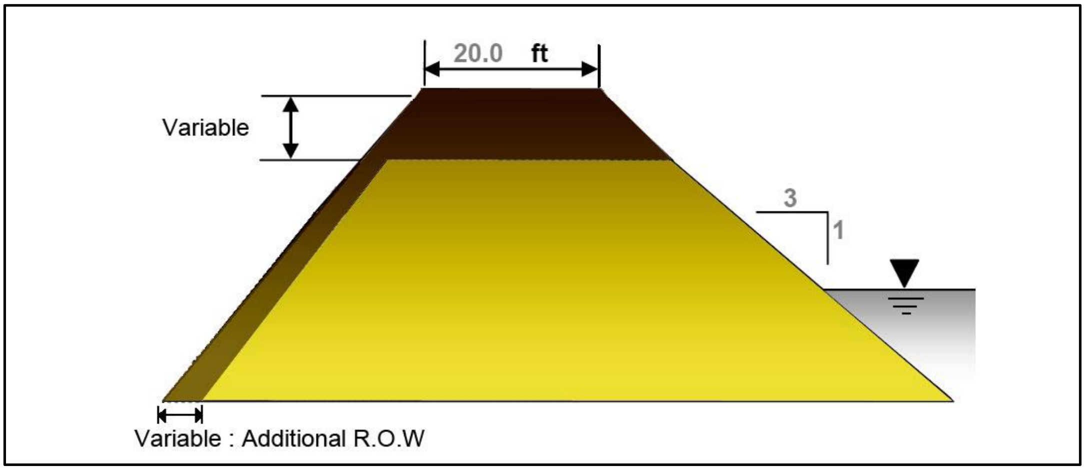

Figure 25 -Typical levee raise using fill material (adapted from Strong Levees: http://www.stronglevees.com)

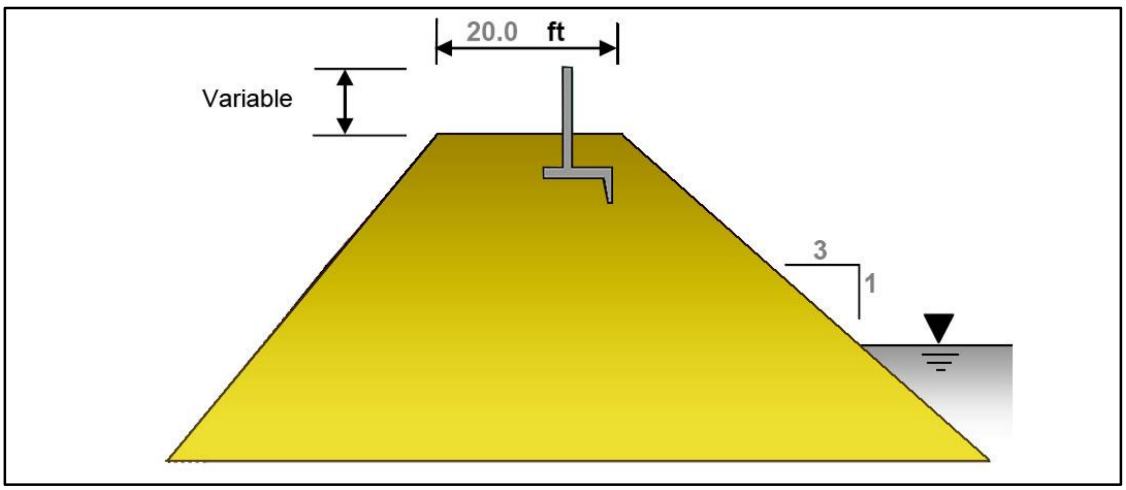

Figure 26 -Typical levee raise using T-type cantilever wall, (adapted from Strong Levees: http://www.stronglevees.com)

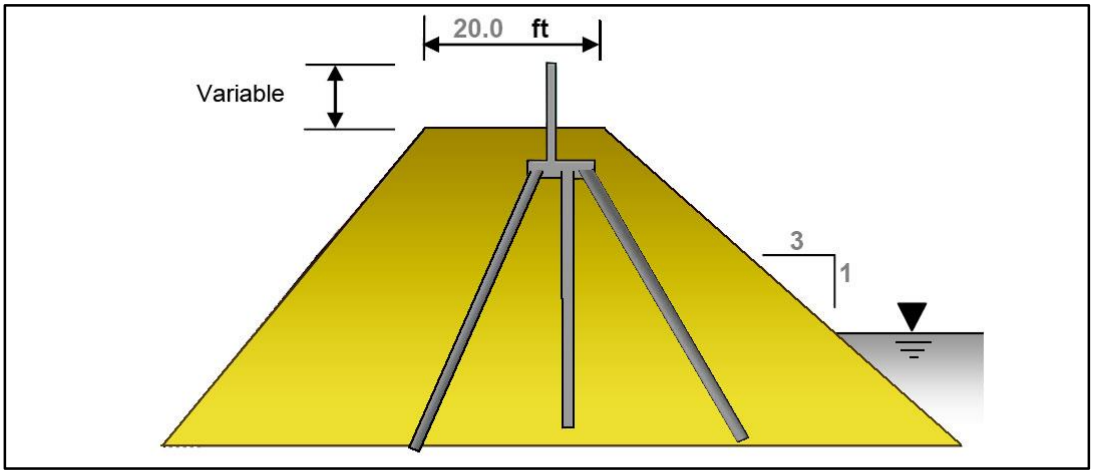

Figure 27 -Typical levee raise using T-Wall supported on sheet piles, (adapted from Strong Levees: http://www.stronglevees.com)

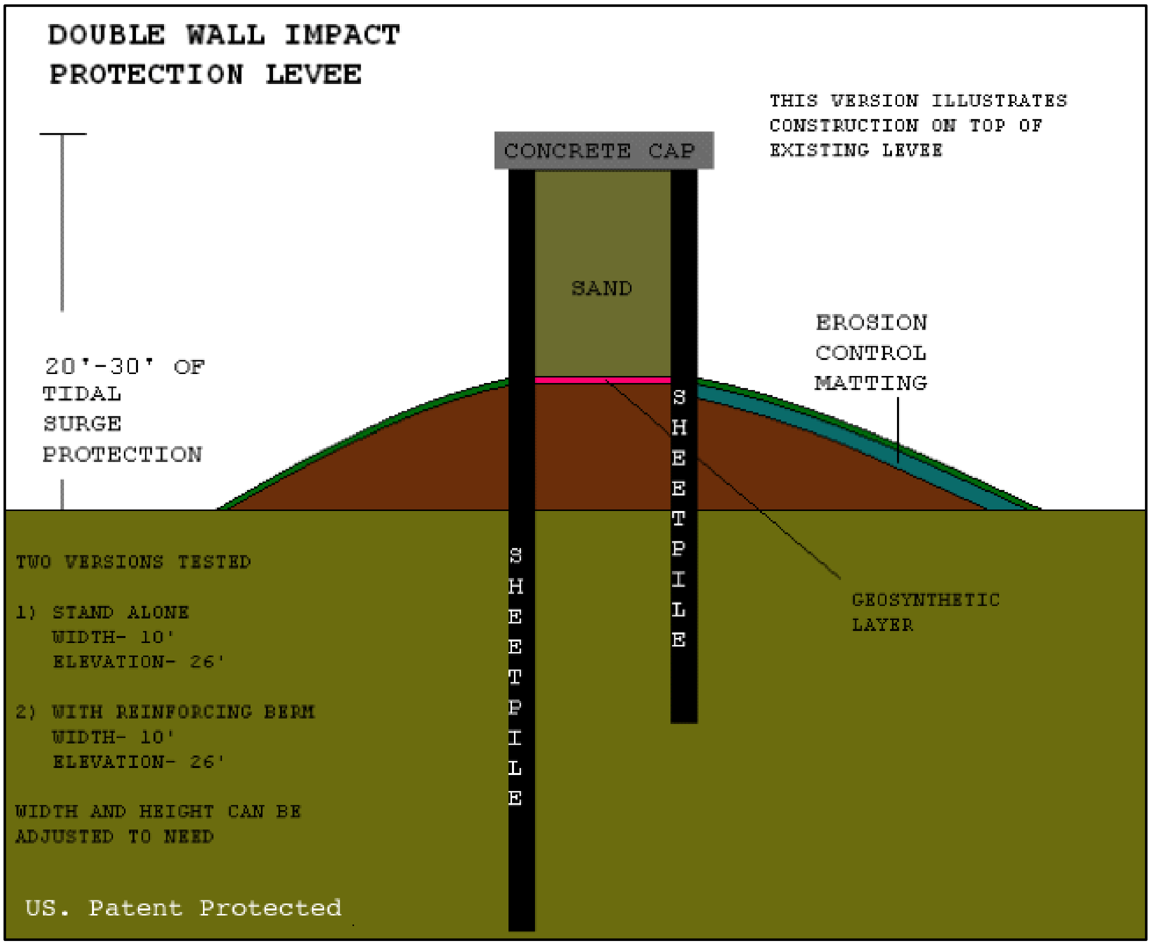

Figure 28- Double wall through existing levee, (adapted from Strong Levees: http://www.stronglevees.com)

2. In-Water Closure Devices

It is proposed that in-water closure devices be installed along the Cohansey and Maurice Rivers. Communities along the banks of these waterways are located either partially or fully within the 100 year flood zone and will also experience flooding from anticipated sea level rise. Coastal flooding can be mitigated with the installation of these devices which will only be activated in anticipation of serious coastal storm events.

With the implementation of the regional causeway flood protection system there will be no need for these in-water closure devices since river closure will be built into the causeway wherever there is a river crossing.

3. Flood Water Pumping

There is also the risk of coastal storm surge overtopping or breaching levees that could result in flood waters being trapped for extended periods. Although it is difficult to estimate the amount of surge water that can become trapped behind a levee under these circumstances, it is likely to be large volumes.

Low cost wind powered pumps can be considered to bring some relief to this type of flooding (see

Figure 29 for photograph of a wind powered pump). Wind powered water pumps can usually operate even in light winds and Table 4 below provides information on the amount of pumping capacity that can be generated by the 6 meter diameter model.

For safety of operations it is recommended that 6 meter diameter windmills' wind wheel should be located at least 6 meters above any obstructions within a 120 meters radius. Also, if the windmill tower is located in areas subjected to high winds, the wind wheel should be located high enough to avoid damage caused by blowing debris, building materials, trees, etc.

Figure 29 - The 6m dia. windmill tower (Ironmanwindmill, 2014)

Table 4 below summarizes pumping capacities based on various wind speeds. In nearby Atlantic City the average annual wind speed is 9.8 m/s which qualifies as a strong wind according to Table 4.

Table 4-Windmill tower pumping capacity in wind speed ranges (http://www.ironmanwindmill.com)

Common Wind Environment	Pumping Capacity (gallons per hour)
Strong winds (above 7.0 m/s)	56,982 gallons
Medium winds (4.5 to 7.0 m/s)	31,340 gallons
Light winds (1.6 to 4.5 m/s.)	14,245 gallons

4. Wetlands Restoration

Situated between the suggested levee system and the Delaware Bay are salt marshes (Figure 30) which, if healthy, can provide for significant surge attenuation (Mary E. Anderson, 2013). It is suggested that these salt marshes (approximately 75,000 acres) be restored, enhanced and protected as part of the regional approach to flood mitigation. Part of the effort of to restore the existing marshes should include the installation of living shorelines or hybrid living shorelines along the bay or estuary edge to help protect existing marshes where possible (Whalen, Kreeger, & Bushek, 2012) (PDE, 2012). Any efforts to reduce coastal surge and wave will result in savings on the cost of new or elevated levees.

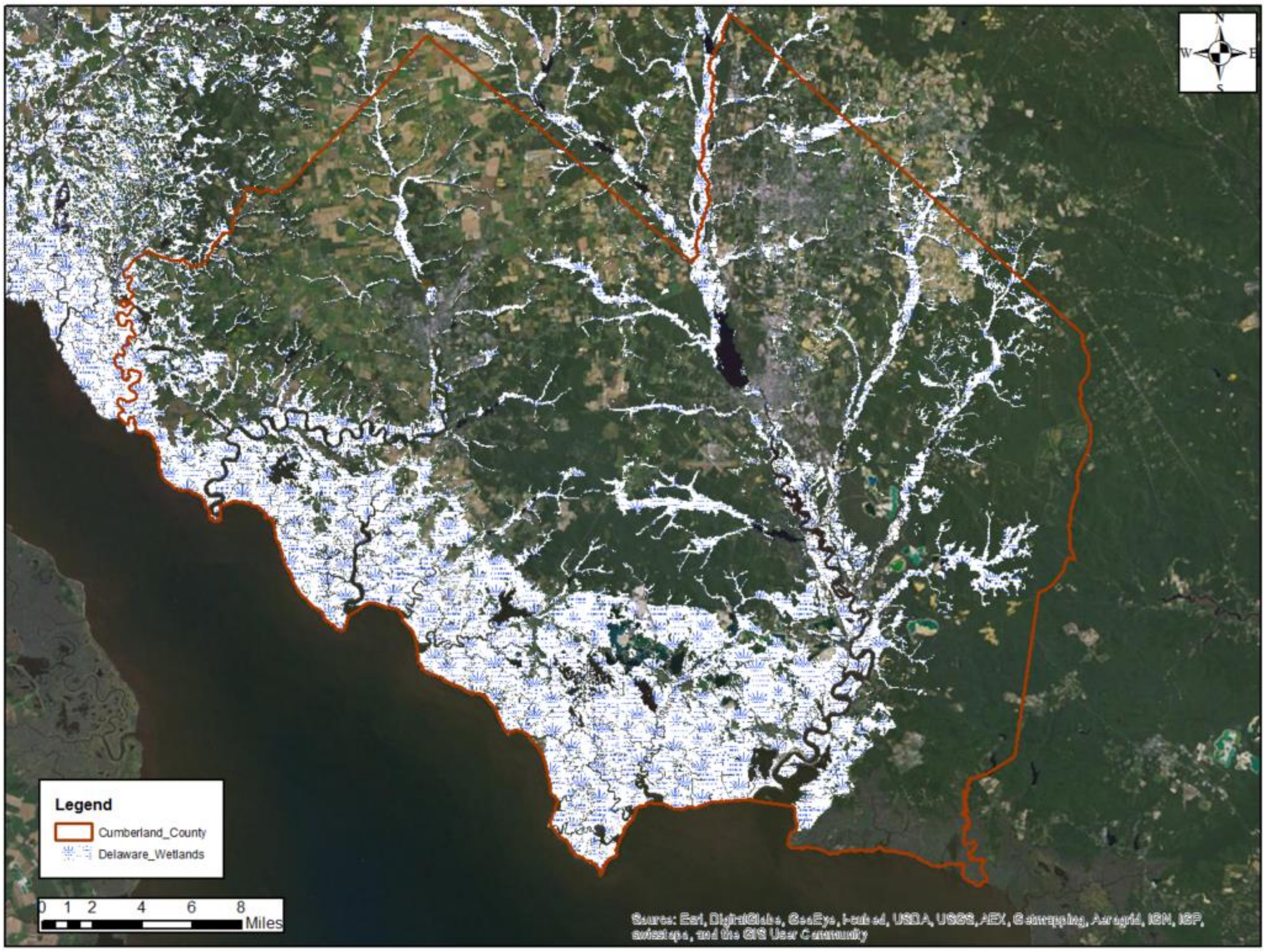

Figure 30-Wetlands in the Study Area (Obtained from NJ Land-use Maps)

D. Regional Stormwater-Related Flood Mitigation Considerations

1. Overview

The Delaware Bay Study area is not highly urbanized therefore stormwater runoff is not a major problem as is in the case in heavily urbanized areas. Initial assessment of the study area seems to indicate that there is indeed very little risk from stormwater drainage related flooding.

Accordingly, there is no need for flood mitigation measures to be implemented for stormwater-drainage related flooding. However, there are other benefits that can be derived from commonly used stormwater mitigation strategies such as green infrastructure and analysis was performed to determine optimal implementation of such measures in the study area.

2. Green Infrastructure

An analysis was performed on the study area to determine the potential for installation of green infrastructure for benefits other than stormwater runoff relief such as water quality improvements and the results of this analysis is provided for consideration. See Appendix 1-Stormwater Green Infrastructure Methodology for information on how this analysis was performed.

To determine the optimal application for green infrastructure, only the areas in the 100-year storm (Table 5) are considered in the calculations. From the land use map, areas such as wetlands, forests, water bodies and agricultural lands are also excluded. Included classifications considered for green infrastructure implementation are commercial, industrial, residential, athletic fields, urban lands and built up lands.

Table 5- Green Infrastructure Summary Data for Study Area

	Rainfall amount(1-Year Storm) (in)	Runoff from 1 year storm (in)	Total area (acres)	Area in 100 year flood zone (acres)	Excluded area (acres)	Area used for analysis (acres)	Percentage of area in the town
Greenwich	2.8	1.35	11862	6555	6468	87	0.18
Port Norris	2.8	1.6	2443	2424	2234	190	8
Fortescue	2.8	1.7	992	992	976	16	2
Leesburg	2.8	1.29	319	74	55	19	25.86
Heislerville	2.8	1.33	788	716	570	146	20.37
Dorchester	2.8	1.51	240	38	23	15	40.58

E. Flood Mitigation Cost

The regional flood mitigation cost for the Delaware Bay Study Area is based on the regional causeway flood barrier system considered for mitigation of flood risk from the FEMA 100-year coastal storm event and MHHW plus 6 feet of future sea level rise (Table 6). Table 7 below shows the cost of using earthen levees instead of causeways. (All nit prices used are contained in Appendix 2-Unit Cost Tables)

Table 6-Summary of Cost for Regional Causeway Flood Barrier System-100-year and Sea Level Rise

Measure Proposed	Unit	Quantity	Unit Cost	Cost
New Causeway	Miles	34	$ 22,000,000.00	$ 748,000,000.00
Elevate Existing Levees	Miles	27	$ 5,000,000.00	$ 135,000,000.00
Wetlands Restoration	Acres	75,000	$ 4,000.00	$ 300,000,000.00
Total				$ 1,183,000,000.00

Table 7-Summary of Cost for Regional Clay Levee Flood Barrier System-100-year and Sea Level Rise

Measure Proposed	Unit	Quantity	Unit Cost	Cost
New Clay Levees	Miles	34	$ 31,680,000.00	$ 1,077,120,000.00
Elevate Existing Levees	Miles	27	$ 5,000,000.00	$ 135,000,000.00
In-Water Closures	Cubic Feet	7,080	$ 31,000.00	$ 220,000,000.00
Wetlands Restoration	Acres	75,000	$ 4,000.00	$ 300,000,000.00
Total				$ 1,732,120,000.00

- Cost estimates of regional causeway and levee systems are averaged and may cost more or less depending on the actual location.

F. Conclusion

For the Delaware Bay Study Area, it is suggested that a regional coastal storm barrier system be considered that can protect the entire region from coastal storm surge and future sea level rise. The existing levee system is generally too low to protect the area against the 100-year coastal storm event and is insufficient laterally to protect all the areas that need protection. The suggested levee system is comprised of several components that include elevated roadways (causeways with operable flood barriers), elevated existing levees and new levees. In addition, in-water closure devices should be installed in the Cohansey and Maurice rivers to prevent storm surge from propagating upstream during major coastal flooding events.

Furthermore, approximately 75,000 acres of wetlands that are located between the levee system and the Delaware Bay could be protected, restored and expanded where possible to help attenuate wave action and surge during storms. This effort will allow the proposed levee system to be installed at a lower top elevation resulting in reduced cost.

Finally, it is proposed to provide wind powered pumps to help drain the trapped surge resulted from levee overtopping or breaching. This will be useful in draining flooded areas at a low cost and can provide some pumping when electrical power is unavailable.

One significant advantage of the regional coastal protection system is that it will more efficiently protect areas such as Port Norris, Leesburg and Dorchester compared to if each community had to install its own coastal storm protection plan. Additionally, with the implementation of a robust and reliable regional coastal flood protection system there is likely to be increased economic stability as investment risk is reduced particularly in the farming, commercial fisheries (especially oyster), ship building, residential housing, sport fishing, recreation and ecotourism businesses that dominated the region. This type of stability will ensure continued investment in flood protection and other infrastructure.

IV. Municipality Flood Vulnerabilities and Mitigation Recommendations

A. Port Norris

1. Background Information

Port Norris is a community of population 1,377 (2010 US Census) located in Commercial Township in Cumberland County NJ. Commercial Township bounded by Delaware Bay to the south and the Maurice River to the east. The Port Norris community is located just west of the Maurice River and just north of the wetlands that extend to the Delaware Bay (Figure 31 below is an aerial photograph of the community).

Figure 31-Aerial Map of Port Norris

2. Coastal Flood Threat Assessment

The vulnerability of Port Norris to coastal flooding was assessed by overlaying the FEMA Preliminary FIRM Map on an aerial photograph of the community (Figure 32) to determine which areas would be inundated by the 100-year coastal storm event.

From this map overlay it is apparent that areas adjacent to headwaters of Maple Creek and the Maurice River are extremely vulnerable to a 100-year coastal storm event. Figure 33 is a photo showing a levee failure location caused by Superstorm Sandy.

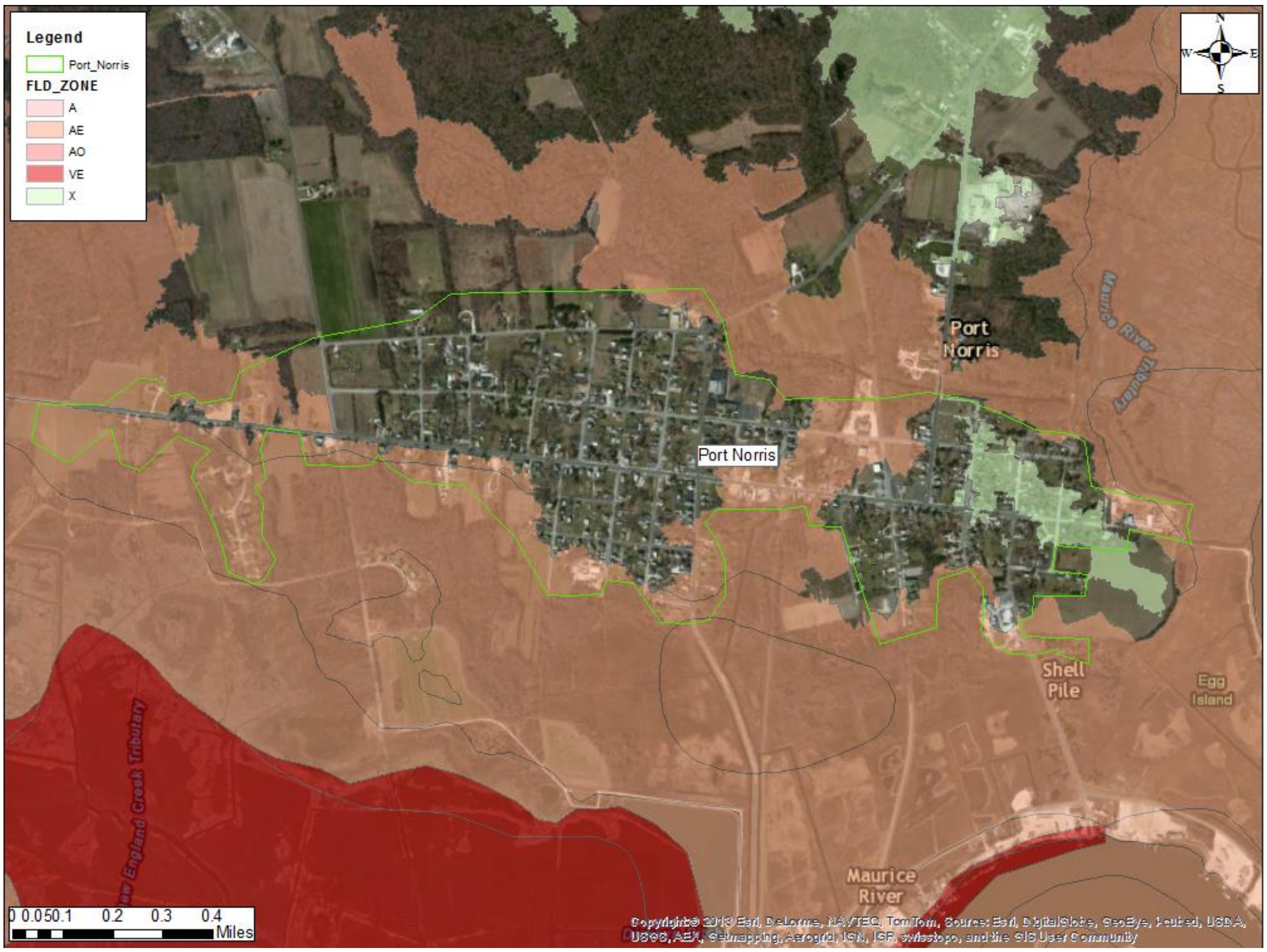

Figure 32 – Port Norris with FEMA PRELIMINARY FIRM Map Overlay (FEMA, 2013)

Figure 33-Failure of Peak of the Moon dike within Bivalve community, Port Norris, NJ

3. Future Sea Level Rise Coastal Flooding Assessment

For the analyses of how sea level rise will affect Port Norris an overlay of a map developed by NOAA depicting the MHHW plus 6 feet was superimposed on top of a map of the Port Norris and the areas of inundation were observed. After reviewing this overlay, it is apparent that in the future Port Norris will be at risk of flooding from the future MHHW at close to the level of flood threat posed by the current 100-year coastal storm event (Figure 34).

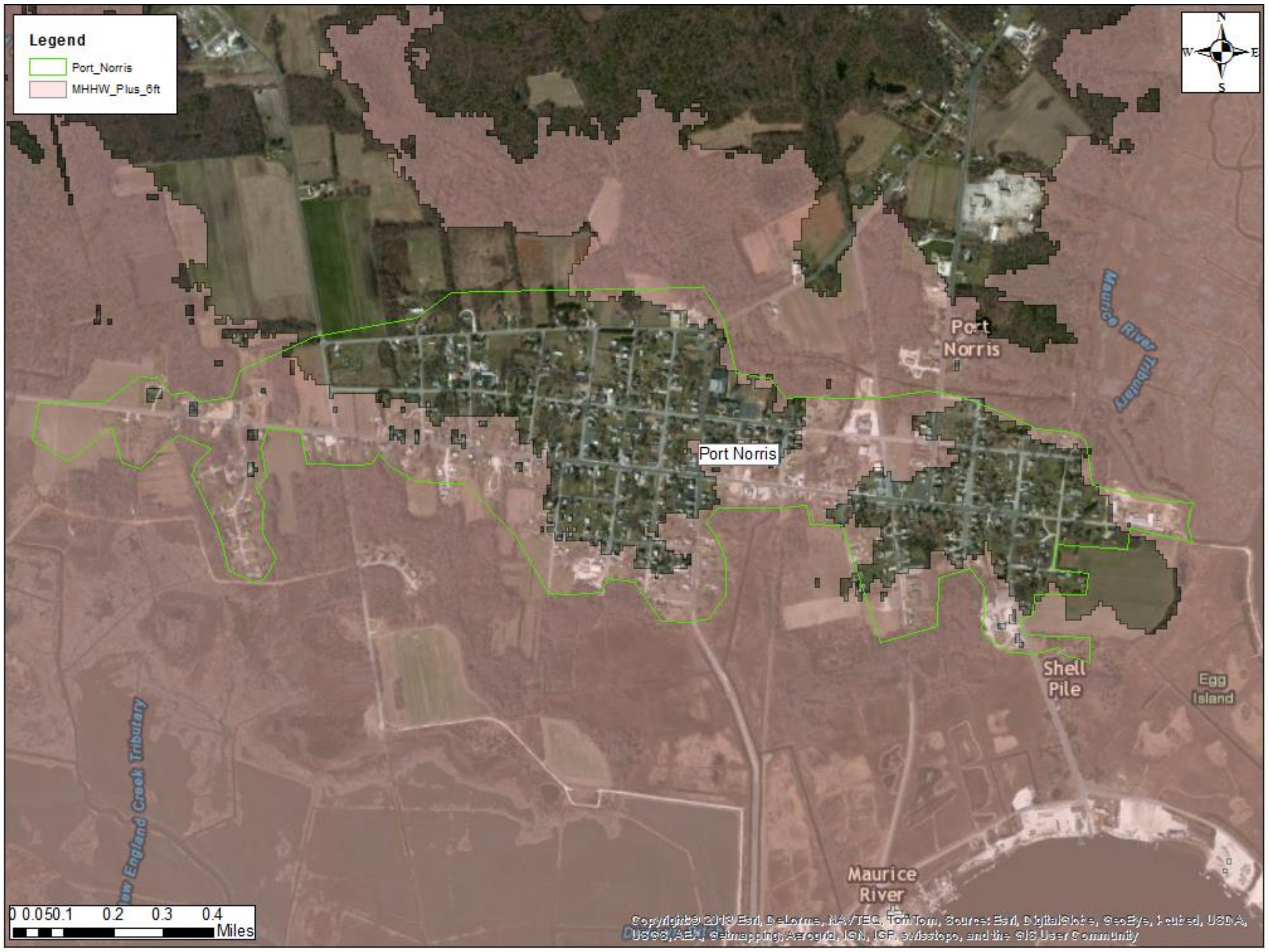

Figure 34-Map of Port Norris with MHHW plus 6 Feet superimposed (NOAA, NOAA Coastal Services Center Sea Level Rise Data: 1-6 ft Sea Level Rise Inundation Extent, 2012)

4. Stormwater-Related Flood Threat Assessment

Although the community of Port Norris is located within a rural setting, it is urbanized and as such does generate stormwater runoff. Initial assessment confirms that there is minimal risk of flooding from this source.

5. Coastal Flood Threat Mitigation for 100 Year Event & SLR

After reviewing the sources for coastal flooding and the existing flood protection level, the following flood mitigation measures are proposed to reduce the level of vulnerability (Figure 35) in Port Norris:

- Elevate the existing Port Norris and Port Norris North levees to the 100 year elevation
- Install a new levee between the Port Norris and Berrytown levees
- Install a new levee between the Berrytown Levee and Main Street
- Install new tide gate where the North Port Norris Levee crosses a tributary to the Maurice River

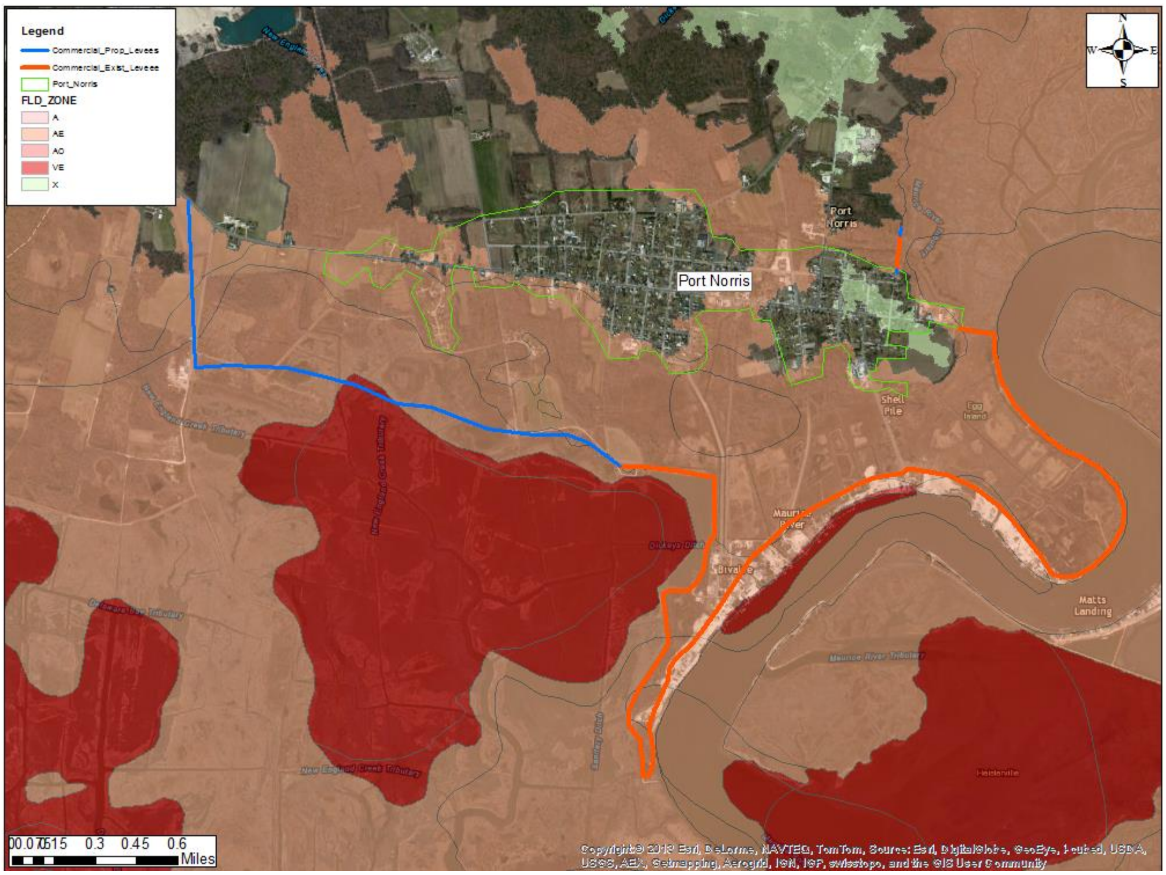

Figure 35-Map showing Location of suggested Existing Levees to be Elevated and Proposed Levees (FEMA, 2013)

6. Green Infrastructure Analysis

Although green infrastructure is not needed to mitigate flooding in the community of Port Norris, analysis was performed using the green infrastructure optimization software developed by the Rutgers University Flood Study Team to identify various measures that can be considered for other benefits such as water quality improvement. Following are green infrastructure solutions and costs that were developed for areas in the community located in the 100 year flood zone:

- Maximum runoff capture: 1.2 inch
- Cost to remove 1.2 inch of runoff (10 year horizon) = $ 33,355,507
- Cost to remove 1.2 inch of runoff (50 year horizon) = $ 37,273,230

Table 8, Table 9 and Table 10 below provide Green Infrastructure measures and costs to remove 1 inch of runoff.

Table 8 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	782105	1261241
Swales	236482	236482
Planter box	12612	12612
Vegetated filter strips	236482	236482
Permeable sidewalk	220634	220634
Permeable driveway	268013	268013
Permeable parking	80569	80569
Rain garden	63060	63060
Total cost ($) – 10 year	$25,462,405	
Total cost ($) – 50 year	$28,724,561	

Table 9 Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	$19,061,034.00	0.74
50 year	$25,932,969.00	0.90

Table 10-Cost Breakdown

	Cost breakdown ($)- 10 year	Cost breakdown ($)- 50 year
Green roof	$15,623,465.00	$ 16,921,083.00
Swales	$ 3,749,189.00	$ 4,089,231.00
Planter box	$ 201,108.00	$ 286,203.00
Vegetated filter strips	$ 512,585.00	$ 695,685.00
Permeable sidewalk	$ 1,772,800.00	$ 2,187,670.00
Permeable driveway	$ 2,153,492.00	$ 2,657,451.00
Permeable parking	$ 647,374.00	$ 798,872.00
Rain garden	$ 802,388.00	$ 1,088,363.00

7. Coastal Flood Mitigation Cost

Based on the measures proposed, the mitigation cost were computed and summarized in Table 11.

Table 11 – Coastal Flood Mitigation Cost

Proposed Measure	Unit	Quantity	Unit Cost	Cost
New Levees	Miles	2	$ 43,000,000.00	$ 86,000,000.00
Elevate Existing Levees	Miles	5	$ 5,000,000.00	$ 22,500,000.00
Tide Gate	Lump Sum	1	$ 100,000.00	$ 100,000.00
Total				$ 108,600,000.00

8. Conclusion

The community of Port Norris is located along the banks of the Maurice River and as such is vulnerable to coastal flooding directly from Delaware Bay and via the Maurice River from the 100-year coastal storm and from future sea level rise.

Currently the levees protecting the community are not high enough and do not adequately block flood waters from the 100-year recurrence interval coastal flood event or future sea level rise. Therefore, the measures proposed for consideration are designed to provide reduction of flooding risk by elevating existing levees and adding new levees where needed to block flood waters. In so doing the risk of daily flooding from future sea level rise is also mitigated.

Finally, another measure to be considered for coastal flood mitigation in this community involves restoring marshlands located between inhabited communities and Delaware Bay to attenuate coastal storm surge (Mary E. Anderson, 2013). Living shorelines or hybrid living shorelines should be considered to help protect existing marshes where possible (Whalen, Kreeger, & Bushek, 2012) (PDE, 2012).

B. Fortescue

1. Community Background

Fortescue is a community of population 400 located on the shore of the Delaware Bay in Downe Township in Cumberland County NJ. Figure 36 below is an aerial photograph of the Community.

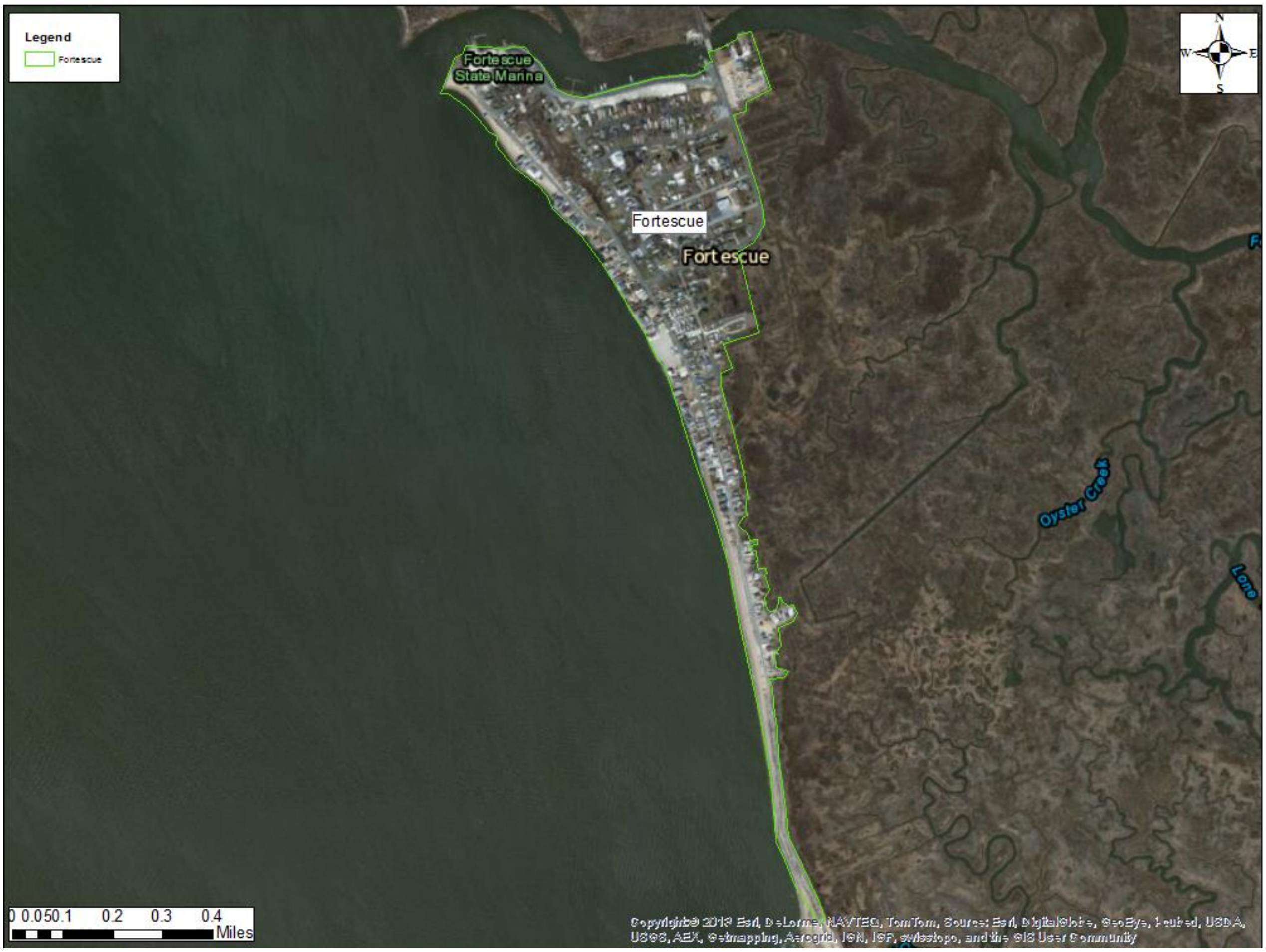

Figure 36-Aerial Map of Fortescue

2. Coastal Flood Threat Assessment

The vulnerability of Fortescue to coastal flooding was assessed by overlaying the most updated FEMA PRELIMINARY FIRM Map on an aerial photograph of the community (Figure 37) to determine which areas would be inundated by the 100-year coastal storm event.

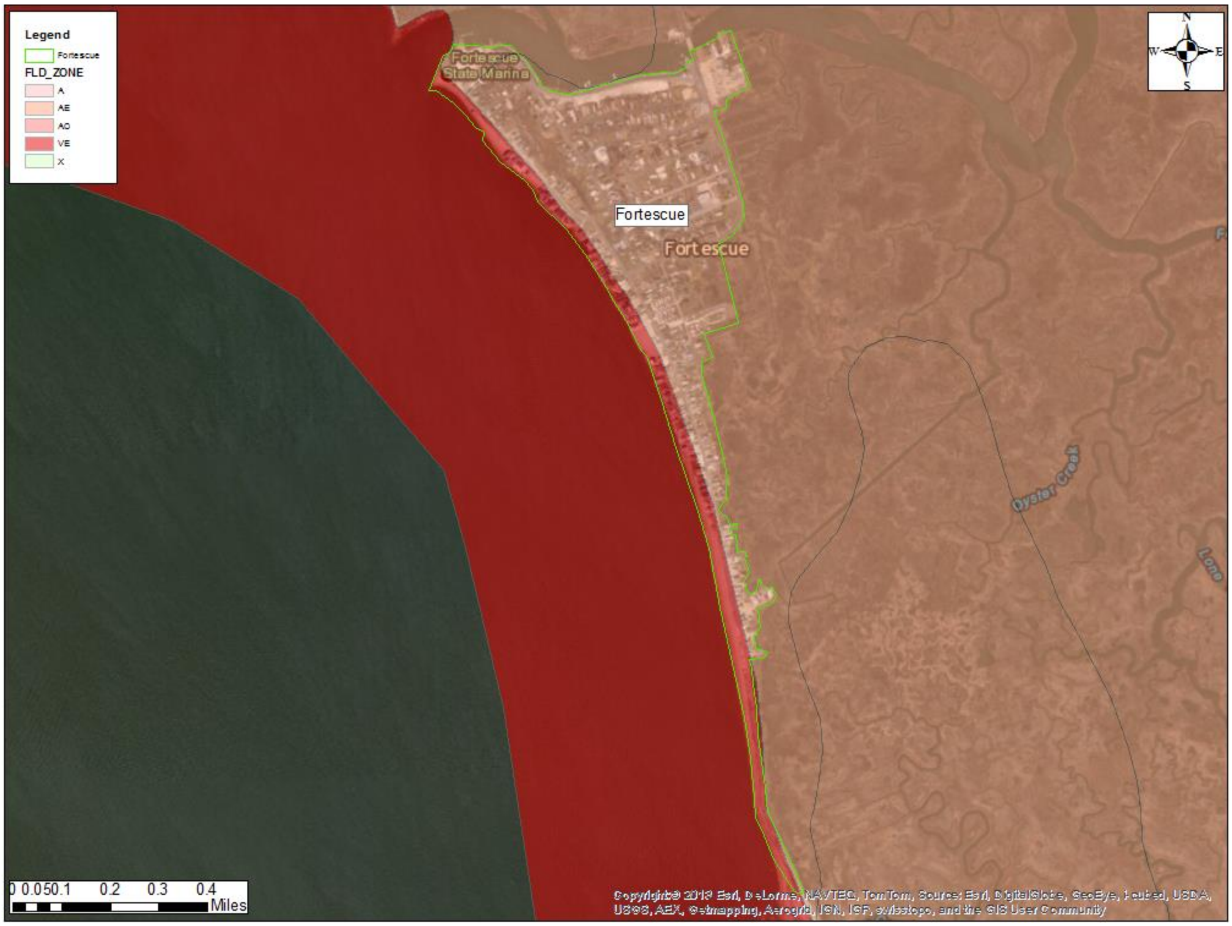

Figure 37- Fortescue with FEMA PRELIMINARY FIRM Map Overlay (FEMA, 2013)

From the FEMA PRELIMINARY FIRM map overlay it is apparent that the entire community is vulnerable to coastal flooding from a 100-year coastal storm. Furthermore, the section of the community that is situated directly on the shore is also vulnerable to velocity wave hazard in addition to inundation. Figure 38 and Figure 39 are photos showing some of the damage caused by Superstorm Sandy on the community.

Figure 38-Jersey Ave road severely damaged but largely repaired with vinyl sheet pile in Fortescue, Downe Township, NJ

Figure 39-Damaged house in Fortescue, Downe Township, NJ

3. Future Sea Level Rise Coastal Flooding Assessment

For the analyses of how sea level rise will affect Fortescue an overlay of a map developed by NOAA depicting the MHHW plus 6 feet was superimposed on top of a map of the Port Norris and the areas of inundation were observed. After reviewing this overlay, it is apparent that in the future Fortescue will be at risk of flooding from the future MHHW at close to the level of flood threat posed by the current 100-year coastal storm event (Figure 40).

Figure 40- Map of Fortescue with MHHW plus 6 Feet superimposed (NOAA, NOAA Coastal Services Center Sea Level Rise Data: 1-6 ft Sea Level Rise Inundation Extent, 2012)

4. Stormwater-Related Flood Threat Assessment

The community of Fortescue is located within a rural setting and generates a relatively small volume of stormwater runoff. Initial assessment confirms that there is minimal risk of flooding from this source.

5. Coastal Flood Threat Mitigation for 100 Year Event & SLR

Option 1

After reviewing the sources for coastal flooding and the existing flood protection level, the following flood mitigation measures are proposed to reduce the level of vulnerability in Fortescue (Figure 41):

- Install new bulkheads or elevate existing bulkheads along Delaware Bay and Fortescue Creek
- Construct new levee on the eastern side of community
- Install flood gate at Downe Road to provide continuity for proposed bulkheads along Fortescue creek
- Install flood gate at the southern tip of Fortescue at Jersey Ave.

Option 2

Another strategy to mitigate coastal flooding in this community is to elevate the properties to allow waves and surges to pass under the buildings without impacting the walls.

Figure 41-Proposed Coastal Flood Mitigation Measures for Fortescue

6. Green Infrastructure Analysis

Although green infrastructure is not needed to mitigate flooding in the community of Fortescue, analysis was performed using the green infrastructure optimization software developed by the Rutgers University Flood Study Team to identify various measures that can be considered for other benefits such as water quality improvement. Following are green infrastructure solutions and costs that were developed for areas in the community located in the 100 year flood zone:

- Maximum runoff capture: 1.2 inch
- Cost to remove 1.2 inch of runoff (10 year horizon) = $ 2,885,083
- Cost to remove 1.2 inch of runoff (50 year horizon) = $ 3,223,921

Table 12 Table 13 and Table 14 below provide the GI measures and costs to remove 1 inch of runoff.

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	67656	109085
Swales	20453	20453
Planter box	1090	1090
Vegetated filter strips	20453	20453
Permeable sidewalk	19082	19082
Permeable driveway	23180	23180
Permeable parking	6968	6968
Rain garden	5450	5450
Total cost ($) – 10 year	$2,202,407	
Total cost ($) – 50 year	$2,484,544	

Table 13 Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	$1,648,675.00	0.74
50 year	$2,243,056.00	0.90

Table 14-Cost Breakdown

	Cost breakdown ($)- 10 year	Cost breakdown ($)- 50 year
Green roof	$ 1,351,520.00	$1,463,771.00
Swales	$ 324,262.00	$ 353,671.00
Planter box	$ 17,380.00	$ 24,735.00
Vegetated filter strips	$ 44,332.00	$ 60,168.00
Permeable sidewalk	$ 153,324.00	$ 189,205.00
Permeable driveway	$ 186,251.00	$ 229,838.00
Permeable parking	$ 55,988.00	$ 69,090.00
Rain garden	$ 69,346.00	$ 94,062.00

7. Flood Mitigation Cost

Based on the measures proposed, the mitigation cost were computed and summarized in Table 15 and Table 16 below.

Table 15-Coastal Flood Mitigation Cost Option 1

Proposed Measure	Unit	Quantity	Unit Cost	Cost
Increase Bulkhead Height	Miles	1.10	$ 2,640,000.00	$ 2,904,000.00
Construct new Bulkhead	Miles	0.61	$ 4,000,000.00	$ 2,440,000.00
Construct new Levee	Miles	1.40	$ 43,000,000.00	$ 60,200,000.00
Flood Gates	Lump Sum	2.00	$ 100,000.00	$ 200,000.00
Total				$ 65,744,000.00

Table 16-Coastal Flood Mitigation Cost Option 2

Proposed Measure	Unit	Quantity	Unit Cost	Cost
Elevate Buildings	Acres	55.00	$ 1,470,000.00	$ 80,850,000.00
Total				$ 80,850,000.00

8. Conclusion

Fortescue is located along the shore of the Delaware Bay and as such is vulnerable to coastal flooding directly from Delaware Bay. The bulkheads currently protecting the community are not high enough to contain flood waters from a 100-year coastal flood event or for future sea level rise. Therefore, the measures proposed for consideration are designed to provide reduction of flood risk by elevating existing bulkheads, adding new bulkheads and new levees where needed to block flood waters.

The other option which entails elevating the building above the floodplain plus waves is a way of preventing damage to the properties while the community is flooded. Since this option still allows the community to flood it may have a limited appeal to residents unless it is combined with the previously described option.

C. Greenwich Township

1. Community Background

Greenwich is a small community located in Greenwich Township with a population of a few hundred located in Cumberland County NJ. Figure 36 below is an aerial photograph of the community.

Figure 42-Aerial photograph of Greenwich Township

2. Coastal Flood Threat Assessment

The vulnerability of Greenwich to coastal flooding was assessed by overlaying the most updated FEMA PRELIMINARY FIRM Map on an aerial photograph of the community (Figure 37) to determine which areas would be inundated by the 100-year coastal storm event.

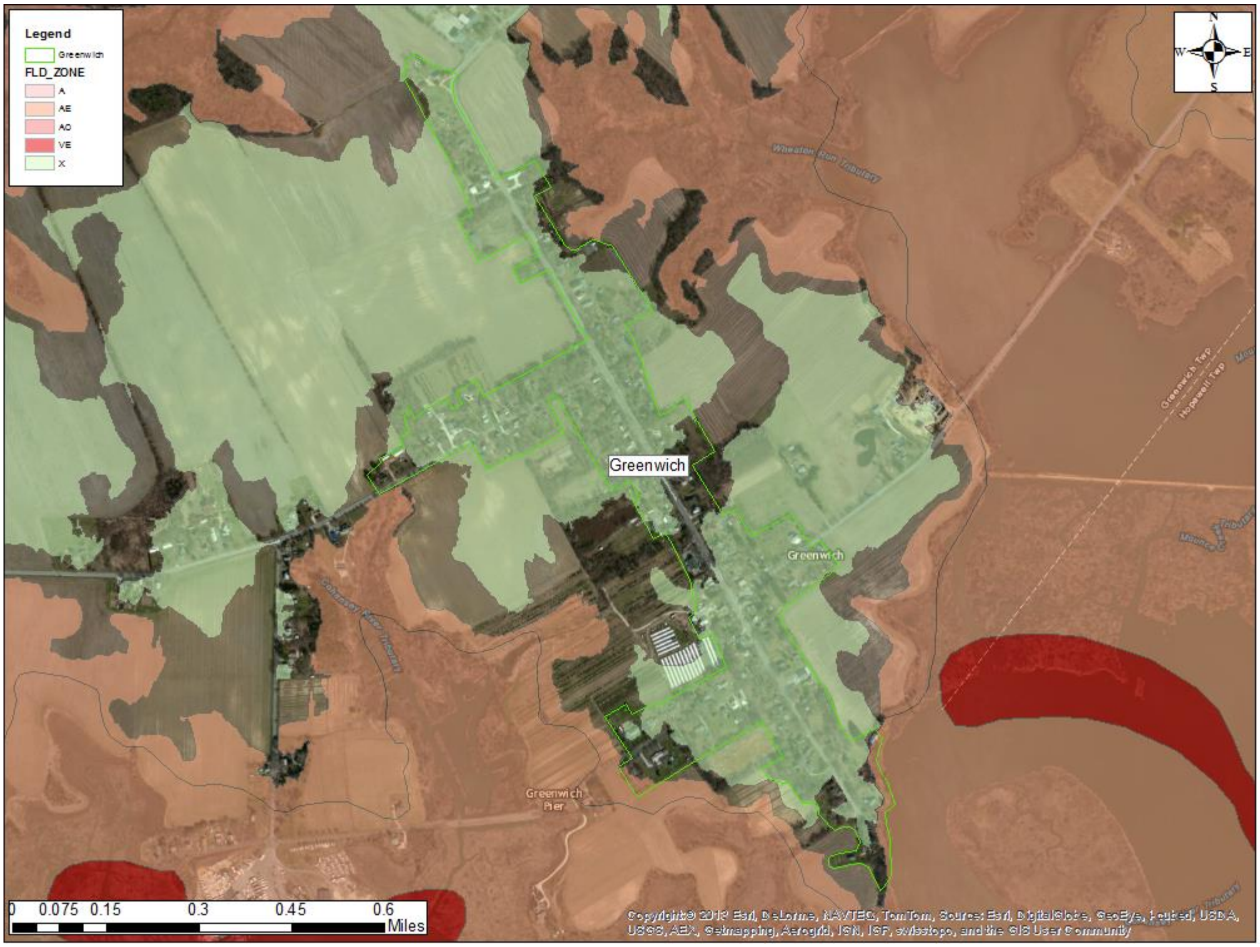

Figure 43- Greenwich Community with FEMA Preliminary FIRM Map Overlay (FEMA, 2013)

From the FEMA PRELIMINARY FIRM map overlay it is apparent that areas adjacent to the floodplain of Cohansey River are somewhat vulnerable to coastal flooding from a 100-year coastal storm. Figure 44 is a photo of a failed dike.

Figure 44-Failed Pile Mount Dike looking across from Greenwich Boat Works Marina in Greenwich, NJ

3. Future Sea Level Rise Coastal Flooding Assessment

For the analyses of how sea level rise will affect Greenwich an overlay of a map developed by NOAA depicting the MHHW plus 6 feet was superimposed on top of a map of the Port Norris and the areas of inundation were observed. After reviewing this overlay, it is apparent that in the future Fortescue will be at risk of flooding from the future MHHW at close to the level of flood threat posed by the current 100 year coastal storm event (Figure 45).

Figure 45- Map of Greenwich with MHHW plus 6 Feet Superimposed (NOAA, NOAA Coastal Services Center Sea Level Rise Data: 1-6 ft Sea Level Rise Inundation Extent, 2012)

4. Stormwater-Related Flood Threat Assessment

The community of Greenwich is located within a rural setting and as such generates very little stormwater runoff. Initial assessment confirms that there is minimal risk of flooding from this source.

5. Coastal Flood Threat Mitigation for 100 Year Event & SLR

After reviewing the sources for coastal flooding and the existing flood protection level, the following flood mitigation measures are proposed to reduce the level of vulnerability (Figure 46) in the community of Greenwich:

- Extend the Market Street Levee as shown in Figure 46
- Elevate the existing Market Street Levee
- Install new tide gate under Market Street Levee

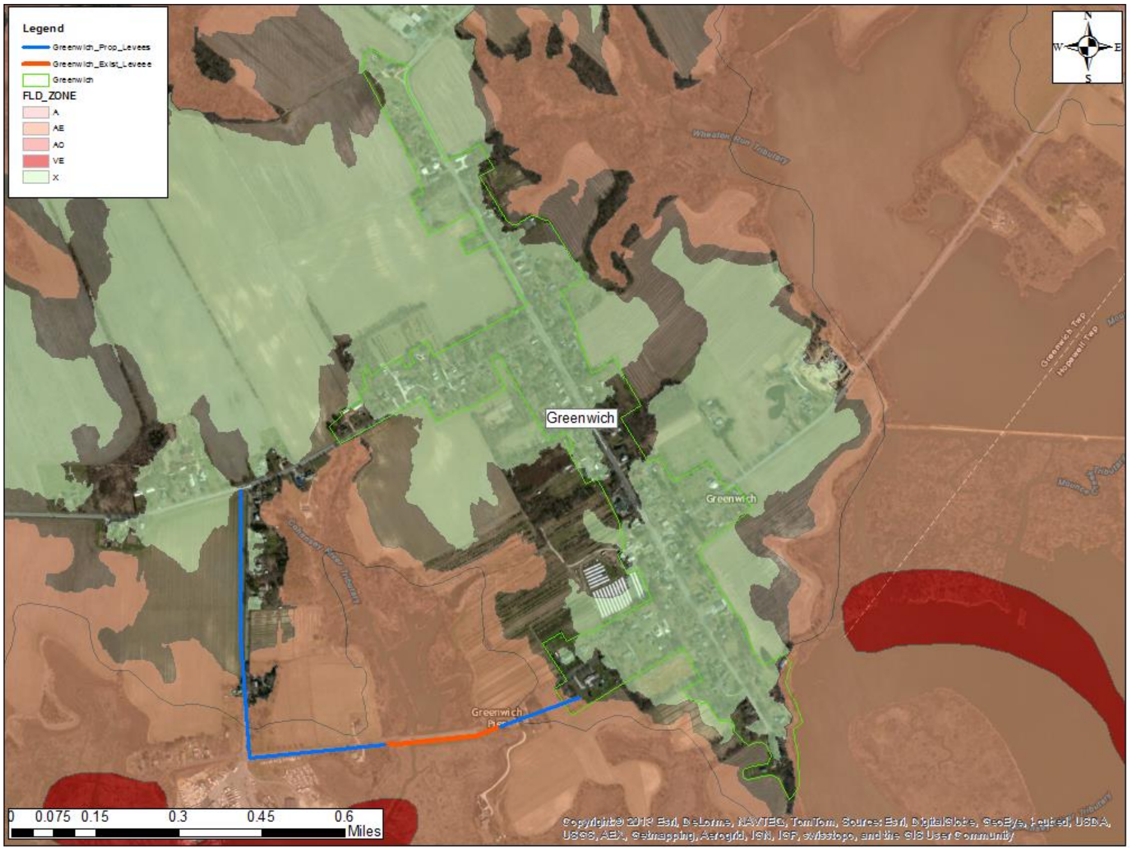

Figure 46- Flood Mitigation Measures for Greenwich

6. Green Infrastructure Analysis

Although green infrastructure is not needed to mitigate flooding in the community of Greenwich, analysis was performed using the green infrastructure optimization software developed by the Rutgers University Flood Study Team to identify various measures that can be considered for other benefits such as water quality improvement. Following are green infrastructure solutions and costs that were developed for areas in the community located in the 100 year flood zone:

- Maximum runoff capture: 0.56 inch

Table 17, Table 18 and Table 19 below provide the GI measure and costs to remove 1 inch of runoff.

Table 17- Optimal combination of green infrastructure and associated cost to remove 1 inch of runoff

	Optimal area (ft^2) for 0.56 inch runoff removal	Maximum potential area (ft^2)
Green roof	38077	38077
Swales	14880	14880
Planter box	380	380
Vegetated filter strips	14880	14880
Permeable sidewalk	11160	11160
Permeable driveway	12979	12979
Permeable parking	0	0
Rain garden	1900	1900
Total cost ($) – 10 year	$1,221,608	
Total cost ($) – 50 year	$1,371,664	

Table 18- Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	$818,352	0.66
50 year	$1,019,339	0.74

Table 19-Cost Breakdown

	Cost breakdown ($)- 10 year	Cost breakdown ($)- 50 year
Green roof	$ 7,129,387.00	$ 7,721,524.00
Swales	$ 1,710,838.00	$ 1,866,007.00
Planter box	$ 91,767.00	$ 130,597.00
Vegetated filter strips	$ 233,904.00	$ 317,456.00
Permeable sidewalk	$ 808,966.00	$ 998,280.00
Permeable driveway	$ 982,684.00	$ 1,212,651.00
Permeable parking	$ 295,407.00	$ 364,539.00
Rain garden	$ 366,139.00	$ 496,632.00

7. Flood Mitigation Cost

Based on the measures proposed, the mitigation cost were computed and summarized in Table 20 below.

Table 20-Coastal Flood Mitigation Cost

Proposed Measure	Unit	Quantity	Unit Cost	Cost
New Levees	Miles	0.75	$ 43,000,000.00	$ 32,250,000.00
Elevate Existing Levees	Miles	0.25	$ 5,000,000.00	$ 1,250,000.00
Tide Gate	Lump Sum	1	$ 100,000.00	$ 100,000.00
Total				$ 33,600,000.00

8. Conclusion

Greenwich is located along the shore of the Cohansey River and as such is vulnerable to coastal flooding from this source. The current levee system that protects the community is not high enough or extensive enough to adequately block flood waters from the 100-year coastal flood event and from future sea level rise. Therefore, the measures proposed for consideration to mitigate flooding are designed to reduce flooding risk by elevating and extending the existing levee and adding a tide gate under the existing levee.

Another measure proposed for consideration for coastal flood mitigation in this community involves restoring marshlands to attenuate wave and coastal storm surge (Mary E. Anderson, 2013), and utilizing living shorelines to protect and maintain existing marshes where they are threatened by shoreline erosion.

D. Maurice River Township

1. Community Background

Maurice River Township is a community with a population of approximately 8,000 located in Cumberland County NJ, bounded by Delaware Bay to the south and the Maurice River to the west. Figure 47 below is an aerial photograph of the communities of Leesburg, Heislerville and Dorchester in Maurice Township on which this study focused.

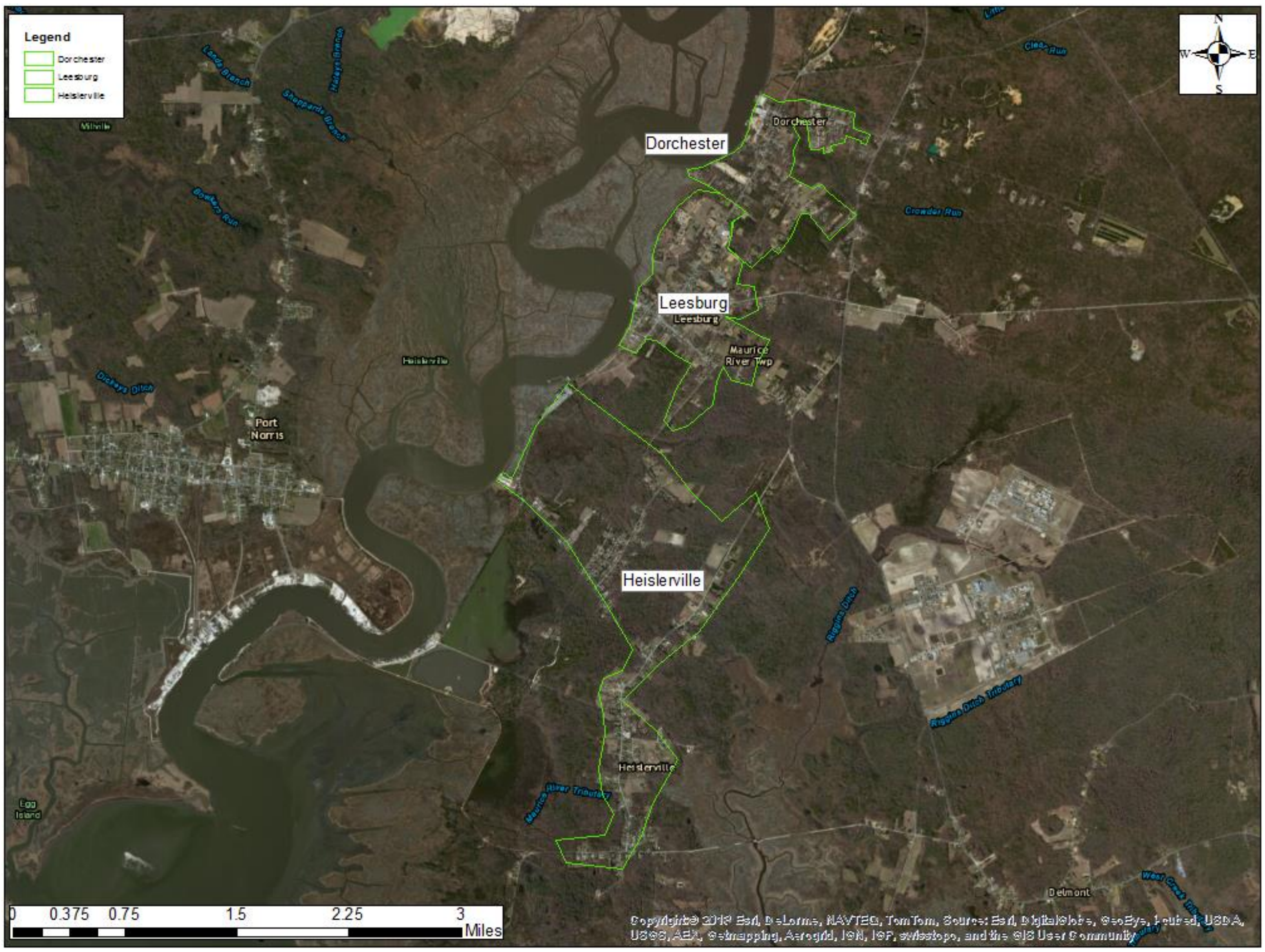

Figure 47-Aerial photograph of Leesburg, Heislerville and Dorchester

2. Coastal Flood Threat Assessment

The vulnerability of Maurice River Township to coastal flooding was assessed by overlaying the most updated FEMA PRELIMINARY FIRM Map on an aerial photograph of the Township (Figure 48) to determine which areas would be inundated by the 100-year coastal storm event.

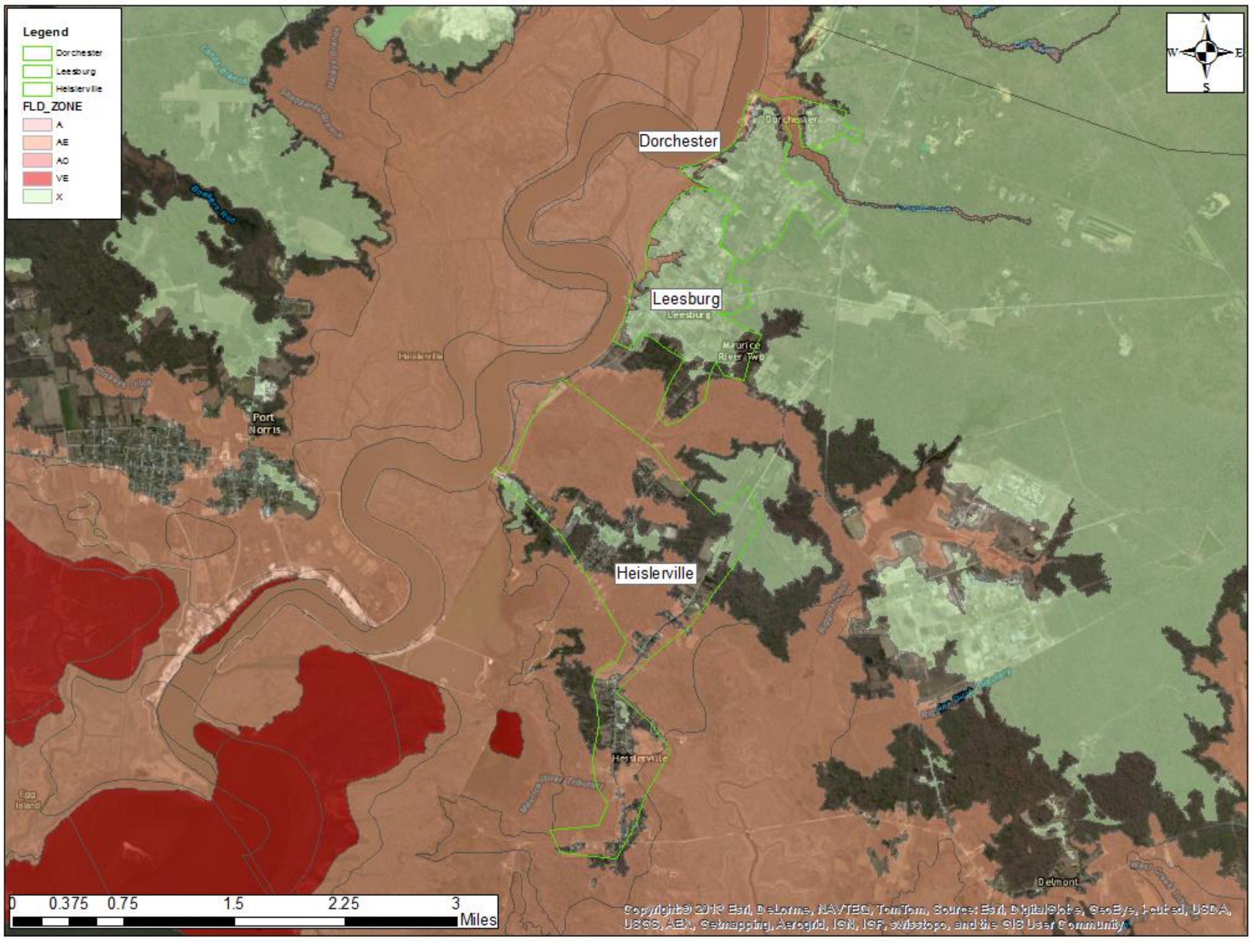

Figure 48- Map of Leesburg, Heislerville and Dorchester with FEMA PRELIM FIRM Map Overlay (FEMA, 2013)

From the FEMA PRELIMINARY FIRM map overlay it is apparent that areas adjacent to Delaware Bay and the floodplain of Maurice River are vulnerable to coastal flooding from the 100-year coastal storm. Communities such as Heislerville, Leesburg and Dorchester are all within the 100-year flood zone. Figure 49 is a photo of a dike that was damaged by Superstorm Sandy.

Figure 49- Heislerville Dike breached and subsequently repaired in Maurice River Township, NJ

3. Future Sea Level Rise Coastal Flooding Assessment

For the analyses of how sea level rise will affect Greenwich an overlay of a map developed by NOAA depicting the MHHW plus 6 feet was superimposed on top of a map of Heislerville, Leesburg and Dorchester and the areas of inundation were observed. After reviewing this overlay, it is apparent that in the future Fortescue will be at risk of flooding from the future MHHW at close to the level of flood threat posed by the current 100 year coastal storm event (Figure 50).

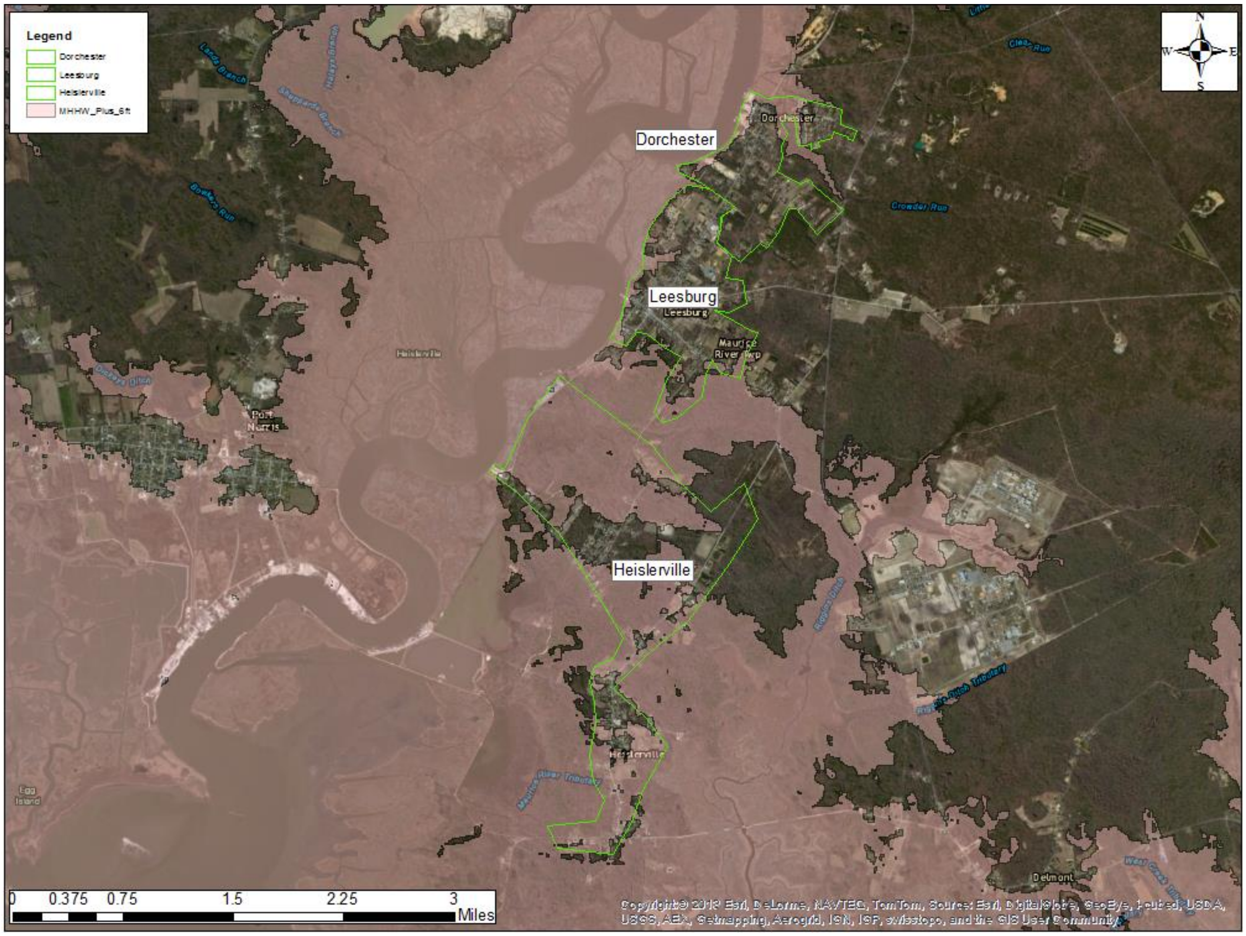

Figure 50- Map of Leesburg, Heislerville and Dorchester with MHHW plus 6 Feet Superimposed (NOAA, NOAA Coastal Services Center Sea Level Rise Data: 1-6 ft Sea Level Rise Inundation Extent, 2012)

4. Stormwater-Related Flood Threat Assessment

The communities of Heislerville, Leesburg and Dorchester are located within rural settings and generate very little stormwater runoff. Initial assessment confirms that there is minimal risk of flooding from this source.

5. Coastal Flood Threat Mitigation for 100 Year Event & SLR

After reviewing the sources for coastal flooding and the existing flood protection level, the following flood mitigation measures are proposed to reduce the level of vulnerability (Figure 51) in the inhabited locations within Maurice River Township:

- Extend the Heislerville Impoundment Levee to the north along the Maurice River
- Extend the Heislerville Impoundment Levee to the east
- Elevate the Heislerville Impoundment Levee
- Elevate the Thompson Levee
- Install new levee north and east of the Thompson levee

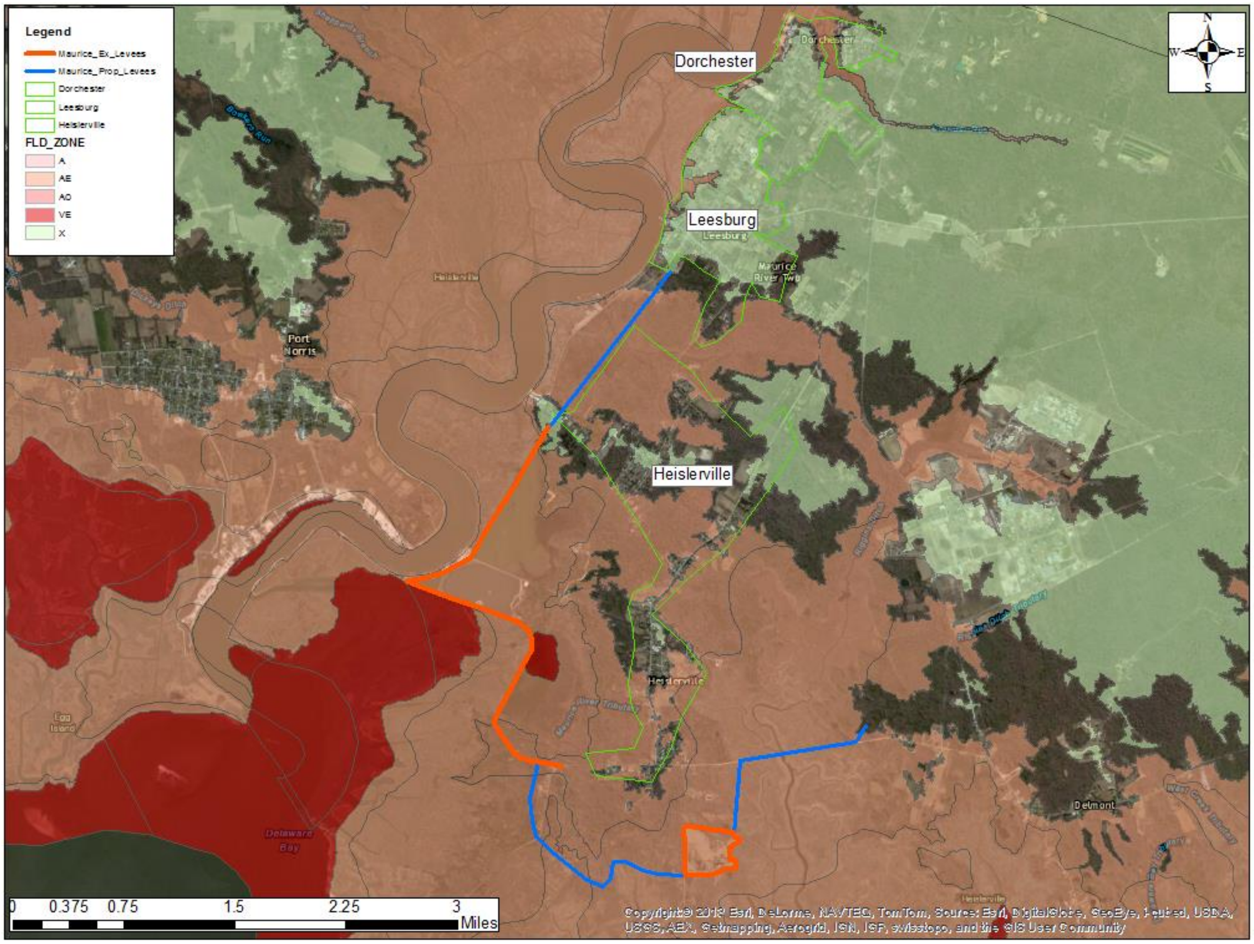

Figure 51-Flood Mitigation Measures for Leesburg, Heislerville and Dorchester

6. Green Infrastructure Analysis

Although green infrastructure is not needed to mitigate flooding in the communities of Heislerville, Leesburg and Dorchester in Maurice River Township, analysis was performed using the green infrastructure optimization software developed by the Rutgers University Flood Study Team to identify various measures that can be considered for other benefits such as water quality improvement. Following are green infrastructure solutions and costs that were developed for areas in the community located in the 100 year flood zone:

- Maximum runoff capture: 1.24 inch
- Cost to remove 1.24 inch of runoff (10 year horizon) = $ 109,165,598
- Cost to remove 1.24 inch of runoff (50 year horizon) = $ 121,817,714

Table 21 to Table 29 below provides the green infrastructure measures and costs to remove 1 inch of runoff in the three communities.

a) Leesburg

- Maximum runoff capture: 0.43 inch
- Cost to remove 0.43 inch of runoff (10 year horizon) = $ 920166
- Cost to remove 0.43 inch of runoff (50 year horizon) = $ 1059577

Table 21- Optimal combination of green infrastructure and associated cost to remove 1 inch of runoff

	Optimal area (ft^2) for 0.43 inch runoff removal	Maximum potential area (ft^2)
Green roof	1812	18212
Swales	12320	12320
Planter box	182	182
Vegetated filter strips	12320	12320
Permeable sidewalk	7639	7639
Permeable driveway	33598	33598
Permeable parking	0	0
Rain garden	910	910
Total cost ($) – 10 year	$ 920,166.00	
Total cost ($) – 50 year	$1,059,577.00	

Table 22- Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	$ 762,550.00	0.82
50 year	$ 924,095.00	0.87

Table 23- Cost breakdown

	Cost breakdown ($)- 10 year	Cost breakdown ($)- 50 year
Green roof	$ 352,319.00	$381,581.00
Swales	$ 195,321.00	$213,036.00
Planter box	$ 2,902.00	$ 4,130.00
Vegetated filter strips	$ 26,704.00	$ 36,243.00
Permeable sidewalk	$ 61,379.00	$ 75,743.00
Permeable driveway	$ 269,960.00	$333,137.00
Permeable parking	$ -	$ -
Rain garden	$ 11,579.00	$ 15,705.00

b) Heislerville

- Maximum runoff capture: 0.65 inch
- Cost to remove 0.65 inch of runoff (10 year horizon) = $ 13,356,029
- Cost to remove 0.65 inch of runoff (50 year horizon) = $ 14,939,094

Table 24- Optimal combination of green infrastructure and associated cost to remove 1 inch of runoff

	Optimal area (ft^2) for 0.65 inch runoff removal	Maximum potential area (ft^2)
Green roof	455342	455342
Swales	128440	128440
Planter box	4553	4553
Vegetated filter strips	128440	128440
Permeable sidewalk	8693	8693
Permeable driveway	218486	218486
Permeable parking	2019	2019
Rain garden	22765	22765
Total cost ($) – 10 year	$13,356,029	
Total cost ($) – 50 year	$14,939,094	

Table 25- Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	$8,741,327	0.65
50 year	$10,938,269	0.73

Table 26-Cost Breakdown

	Cost breakdown ($)- 10 year	Cost breakdown ($)- 50 year
Green roof	$8,837,459.00	$9,571,460.00
Swales	$2,036,289.00	$2,220,975.00
Planter box	$ 72,601.00	$ 103,320.00
Vegetated filter strips	$ 278,399.00	$ 377,846.00
Permeable sidewalk	$ 69,848.00	$ 86,194.00
Permeable driveway	$1,755,541.00	$2,166,372.00
Permeable parking	$ 16,222.00	$ 20,019.00
Rain garden	$ 289,666.00	$ 392,905.00

c) Dorchester

Maximum runoff capture: 0.91 inch

- Cost to remove 0.91 inch of runoff (10 year horizon) = $ 1877931
- Cost to remove 0.91 inch of runoff (50 year horizon) = $ 2116409

Table 27- Optimal combination of green infrastructure and associated cost to remove 1 inch of runoff

	Optimal area (ft^2) for 0.91 inch runoff removal	Maximum potential area (ft^2)
Green roof	58292	58292
Swales	17648	17648
Planter box	583	583
Vegetated filter strips	17648	17648
Permeable sidewalk	13236	13236
Permeable driveway	12392	12392
Permeable parking	21017	21017
Rain garden	2915	2915
Total cost ($) – 10 year	1877931	
Total cost ($) – 50 year	2116409	

Table 28- Comparison of costs of green and gray infrastructures

Time Horizon	Gray Infrastructure Cost ($)	Gray Infrastructure /Green Infrastructure cost
10 year	$ 1,313,157.00	0.69
50 year	$ 1,675,010.00	0.79

Table 29- Cost breakdown

	Cost breakdown ($)- 10 year	Cost breakdown ($)- 50 year
Green roof	$1,138,705.00	$1,233,281.00
Swales	$ 279,791.00	$ 305,168.00
Planter box	$ 9,296.00	$ 13,229.00
Vegetated filter strips	$ 38,252.00	$ 51,917.00
Permeable sidewalk	$ 106,351.00	$ 131,240.00
Permeable driveway	$ 99,570.00	$ 122,871.00
Permeable parking	$ 168,872.00	$ 208,391.00
Rain garden	$ 37,091.00	$ 50,310.00

7. Flood Mitigation Cost

Based on the measures proposed, the mitigation cost were computed and summarized in Table 30 below.

Table 30-Coastal Flood Mitigation Cost

Proposed Measure	Unit	Quantity	Unit Cost	Cost
New Levees	Miles	4	$ 43,000,000.00	$ 150,500,000.00
Elevate Existing Levees	Miles	4	$ 5,000,000.00	$ 20,000,000.00
Tide Gate	Lump Sum	1	$ 100,000.00	$ 100,000.00
Total				$ 170,600,000.00

8. Conclusion

Sections of the communities of Heislerville, Leesburg and Dorchester are located within the 100-year flood zone. Currently the levees that protect these communities are not high enough or extensive enough to adequately block flood waters from the 100-year coastal flood event and future sea level rise. Therefore, the flood mitigation measures proposed for consideration are designed to reduce flooding risk by elevating and extending the existing levees and adding a tide gate where one of the proposed levees intersects Riggins Ditch

Another measure proposed for coastal flood mitigation in this community involves restoring marshlands located between inhabited communities and Delaware Bay to attenuate coastal storm surge (Mary E. Anderson, 2013). Living shorelines and offshore breakwaters (perhaps of oyster reefs) should be considered to protect existing marshes and facilitate restoration.

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VI. Appendices

A. 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.

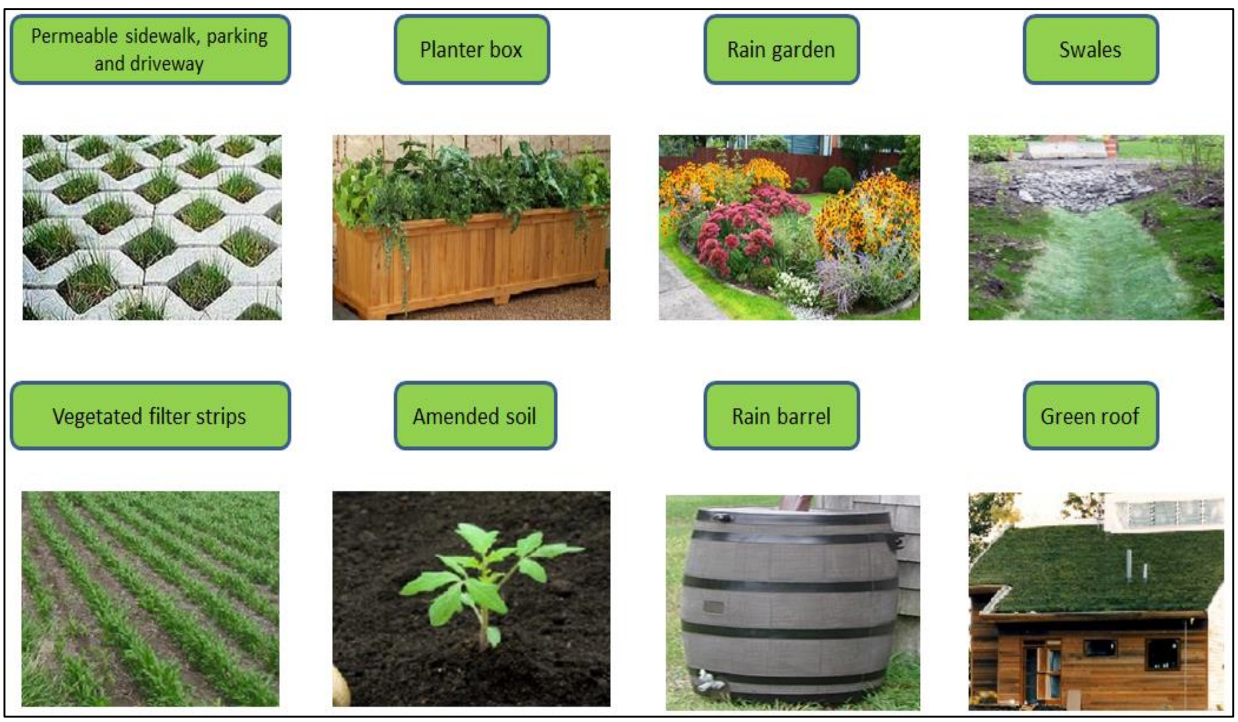

Figure 1: Green Infrastructure types

US Department of Environmental Protection (DEP) is conducting a comprehensive research to quantify non-stormwater benefits of green infrastructure deployment [1]. For instance, City of Hoboken, New Jersey, is conducting a green infrastructure strategic plan to develop place–based stormwater management and flood control strategies and identify implementable climate adaptation action steps. More details of the Hoboken Green Infrastructure Strategic plan is available on [2]. There are other ongoing green infrastructure projects in a number of cities all around the U.S such as Philadelphia, New York City, San Francisco, Chicago, Seattle and St. Louis. More details of these projects are available on [3], [4], [5], [6], [7] and [8] respectively.

Green infrastructure can reduce the volume of water going into combined systems during precipitation events by removing surface runoff, which may reduce number and volume of overflows. Green infrastructure can also slow the delivery of wet weather flows to sewer systems, helping to mitigate peak flows while providing filtration through soil for some portion of the release into the sewer system, thereby reducing pollutant loads. The implementation of green infrastructure practices may allow communities to downsize certain grey infrastructure components of their CSO control plans. This may provide some CSO communities with significant cost savings [9]. By implementing Green Infrastructure, need for piping, pumping and storage of stormwater could be reduced. In this project, the main reason to consider green infrastructures deployment is also to reduce the stormwater inflow to the drainage system by removing fraction of runoff. Table 1 summarizes the problem, our approach and source of floodwater.

Table 1: Problem and solution description

Problem to solve	Reduce surface floodwater inlet to the drainage system

[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

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.

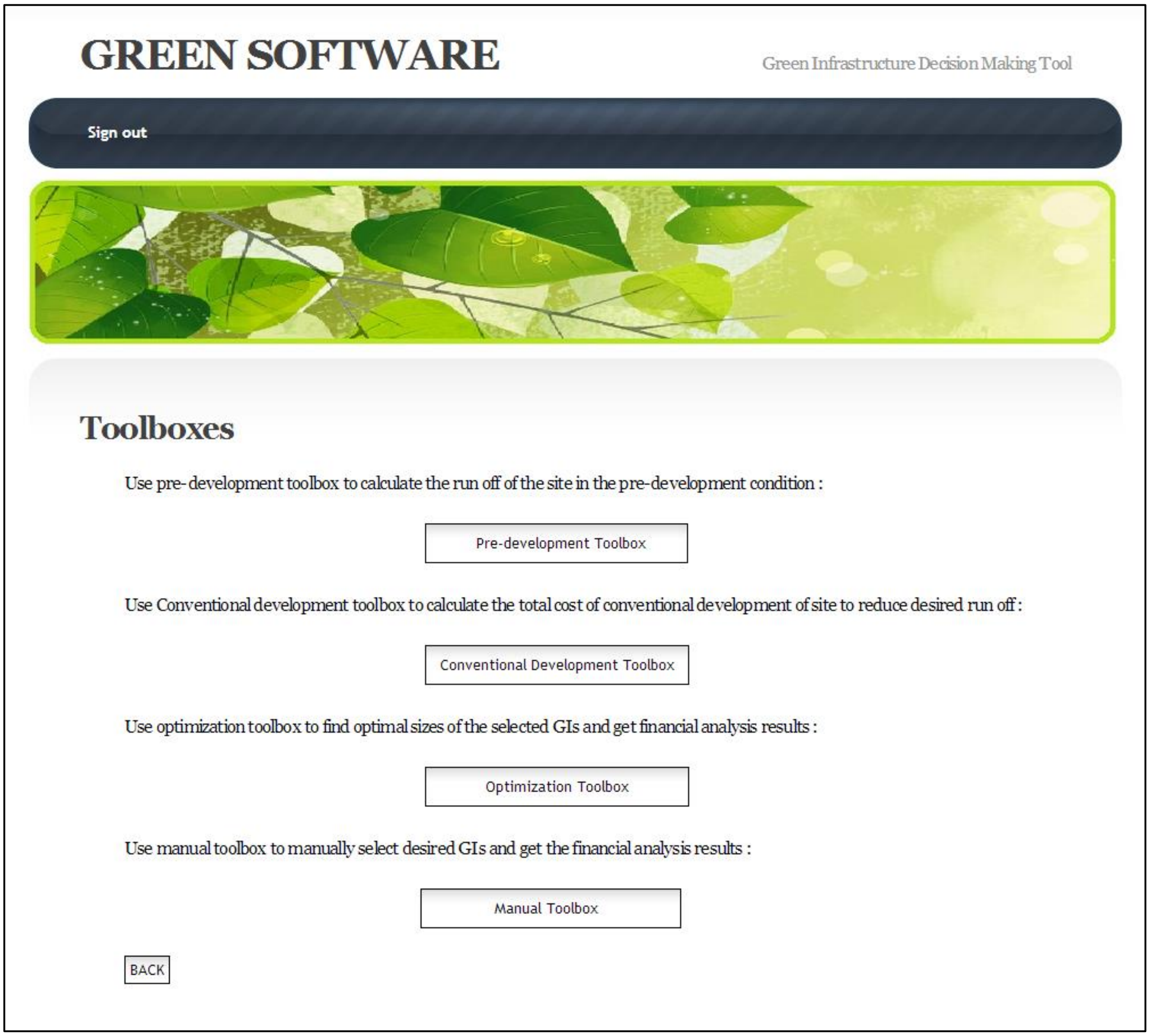

Figure 2: Snapshot of the Green Software

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.

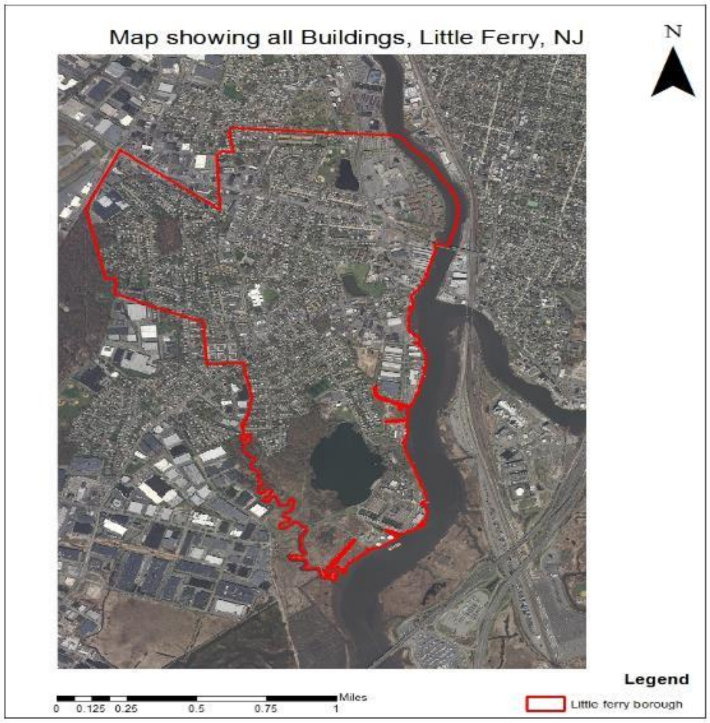

Figure 3: Sample layer of a municipality

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 31 : Extracted information for three selected polygons

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

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

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

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

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

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

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

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

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

By getting the map of NJ road networks and clipping it for the area of the required municipality, we can find the total length of the road network. From this we can find the length of the road where sidewalks is present. By multiplying the width of the side walk we can find the area of the pavement where we can apply permeable sidewalk.

The average width of the side walk for the major highway is calculated from the widths measured at several selected locations (by using the GIS measure tool). The average width was found to be 6ft on each side of the roadway. Considering the intersections of roadways, roadways with sidewalk on only one side and roadways without a sidewalk on both sides, only 50% of the total length of roadways in the town is used to calculate the area of sidewalk.

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

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

4) Default values used in the software

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

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

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

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

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

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

Reference: [[10]]

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

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.

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

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

B. 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	http://www.allcostdata.info/browse.html/059110009

	Hydraulic structures, 72" x 72", HD, self cont with crank, sluice Detail $ 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