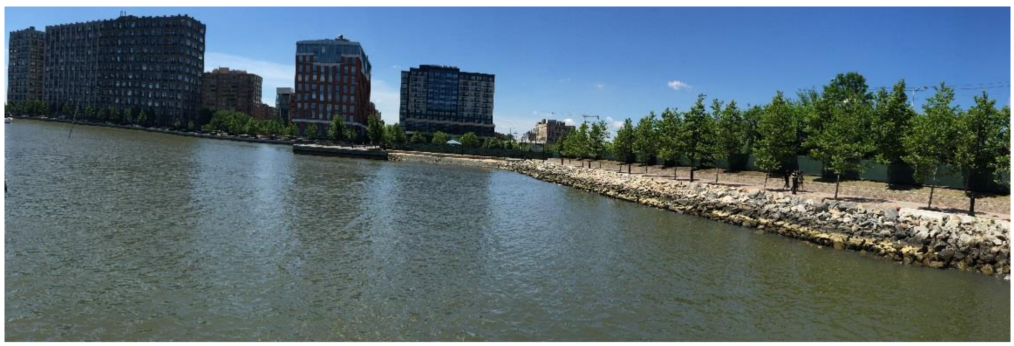

Rebuild by Design - Hudson River Project

Hydrology and Flood Risk Assessment Report

Original: October 10th, 2016
Final: January 26th, 2017

SUBMITTED BY:

Dewberry

SUBMITTED TO:

State of New Jersey Department of Environmental Protection

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Table of Contents

List of Tables

List of Figures

1 Executive Summary

The Rebuild by Design- Hudson River feasibility assessment and Environmental Impact Statement (EIS) study involves the development and evaluation of flood risk reduction measures to reduce flood risk from coastal storm surge and rainfall events within the entire City of Hoboken and adjoining portions of Weehawken and Jersey City (also referred to as study area). A coastal hydrodynamic and stormwater management model is required to understand the flooding effects of coastal storm surge and rainfall events and evaluate the effectiveness of proposed flood risk reduction measures. The main objectives of modeling is to aid in the development of potential flood risk reduction measures, evaluate flood risk reduction benefits and potential residual flooding impacts from the proposed alternatives.

A two-dimensional (2D) coastal hydrodynamics model was developed using the Danish Hydraulic Institute's (DHI) MIKE 21 software to evaluate the coastal storm surge conditions. Additionally, a combined stormwater and coastal conditions model was developed using DHI's MIKE FLOOD program to assess flooding within the study area from rainfall events.

The best available data was utilized as inputs for the development of the MIKE 21 coastal hydrodynamic model including Post Sandy Light Detection and Ranging (LiDAR) overland topography, recent topographic surveys developed as part of this effort, bathymetry from NOAA and Stevens Institute of Technology and others. The MIKE 21 model captures street-level flooding in the study area and has a minimum horizontal resolution of approximately 3 meters (10 feet) with a total of approximately 1 million computation nodes in the entire MIKE 21 model domain. The MIKE 21 model mesh also includes building footprints located within the study area that are modeled as blocked obstructions to replicate flow volume for the coastal storm surge through the streets of the project area. In reality it is likely that a volume of surge floodwater would enter some buildings, but given the difficulty of simulating flow volume into buildings, the approach used results in a somewhat conservative coastal hydrodynamic model.

A hindcast of Superstorm Sandy was conducted to validate the MIKE 21 coastal hydrodynamics model. Measured high water mark (HWM) data obtained from USGS (Unites States Geological Survey) and Stevens Institute of Technology allowed for the MIKE 21 coastal model results to be evaluated and verified against observed data for Sandy. An overall comparison of water depth between the model and the observed HWM data showed Root Mean Square Error (RMSE) of less than 6 inches (0.5ft). Overall these minor differences in water depths are within the uncertainty of the measured height and time of the HWM data and thus indicates that the MIKE 21 coastal model performs well to predict the hydrodynamics within the study area. The model results and comparisons with measured water depths are also in good agreement with other past modeling efforts of Superstorm Sandy in the study area (Blumberg et al., 2015).

This validated MIKE 21 coastal hydrodynamics model was utilized to evaluate flooding effects of coastal storm surge during a 10-year (10% annual chance), 50-year (2% annual chance) and 100-year (1% annual chance) storms in the No-Action Alternative (NAA) and the three build alternatives (see Figure 5- 1 and 6-11 for map showing NAA and three "Resist" alternatives, respectively). To accurately reflect future project area conditions the NAA scenario considers completion of two existing independent projects underway: the filling-in of the Long Slip canal located on NJ Transit's property and the development of Newport property in Jersey City. Each of the three build alternatives include "Resist" alignments has potential to reduce the area subject to flood risk from coastal storm surge at varying levels. The maximum flood water depths in NAA and each of the three build alternatives within the study area were compared to evaluate the flood risk reduction benefits and any potential residual flooding. Alternative 1 which includes "Resist" alignment primarily along the waterfront provides the maximum flood risk reduction benefits with 98% percent of the population currently living within the 2013 preliminary Federal Emergency Management Agency (FEMA) 100-year floodplain. Similarly, Alternative 2 which includes a "Resist" alignment along 15th street in Hoboken and Alternative 3 which includes a "Resist" alignment along the pedestrian alleyway between Garden Street and Washington Street provides flood risk reduction benefits for 86% and 85% of the population currently living within the 2013 preliminary FEMA 100-year floodplain, respectively. Residual flooding risk as per NJAC 7:13 rules is defined as an adverse effect or impact with the proposed Resist structure that results in a potential increase of greater than 0.04 feet of flood depths as shown by the coastal model to an existing area that is located within FEMA's 1-percent-annual-chance Special Flood Hazard Area (SFHA). The coastal model results indicate that Alternative 1 has the least residual flooding impacts whereas Alternative 2 and 3 has potential residual flooding impacts at 5 properties within the entire study area.

Storm-sewer data was provided by North Hudson Sewerage Authority (NHSA) in order to develop a stormwater model using DHI's MIKE URBAN and MIKE FLOOD program. The stormwater model primarily covers the City of Hoboken sewersheds, but it takes into account rainfall runoff flow coming into the NHSA sewer system within the City of Hoboken from portions of Jersey City and Union City. DHI's MIKE FLOOD program was utilized to integrate the storm-sewer data with the two-dimensional (2-D) overland topographic flow model developed with DHI's MIKE 21 model. The stormwater model results were validated with the best available data on inland rainfall flood depths from Hurricane Irene. Additionally, NHSA officials confirmed the flooding extents and water depths from the integrated model for Hurricane Irene based on their observations at the time of this hurricane.

Based on discussions with FEMA, the interior drainage in a coastal flood risk reduction project subject to impact from tidal action requires evaluation of the stormwater system in two conditions – with outfalls open (low tide) and with outfalls closed (high tide)– for various rainfall events. The No-Action Alternative (NAA) for stormwater management as well as the "Delay, Store, Discharge (DSD)" alternative for the 5-year (20% annual chance), 10-year (10% annual chance), 25-year (4% annual chance), 50-year (2% annual chance) and 100-year (1% annual chance) rainfall events was simulated under these two conditions. The NAA considers several on-going and completed projects undertaken by the City of Hoboken and NHSA which can be found in Figure 9-1. The DSD alternative includes the implementation of 61 Right-of-Way (ROW) green and grey infrastructure enhancements along with three parcel based stormwater management improvements (BASF, NJ Transit/Housing Authority and Block 10 sites). The extent of flooding demonstrated by the integrated model for various rainfall events in the NAA and DSD alternatives was compared. Model results indicates that the DSD alternative has a potential to reduce rainfall induced flooded area by 73% and 81% over the NAA flooded areas in a 5-year flood event in high tide and low tide conditions, respectively. As the rainfall return period increases, the flood risk reduction benefits provided by the DSD alternative over the NAA flooded areas decreases.

The main conclusions of this task report are as follows –

- Coastal storm surge modeling results shows that all the three "Resist" alternatives provides coastal flood risk reduction benefits within the study area
- Stormwater modeling results shows that the proposed "DSD" alternative provides significant flood risk reduction benefits especially for lower rainfall return period events such as the 5-year rainfall

For the final preferred alternative, we recommend the following major items should be considered during the design phase of this project –

- Perform Wave Height Analysis for Flood Insurance Study (WHAFIS) model analysis using the best available FEMA data to satisfy FEMA's Conditional Letter of Map Revision (CLOMR) requirements
- Perform interior drainage analysis by updating the integrated stormwater and coastal model developed for this project to satisfy the interior drainage requirements for the FEMA levee certification
- Conduct coordination meetings with FEMA Region II before the submittal of CLOMR documentation to ensure appropriate methodology was adopted and implemented

Additional recommendations for the design phase of the project is provided in Section 10 of this report.

2 Project Background

In order to address the need for increased resiliency within the Superstorm Sandy-affected region, the United States Department of Housing and Urban Design (HUD) launched the Rebuild by Design (RBD) competition in 2013 inviting communities to craft pioneering resiliency solutions. During the course of this competition, a comprehensive urban water strategy was developed for the Hoboken, Jersey City and Weehawken area that included hard infrastructure and soft landscape for coastal defense (Resist); policy recommendations, guidelines, and urban infrastructure to slow storm water runoff (Delay); green and grey infrastructure improvements to allow for greater storage of excess rainwater (Store); and water pumps and alternative routes to support drainage (Discharge). The Hudson River RBD (RBDH) proposal was selected in the first round of RBD grants and HUD has awarded $230 million to the State of New Jersey for the "Hudson River Project: Resist, Delay, Store, Discharge" (the Project). HUD assigned New Jersey Department of Community Affairs (DCA) as a grantee for the $230 million Community Development Block Grant-Disaster Recovery (CDBG-DR) funds. The State of New Jersey retained Dewberry Engineers (Dewberry) to carry out a feasibility study and perform an Environmental Impact Statement (EIS) that involves development and evaluation of “Resist” and “DSD” components as part of the RBDH project.

The Project Study Area as shown in Figure 2-1 encompasses the City of Hoboken and includes the southern portion of the Township of Weehawken and the northern portion of Jersey City. The Study Area has the following approximate boundaries: the portion of the Hudson River which encompasses piers within the Study Area to the east; Baldwin Avenue (in Weehawken) to the north; the Palisades to the west; and 18th Street, Washington Boulevard and 14th Street (in Jersey City) to the south.

2.1 Modeling Objectives

One of the main goals of the RBDH project is to obtain levee accreditation from Federal Emergency Management Agency (FEMA) for the proposed “Resist” structure. Upon receiving levee accreditation from FEMA, the communities within the study area will receive reductions in flood insurance premiums. The FEMA levee accreditation process requires adherence to the regulations stated in 44 CFR 65.10 which are based on the best available 100-year (1% annual chance) FEMA flood data. Hence, the modeling portion of this study uses the latest and best available flood data published by FEMA for Hudson County (FEMA, 2013).

The main objectives to perform modeling for the RBDH project as part of this report task are as follows –

- Use the best available FEMA coastal stillwater elevation data to evaluate the pathways for coastal storm surge to enter into the study area

- Evaluate the effectiveness of the proposed “Resist” alternatives developed as part of the Task 5 – Feasibility Report and provide recommendations that would maximize flood risk reduction benefits for the study area
- Identify potential areas to receive residual flood impacts with the proposed “Resist” alternative
- Use the best available North Hudson Sewerage Authority (NHSA) data to evaluate and identify flooding areas for various combinations of rainfall and tidal events
- Evaluate the effectiveness of all the proposed “DSD” alternatives developed as part of the Task 5 – Feasibility Report to estimate areas that would receive flood risk reduction benefits during rainfall flood events

In order to meet the above main objectives of this task, Dewberry performed the following main subtasks -

- Developed a coastal hydrodynamic model using Danish Hydraulic Institute’s (DHI) MIKE 21 model to evaluate coastal storm surge flooding effects with and without “Resist” alternatives
- Developed an integrated stormwater and coastal model using DHI’s MIKE URBAN model and MIKE FLOOD module to evaluate rainfall induced flooding effects with and without “DSD” alternatives
- Evaluated potential residual flooding impacts of the “Resist” alternatives per NJDEP land use regulations and New Jersey Flood Hazard Control Act

The coastal hydrodynamic and rainfall modeling storm scenarios for the combined “Resist” and “DSD” alternatives used in this analysis meet permit requirements from state and federal agencies. The level of model developed for this study is at a feasibility level with adequate detail to demonstrate the effectiveness of the proposed strategies and provide a rough estimate of potential residual flooding risk. The models developed from this feasibility study should not be used “as-is” for other applications such forecasting and others. Additionally, the stormwater model developed for this project does not include any water quality and ecology components and does not address any water quality concerns associated Combined Sewer Overflow (CSO). The stormwater model developed as part of the feasibility study demonstrates the effectiveness of DSD components to reduce flooding from rainfall runoff only. It should be noted the Design Flood Elevation (DFE) calculations for the proposed “Resist” alternatives are part of the Task 5- Feasibility Assessment report.

Figure 2-1. Map showing Project Study Area Boundary

3 Coastal Modeling Methodology

3.1 Model Description

A 2-Dimensional (2D) coastal storm surge model was developed using Danish Hydraulic Institute's (DHI) MIKE 21- Flexible Mesh (FM) Hydrodynamic (HD) Version 2014 module to evaluate flood propagation of coastal storm surge within the study area. MIKE 21 is a well-documented, proven modelling technology that has been applied in many coastal and marine engineering projects around the world. It is a FEMA-approved hydrodynamic model and it offers additional capabilities for application in coastal urban settings through the integration of multiple MIKE models using MIKE FLOOD.

MIKE 21 model is specifically oriented towards establishing flow patterns in complex water systems, such as coastal waterways, estuaries and wide floodplains. MIKE 21-FM HD module is based on a flexible mesh approach which allows variations in the model resolution within the model domain. The MIKE 21 model utilizes the numerical solution of two-dimensional shallow water equations. MIKE 21-FM HD simulates water level variations and flows for depth-averaged unsteady two-dimensional free-surface flows. It includes capabilities for characterizing the following physical processes:

- Bottom shear stress
- Wind shear stress
- Barometric pressure gradients
- Coriolis force
- Momentum dispersion
- Evaporation
- Wetting and drying
- Wave radiation stresses

3.2 Coordinate Systems and Units

3.2.1 Units

All parameters and variables established for in model development and simulation have units according to international SI conventions. The model results are converted into U.S customary units.

3.2.2 Horizontal Coordinate System

The coordinate system used for the model and other horizontal positioning is the Universal Transverse Mercator (UTM) Zone 18 North. All coordinates in this report are given in the above mentioned local UTM system unless otherwise specified.

3.2.3 Vertical Coordinate System

Vertical elevations in the model are relative to the North American Vertical Datum 1988 (NAVD88), All elevations in this report are given in meters or feet relative to NAVD88; unless specified otherwise.

3.2.4 Time Reference

All data related to time are in local Eastern Standard Time (EST), which is 5 hours behind GMT.

3.3 Model Extent and Resolution

The MIKE 21 flexible mesh was developed by using the "Mesh Generator" tool within the MIKE 21 model. The mesh generator creates a mesh from triangular elements covering a defined extent, or model domain. The element size in the mesh is varied throughout the model domain depending upon the complexity of the floodplain and any topographic features that are identified as critical to propagation of coastal storm surge.

The maximum model domain extent covers a portion of the Hudson River from Battery Park, NY at the southern end and up to Albany, NY at the northern end. The southern boundary was chosen with the intent to use water level measurements from the NOAA Battery NY station as a boundary condition. The inland landward extent of the model was selected to be in close proximity to the 30-foot NAVD88 contour to exceed the surge levels of any potential storm to be simulated.

A comparatively small element area (15 m^2) was applied in Hoboken, and parts of Weehawken and Jersey City that allowed to capture various urban features such as streets, open space and others within the model mesh domain. The overall MIKE 21 coastal model mesh has larger element areas of approximately 1350 m^2 to 6000 m^2 near the southern and northern boundaries as shown in Figure 3-1. The model mesh has coarse resolution in the outer mesh and, with use of a nesting technique, the element area is progressively downscaled by a factor of approximately 1/3 (405, 135, 45 and 15 m^2 respectively) as the mesh gets closer to the immediate study area. In the nesting procedure, model parameters are transferred at the interfaces between areas of transition (from coarse to finer elements) in the mesh.

Most of the study area is either urbanized or contains man-made features such as roads, parks, and railway embankments. Urban areas and structures within the floodplain have many obstacles that can affect the free flow of water. The mesh includes roads, parks, open space, parking lots, etc. but excludes individual buildings which allows to conservatively evaluate the flow of coastal storm surge within the study area. Building footprint GIS datasets provided by City of Hoboken were adjusted and digitized using the latest imagery.

Control lines were added to the mesh so that elements followed the alignment of features ensuring the elevations of important features are correctly assigned during the mesh generation as shown in Figure 3-2 through Figure 3-5. The crest levels of linear features, such as road embankments, and railway embankments have been established through direct interpolation from the 1-meter LiDAR data. It should be noted that some of the features described above have been identified through an inspection of the topographic data and oblique aerial imagery.

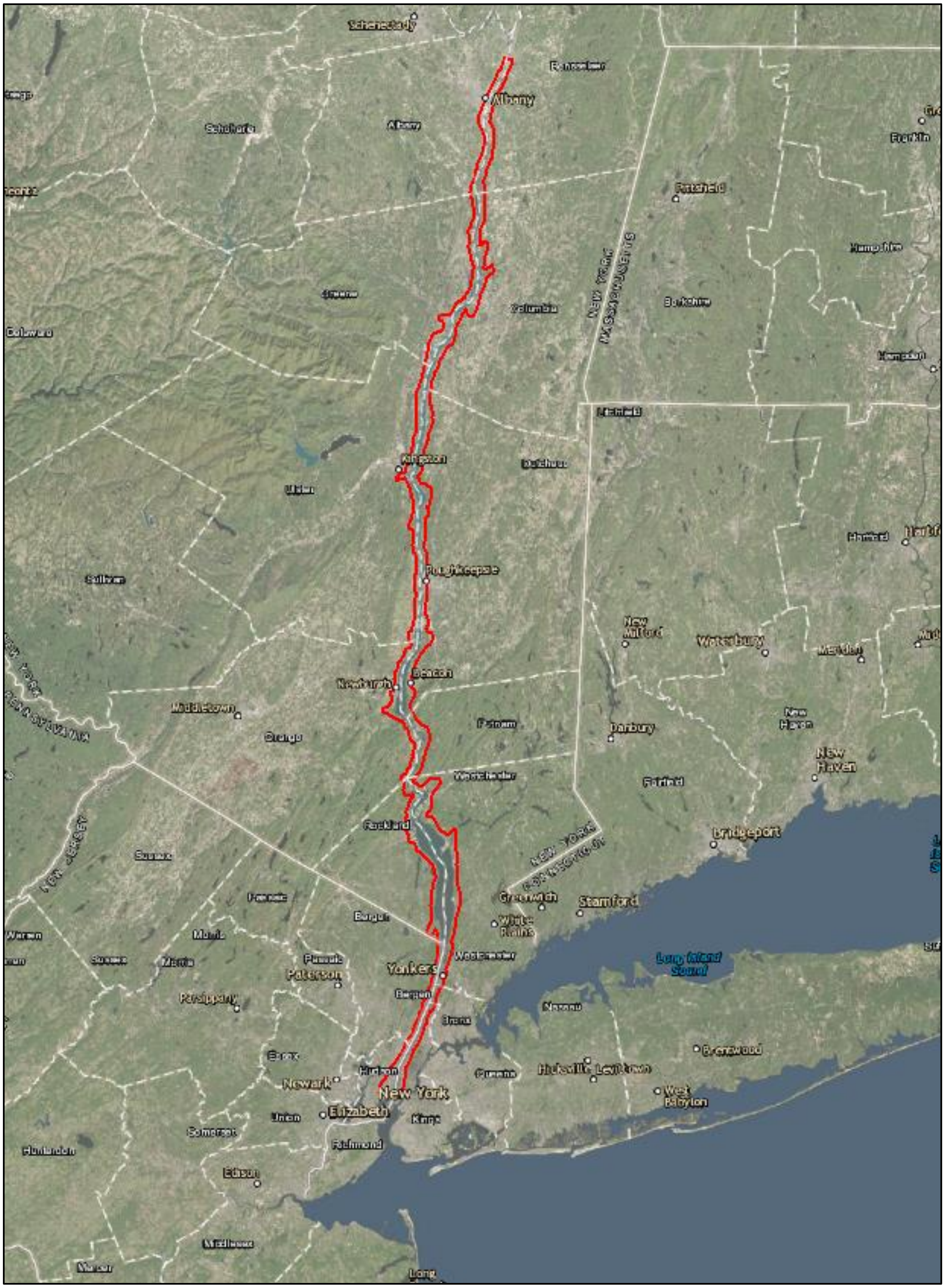


Figure 3-1. Maximum Extent of the Entire Coastal Model Domain Area

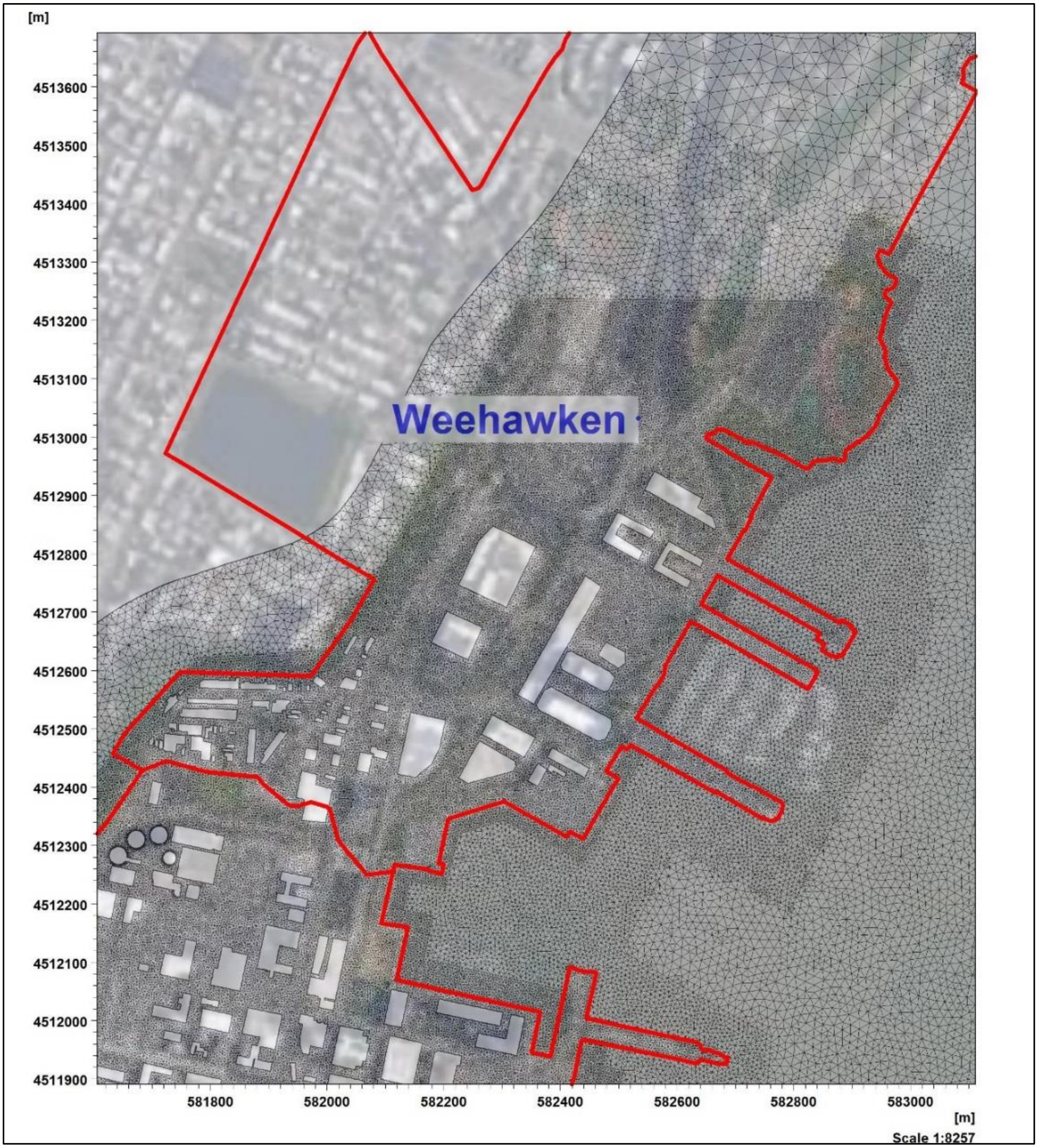


Figure 3-2. Mesh Resolution along the Streets of Weehawken and Weehawken Cove (red line is the municipal boundary)

Figure 3-3. Mesh Resolution along the Streets of Hoboken and Adjacent Open Areas (red line is the municipal boundary)

Figure 3-4. Mesh Resolution along the Southern Portion of Hoboken (red line is the municipal boundary)

Figure 3-5. Mesh Resolution along the Streets of Jersey City and Adjacent Open Areas (red line is the municipal boundary)

3.4 Topography and Bathymetry

A key component of modeling is to accurately represent topography and bathymetry within the model domain which will allow the model to simulate the flow paths and water depths accurately especially within the study area. The topographical information for the modeling is primarily based on LiDAR data that was collected after Superstorm Sandy. Additionally, Dewberry conducted topographic survey along certain portions of the Hoboken waterfront. The bathymetry data used in the model included the most recent surveys from NOAA in the Hudson River, as well as detailed bathymetry surveys for Weehawken Cove from Stevens Institute of Technology and the Long Slip Canal from NJ Transit. These survey data are further described in subsections to follow and

3.4.1 Topography Data

The base topography data used for the MIKE 21 mesh was the 1-meter Digital Elevation Model (DEM) derived from post-Sandy LiDAR collected in November 2012 by the USACE Joint Airborne LiDAR Bathymetry Technical Centre of Expertise (JALBTCX).

To supplement this data, Dewberry conducted a topographic survey to obtain elevations of existing waterfront structures and shoreline features. The extent of the waterfront topographic survey and captured elevations are shown in Figure 3-6.

Figure 3-6. Topographic Survey Data Collected Along Portions of Hoboken Waterfront in July 2015 (Northern Portion in Left, and Southern in Right)

3.4.2 Bathymetry Data

The bathymetry datasets included NOAA survey data downloaded from National Ocean Service (NOS) Office of Coast Survey Hydrographic Survey Geophysical Data System (GEODAS).

Additionally bathymetric surveys for Weehawken Cove and Long Slip Canal were obtained through Stevens Institute of Technology and NJ Transit, respectively.

Figure 3-7 represents the integrated topography/bathymetry surface elevation converted into feet within the study area. It should be noted that the MIKE 21 model uses elevation dataset in meters.

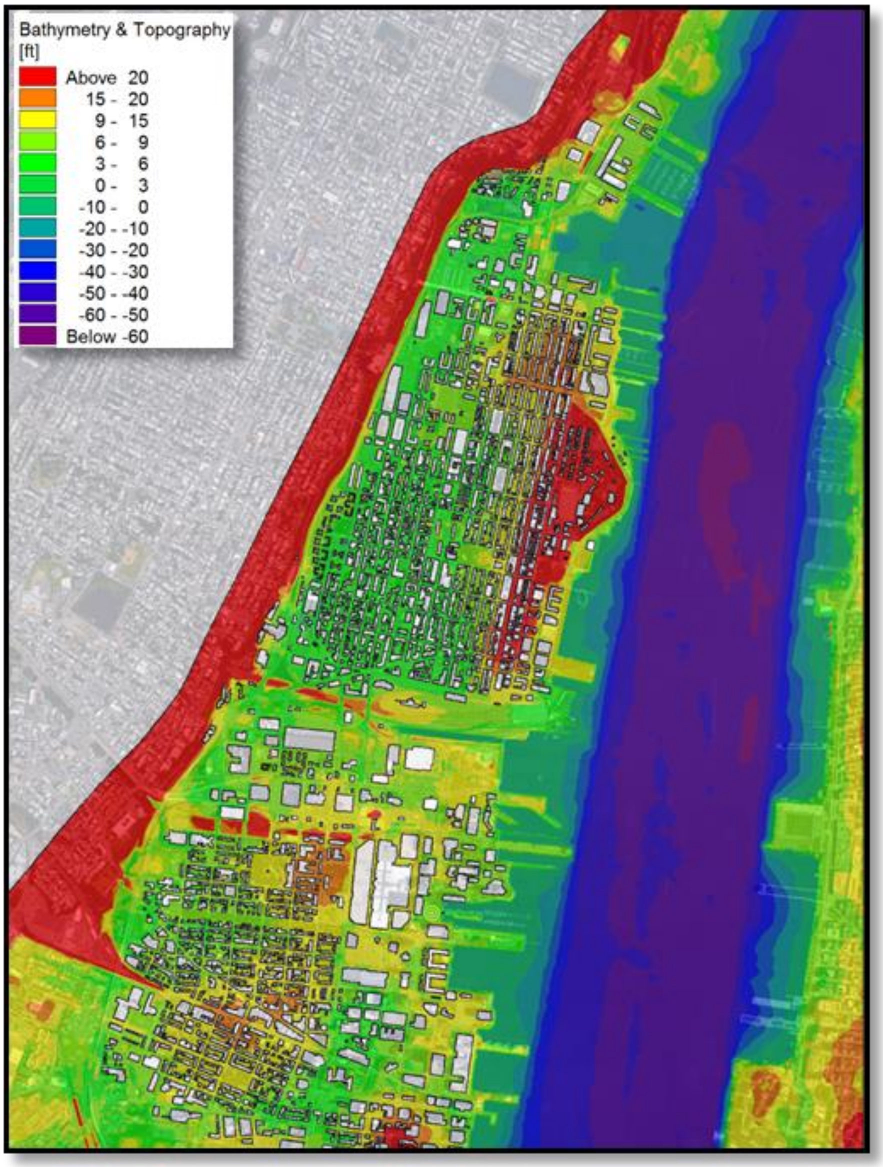


Figure 3-7. Topography and Bathymetry as Defined in the MIKE 21 Model Mesh (in feet, NAVD88)

3.5 Hydraulic Roughness

Hydraulic roughness (also referred to as bottom bed roughness) represents the conveyance capacity of the vegetative growth, bed and bank material, channel, sinuosity and structures of the floodplain. In hydrodynamic models, hydraulic roughness is often accounted for by assigning roughness coefficients. Heavily vegetated or densely developed areas would be assigned a higher hydraulic roughness coefficient, while paved open areas would be assigned a lower roughness coefficient. In using Manning's formula for uniform flow, the roughness coefficient is referred to as Manning's n. Within the MIKE 21 model, hydraulic roughness is defined by a dimensionless Manning's 'M' roughness coefficient which is calculated as 1/Manning's n roughness coefficient (1/n). The roughness coefficients vary spatially, but are kept constant in time.

A detailed Manning's roughness coefficient map was created based on existing land use/land cover as shown in Figure 3-8. A land cover map was developed using the land cover data provided by the City of Hoboken, City of Jersey City and NJDEP. Table 3-1 below shows the Manning's n and M values for various land use/land cover classes. The Manning's n roughness coefficients for various land use/land cover classes were obtained from FEMA Region II Storm Surge Project (FEMA, 2014).

Table 3-1. Manning's "M" and "n" Roughness Coefficients for Landuse/Landcover Classes

Land Cover Classes	Manning's "M"	Manning's "n"
Water	40.0	0.025
Roads	50.0	0.020
Buildings	6.66	0.150
Open Space/Parks	22.2	0.045

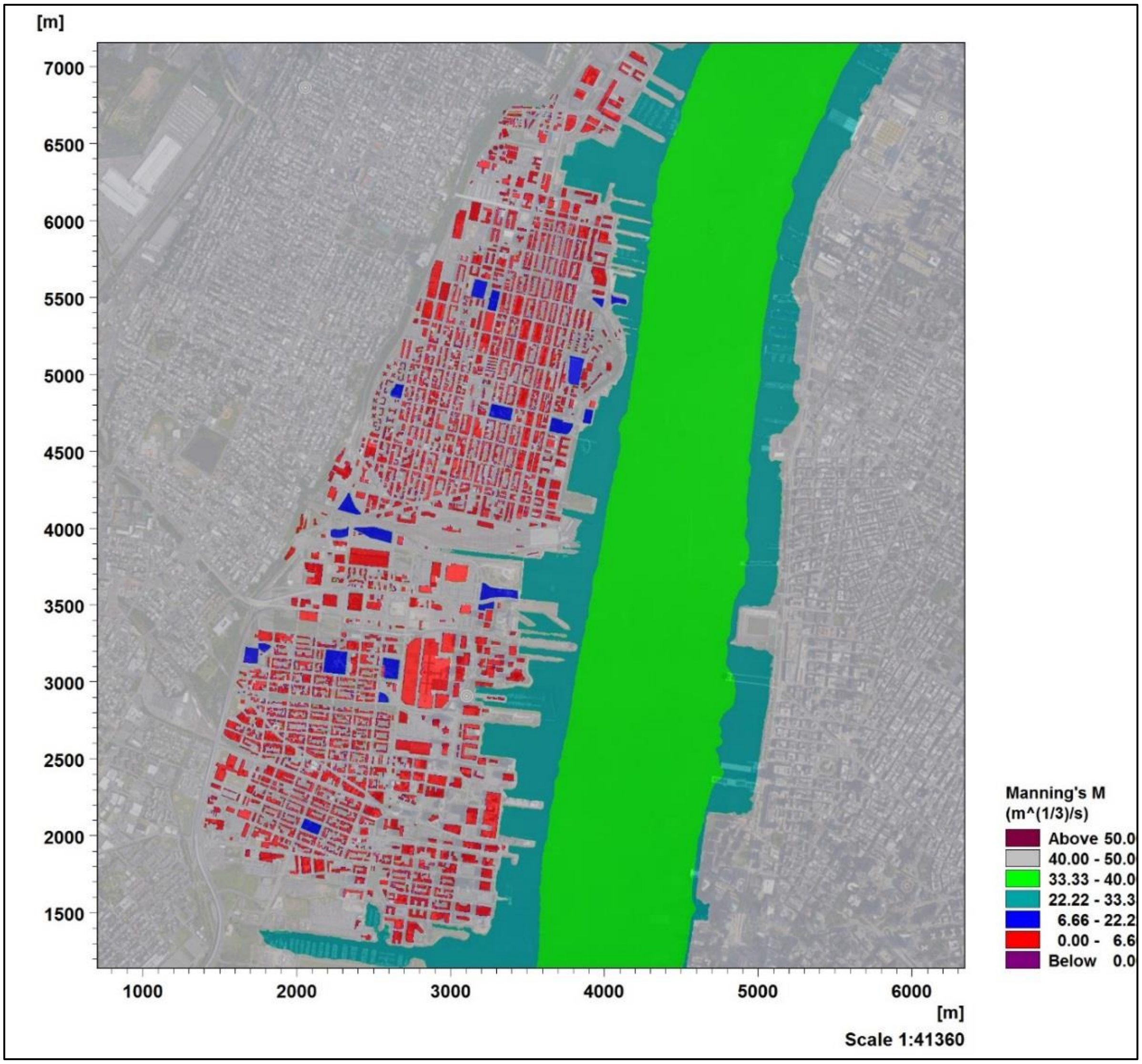


Figure 3-8. Manning's M Roughness Coefficients within the Study Area

3.6 Wetting and Drying

MIKE 21 model is capable of including and excluding computational areas dynamically during the simulation, or in other words, compute the flow in an area which sometimes dries out and is sometimes flooded. The water depths at the points that are dry are saved and then added back into the solution when those points becomes flooded again. To enable wetting and drying within the model, it is required to specify at what depth the computational points should be taken out or re-entered into the computations.

To account for large areas that would only be flooded during a portion of the storm simulations, the "Advanced flood and dry (floodplain)" option was used in the MIKE 21 coastal model. For the model setup, a drying water depth of 0.005m (h_{dry}), a flooding water depth of 0.05m (h_{flood}) and a wetting depth of 0.1m (h_{wet}) were specified. These are the recommended values and no further adjustments were necessary based on initial model simulations.

3.7 Time Step

The model time step specified for the MIKE 21 simulations is important with respect to the numerical stability of the hydrodynamic model. The stability of the model is defined by two stability criteria, namely the courant number and the Courant-Friedrich- Lévy (CFL) stability condition. In order to ensure numerical stability the courant number was kept smaller than 0.80 during the entire simulation while the maximum CFL stability condition was kept less than 1.0. For all of the MIKE 21 coastal model simulations, a time step of 30 seconds was specified.

3.8 Boundary Conditions

Another critical component in the modeling process is the specification of the water levels and flow at the open boundaries (i.e. the "boundary conditions"). Well defined boundary conditions will give better results and fewer instability problems.

The MIKE 21 model has two boundaries - tidal/surge water level and river discharge. The time-dependent tidal water level boundary is located near Battery Park which replicates the extreme water level occurring during a tidal flood event and provides the important input of tides and storm surge to the model. The generation of the extreme tidal boundary conditions is discussed below. The Hudson River discharge boundary was located at the upstream end of the model domain.

3.8.1 Water Level

Hourly verified water surface elevation measurements were obtained from the nearest NOAA water level station at The Battery, NY (Station 8518750). The hourly measurements at the Battery NOAA station for the period of October 23 through November 1, 2012 are shown in Figure 3-9.

This time series of water levels were used for the hindcast of Sandy. The 2013 preliminary FEMA Flood Insurance Study (FIS) for New York City/Hudson County, NJ provided the stillwater elevations for the 1%, 2% and 10%-annual-chance events as shown in Table 3-2 (FEMA, 2013). The recorded time series of water levels from Sandy at the Battery was used as a base to scale the hydrograph to the target peak return period still water level from the FEMA study. A ratio of the peak Superstorm Sandy water level to the target water level is calculated and then used to inform how the Superstorm Sandy hydrograph is adjusted so that its peak hits the target water level. The shift of the Sandy hydrograph starts gradually and increases towards the target peak then the magnitude of the shift decreases moving past the target peak. The Sandy hydrograph is especially used to inform how a typical large storm would ramp up to and down from the peak water level. Figure 3-9 shows the adjusted hydrographs for the 1%, 2% and 10%-annual-chance events. Appendix A shows the table of values used for the boundary condition hydrographs.

Table 3-2. Stillwater Elevations for Storm Scenarios

Preliminary Annual-Chance Stillwater elevations in feet relative to NAVD (FEMA)		
10% (10-year)	2% (50-year)	1% (100-year)
6.9 feet	9.9 feet	11.3 feet

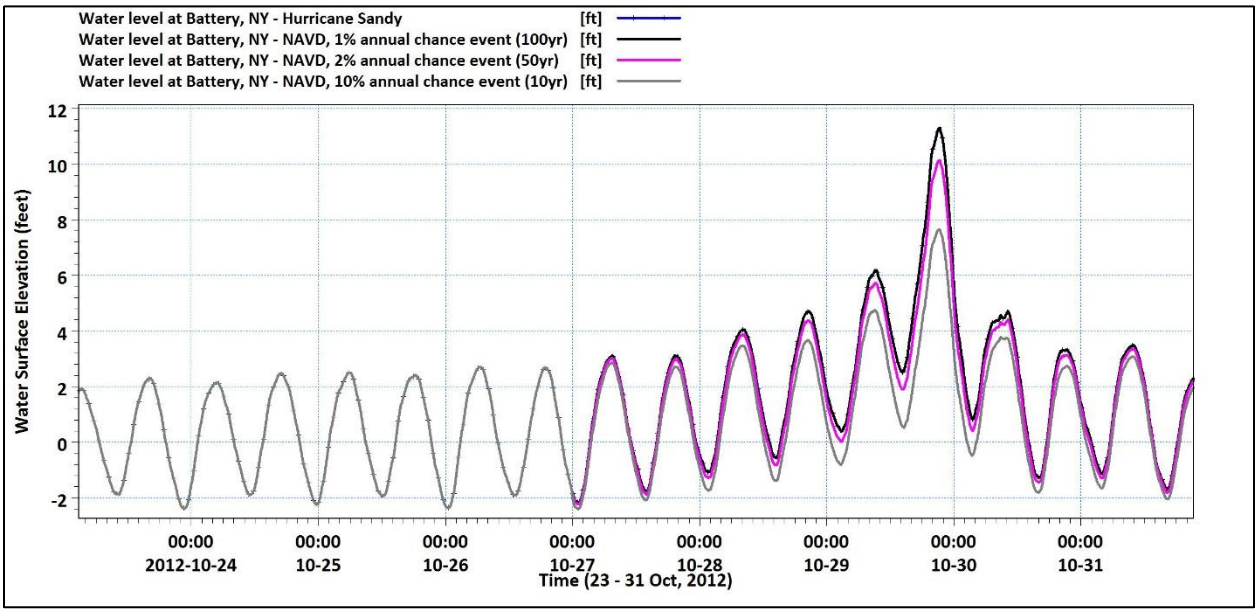


Figure 3-9. Superstorm Sandy and FEMA Water Level Boundary Hydrographs for various Storm Events

It should be noted that due to the scaling of the FEMA's stillwater elevations to the shape of Superstorm Sandy, the peak water levels for the 10- and 50-year events shown in Figure 3-9 are slightly higher than the values shown in Table 3-2. Stillwater Elevations for Storm Scenarios. The water level boundary condition at the Battery acts as a forcing boundary condition for the coastal hydrodynamic MIKE 21 model. As a result, the MIKE 21 model propagates the coastal storm surge water levels from the Battery upstream to the southern boundary of the study area which is approximately 2 miles north of Battery. A wind field was not directly applied to the model. The return period still water levels developed by FEMA area a statistical representation of historic storms, hence it takes into account all the possible wind directions during the storms, particularly that produce the highest water levels for any given location.

It should be noted that several studies were undertaken by various government agencies, institutions and universities to determine the recurrence interval of Superstorm Sandy's coastal storm surge. A study lead by USGS and FEMA indicates that the coastal storm surge produced from Superstorm Sandy measured at the Battery, New York was close to 1% annual chance event (100-year) still water levels as shown in the 2013 FEMA's preliminary coastal storm surge study (USGS, 2015). Another study lead by Stevens Institute of Technology indicates that Superstorm Sandy produces still water elevations close to a 0.4% annual chance event (260-year event) (Orton et.al, 2016). However, since this project seeks to obtain FEMA certification, the best available extreme storm still water levels developed as part of the 2013 FEMA coastal storm surge study for New York and New Jersey were used to develop the boundary conditions. It should be noted that in future these extreme storm water levels can be revised by FEMA and the model boundary conditions would need to be updated to reflect these new still water elevations.

3.8.2 Discharge

Figure 3-10 shows the estimated daily average freshwater discharge data (1947 – 2008) in cubic feet per second (cfs) for the Hudson River at Green Island, NY as obtained from United States Geological Survey (USGS) website (USGS, 2015). The average daily discharge at Green Island NY was around 14,175 cubic feet per second (401 cubic meters per second). The average discharge was applied at the upstream boundary of the MIKE 21 coastal model domain.

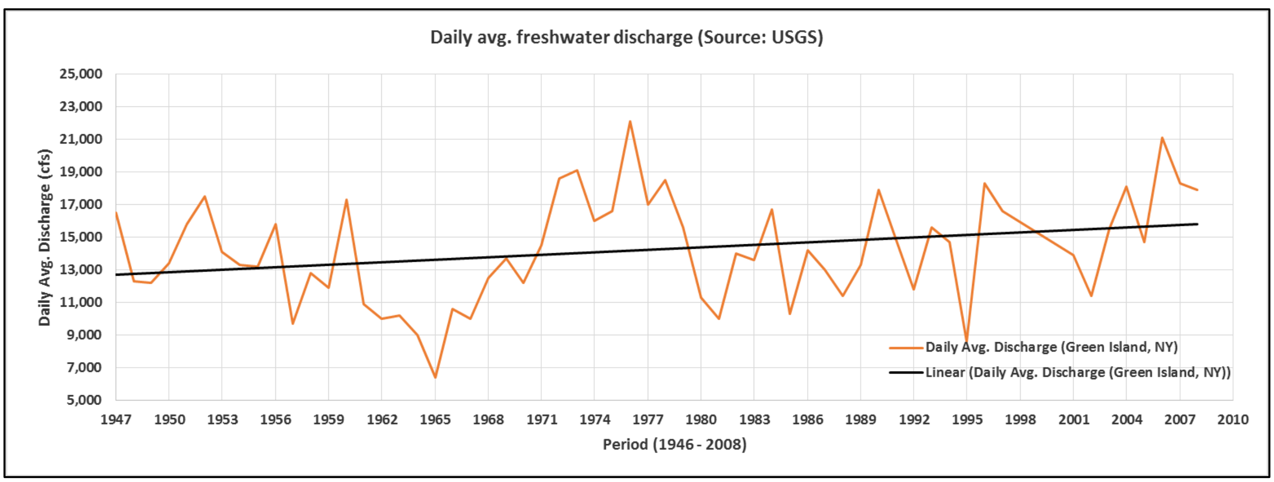


Figure 3-10. Time Series of Daily Average Fresh Water Discharge at Green Island, NY

3.9 Model Setup Parameters and Simulation Scenarios

The MIKE 21 coastal model setup included the parameters as shown in Table 3-3. The MIKE 21 coastal model validation was performed for Superstorm Sandy. Following the MIKE 21 model validation, fifteen (15) coastal storm surge scenarios were simulated for the three "Resist" alternatives that were developed as part of this project. It should be noted that these coastal storm surge scenarios do not include any effects from wave action.

Graphical Processing Unit (GPU) powered computing resources were used to simulate time-intensive coastal hydrodynamic model runs. It should be noted that the Design Flood Elevation (DFE) for the proposed "Resist" alternatives includes sea level rise (SLR) and freeboard as required by 44 CFR 65.10 requirements. The NOAA intermediate high SLR of 2.34 feet for the year 2075 (which corresponds to 50-year design life of this project) was used to in the DFE calculations. This DFE would be higher than the maximum elevations from the 1% annual chance coastal storm event (100-year); thus providing flood risk reduction benefits beyond the 100-year coastal storm surge events. Since the DFE is based on a 1% annual chance coastal storm event, the study does not require to simulate the extremely low probability/frequency coastal storm surge events such as the 500-year (0.2% annual chance) with a coastal storm surge model. Additionally, the current preliminary FEMA flood insurance study for Hudson County (FEMA, 2013) has estimated the stillwater elevations for the 1% and 0.2% annual chance events but estimated the wave heights for the 1% annual chance event only. An analysis was performed to estimate the 0.2% annual chance event wave heights to understand the increases in wave heights beyond the available 1% wave heights. Refer to Appendix B for the analysis on the 0.2% annual chance wave height calculations.

Table 3-3. Parameters Used in the Setup of the MIKE 21 Coastal Hydrodynamic Model

Parameter	Value
Mesh area – coarsest mesh	*1350 m^2*
Mesh size – finest mesh	*15 m^2*
Simulation periods	*10/23/2012 - 10/31/2012*
Maximum time step	*30 Second*
Boundaries	*2 boundaries:* *Boundary 1: Water Level at Battery, NY* *Boundary 2: Upstream Discharge*
Boundary conditions	*Boundary 1: Time series of water surface elevation* *Boundary 2: Constant discharge*
Flood and Dry	*Included*
Density	*Barotropic*
Horizontal eddy viscosity formulation	*Smagorinsky coefficient of 0.28*
Bed resistance	*Manning number varying in domain*

Following is the list of coastal model simulations performed for this study-

- Model Run Scenario 1 - Superstorm Sandy (Validation run)
- Model Run Scenario 2 – No-Action Alternative conditions for 10% annual chance event (10-year)
- Model Run Scenario 3 - No-Action Alternative conditions for 2% annual chance event (50-year)
- Model Run Scenario 4 - No-Action Alternative conditions for 1% annual chance event (100-year)
- Model Run Scenario 5 – Initial Alternative 3 conditions for 10% annual chance event (10-year)
- Model Run Scenario 6 - Initial Alternative 3 conditions for 2% annual chance event (50-year)
- Model Run Scenario 7 - Initial Alternative 3 conditions for 1% annual chance event (100-year)
- Model Run Scenario 8 – Final Alternative 3 conditions for 10% annual chance event (10-year)
- Model Run Scenario 9 - Final Alternative 3 conditions for 2% annual chance event (50-year)

- Model Run Scenario 10 - Final Alternative 3conditions for 1% annual chance event (100-year)
- Model Run Scenario 11 – Final Alternative 1 conditions for 10% annual chance event (10-year)
- Model Run Scenario 12 - Final Alternative 1 conditions for 2% annual chance event (50-year)
- Model Run Scenario 13 - Final Alternative 1 conditions for 1% annual chance event (100-year)
- Model Run Scenario 14 – Final Alternative 2 conditions for 10% annual chance event (10-year)
- Model Run Scenario 15 - Final Alternative 2 conditions for 2% annual chance event (50-year)
- Model Run Scenario 16 - Final Alternative 2 conditions for 1% annual chance event (100-year)

4 Model Validation

This section further describes the validation efforts carried out to ensure that the MIKE 21 coastal hydrodynamic model simulated the propagation of tides and coastal storm surge with high degree of accuracy within the study area. A good validated model provides the basis to adequately assess the effects of various coastal storm surge events with and without "Resist" alternatives.

4.1 Background

The study area is located approximately 2-3 miles north of NOAA's Battery gage that measures observed water level in the Hudson River. Since the study area and the Battery gage are close to each other, it was assumed that the tidal water level variation between the Battery gage and the study area would be similar. Hence, detailed calibration of the coastal hydrodynamic model to simulate normal tidal water level conditions between Battery gage and study area was not deemed necessary for this project. Instead, the coastal hydrodynamic model was validated to simulate Superstorm Sandy with observed high water mark datasets as obtained from USGS and Stevens Institute of Technology.

Several iterations were performed with the MIKE 21 coastal hydrodynamic model to ensure a good fit between the simulated and observed maximum water depths during Superstorm Sandy. After several iterations and discussions with Stevens Institute of Technology, the validation model run that simulated model results from Superstorm Sandy with acceptable accuracy was finalized. As an additional model validation check, the Superstorm Sandy validated model was also used to simulate FEMA's 1% annual chance coastal storm surge event to ensure that the MIKE 21 coastal hydrodynamic model simulated peak water levels that were within +/-6 inches of FEMA's stillwater elevations around the study area. Due to differences in the scale and type of models used by Dewberry and FEMA, it is expected to have minor differences in the stillwater elevations between Dewberry's MIKE 21 model and FEMA's ADCIRC model-derived stillwater elevation within the model domain. Furthermore, a 14-day tidal cycle was simulated using the validated Superstorm Sandy coastal model with forcing observed tidal boundary at Battery as an additional check to ensure the MIKE 21 coastal model simulate propagation of normal tide into study area. A comparison was done with the model simulated tidal data with observed tidal data in the study area to ensure that the validated model accurately simulates the prorogation of tides within the study area.

4.2 Model Validation

Multiple iterative simulations were performed to confirm and validate that the MIKE 21 coastal hydrodynamic model is a good representation of the physical environment for existing conditions and is capable to simulate flooding conditions for various “Resist” alternative scenarios with reasonable accuracy. These iterative simulations included adjusting the following parameters –

- Adjustments to the post Sandy LiDAR topographic data – The MIKE 21 coastal model mesh was adjusted to reflect topographic data that was not captured correctly by the LiDAR data. As an example, the LiDAR data did not capture the existing roadway topography under the NJ Transit rail bridges correctly. The topography in the MIKE 21 coastal model mesh was adjusted to reflect the existing roadway topography.
- Adjustments to building footprints – The MIKE 21 coastal model mesh was adjusted to reflect the building footprints based on imagery and site visits.
- Adjustments to bed roughness – The base NJDEP land cover data was adjusted to reflect the spatial extent of the land cover data and associated bed roughness coefficient.
- Adjustments to the location of model boundary – The MIKE 21 coastal model results were evaluated using various locations as model boundary.

The model validation simulation runs compared the simulated water depths with the observed high water marks (water depths) during Superstorm Sandy. High water mark (HWM) data as published on USGS website (https://water.usgs.gov/floods/events/2012/sandy/sandymapper.html) for 11 locations within the model domain, are shown in Figure 4-1. Details of the measurements including site photographs taken during the measurement of HWM data are provided in Appendix C.

In addition, Figure 4-2 shows HWM data for 17 locations collected by the Stevens Institute of Technology that were used to validate the hydrodynamic model. Table 4-1 and Table 4-2 provide details of HWM data collected from USGS and Stevens Institute of Technology, respectively. Table 4-2 shows the potential uncertainty in the measured water depth and time of observations of the HWMs in the Stevens Institute of Technology datasets. These datasets were measured during the time period of Superstorm Sandy’s landfall in the study area and it is assumed that the location of these measurements were not recorded with exact surveyed coordinates. Hence, these datasets have a potential uncertainty in the exact location of the measurements. USGS measured their HWM data along the water/debris line at structures after the passage of Superstorm Sandy with high level of accuracy.

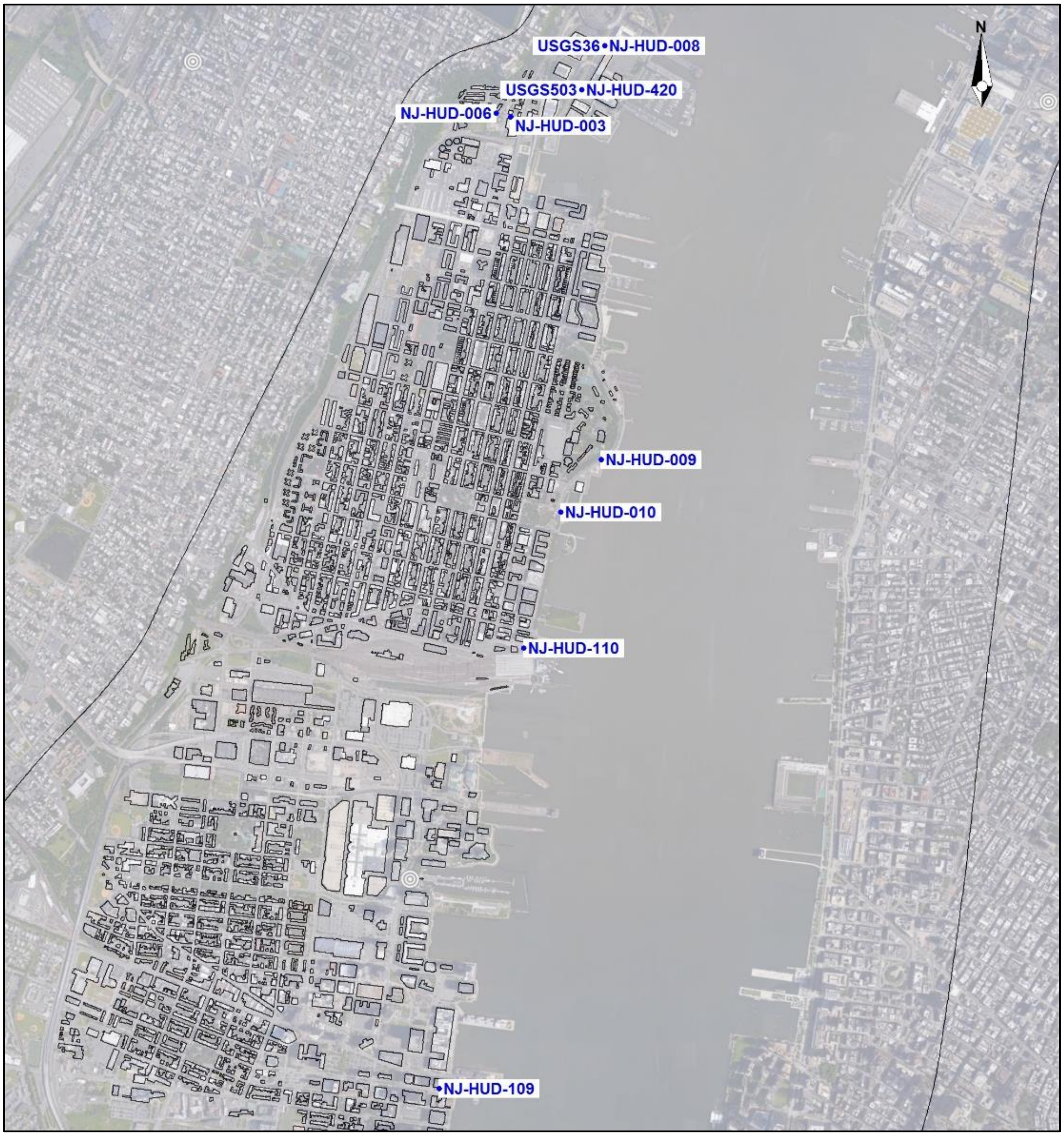


Figure 4-1. Location of Observed High Water Mark (HWM) Data Collected by USGS for Superstorm Sandy

Figure 4-2. Location of Observed High Water Mark (HWM) Data Collected by Stevens Institute of Technology during Superstorm Sandy

Table 4-1. Details of Observed High Water Mark Data during Superstorm Sandy (Source: USGS)

Station ID (USGS)	Latitude	Longitude	Date/Time	Water depth above ground (ft) - Observed	Water Elevation (ft) - Observed	Error in observed data (±ft)	Comments
HWM-NJ-HUD-109	40.71649	-74.03356	10/29/2012 9:24:00	4.10	10.40	0.05	Excellent mud line on glass door of entrance to port authority transit hub
HWM-NJ-HUD-110	40.73564	-74.02846	10/30/2012 9:24:00	5.60	10.60	0.05	Excellent mud line on glass door of food court inside Hoboken terminal
HWM-NJ-HUD-010	40.74155	-74.02625	10/31/2012 9:30:00	0.80	10.50	0.00	Good mudline on glass window
HWM-NJ-HUD-009	40.74383	-74.02390	11/1/2012 9:24:00	2.50	10.70	0.00	Fair debris line on fence
HWM-NJ-HUD-006	40.75896	-74.02969	11/2/2012 9:36:00	9.00	12.00	0.00	Good mud line on building
HWM-NJ-HUD-003	40.75880	-74.02886	11/3/2012 9:36:00	6.50	9.40	0.10	
HWM-NJ-HUD-420	40.75994	-74.02478	11/4/2012 9:30:00	1.10	10.30	0.05	Excellent debris line at southwest corner of parking garage
HWM-NJ-HUD-008	40.76185	-74.02344	10/29/2012 9:24:00	2.50	10.10	0.25	Fair debris line on fence
USGS-503	40.75994	-74.02478	10/29/2012 12:00:00	1.10	10.30	0.05	
USGS-036	40.76185	-74.02344	10/29/2012 22:00:00	2.50	10.10	0.00	
USGS-037	40.78278	-74.00498	10/29/2012 22:30:00	2.30	10.10	0.10	

Table 4-2. Details of Observed High Water Mark Data during Superstorm Sandy (Source: Stevens Institute of Technology)

Station ID (Stevens Institute of Technology, Hoboken NJ)	Latitude	Longitude	Date/Time	Water depth above ground (ft) - Observed	Error in observed Time (±min)	Error in observed water depth (±ft)	Description
WM11	40.753822	-74.029869	10/29/2012 20:15:00	2.00		0.50	
WM12	40.752842	-74.029808	10/29/2012 20:15:00	0.75		0.50	
WM14	40.752945	-74.032249	10/29/2012 20:45:00	2.50		0.50	
WM17	40.752796	-74.023663	10/29/2012 22:30:00	0.70		0.20	
WM18	40.75291	-74.024327	10/29/2012 22:15:00	0.70		0.20	
WM20	40.755125	-74.029549	10/29/2012 23:00:00	5.00	30	0.50	Observed at 15th Street & Willow Ave. car wash
WM21	40.755076	-74.027393	10/29/2012 21:15:00	3.00	15	0.50	Observed at 1500 Garden St.
WM22	40.73571	-74.027861	10/29/2012 21:15:00	7.30	30	0.50	Southeast corner of Hudson Place
WM23	40.738118	-74.034904	10/29/2012 19:30:00	1.40	30	0.20	Observed HWM near Side walk outside coffee shop at 305 1st Street
WM24	40.752772	-74.023465	10/29/2012 20:30:00	1.10	30	0.20	Sinatra drive North and 14th Street
WM25	40.753746	-74.0289	10/29/2012 21:30:00	1.00	30	0.20	14th Street cross walk between Malibu Dinner and BP
WM26	40.739429	-74.041873	10/29/2012 19:30:00	1.70	30	0.20	Side walk Northeast corner of 1st and Harrison Street
WM27	40.737769	-74.035679	10/29/2012 19:30:00	2.10	30	0.20	Side walk of joining approximately 86 Clinton Street
WM28	40.737992	-74.034153	10/29/2012 19:00:00	1.00	30	0.20	
WM29	40.749704	-74.036768	10/30/2012 2:00:00	5.60	30	0.30	Observed HWM at Shoprite
WM30	40.740671	-74.033637	10/30/2012 2:00:00	4.30	30	0.30	Southeast corner of Hoboken University Medical Center
WM31	40.748811	-74.036995	10/30/2012 0:00:00	5.70	30	0.50	Observed at Intersection between 9th St. and Monroe St.

For Superstorm Sandy, the MIKE 21 model validation run was simulated for approximately 24 hours starting from October 29th 2012 2.30am to October 30th, 2012 3.30 am using the data and model setup as described in Section 3. Several iterations were performed with the MIKE 21 coastal model to ensure the flow paths, inundation areas and maximum water depths simulated by the model matched reasonably well with the observations during Superstorm Sandy.

Maximum water depths were extracted from the MIKE 21 coastal model to compare the simulated results with observed high water mark data collected from USGS and Stevens Institute of Technology. Table 4-3 compares the MIKE 21 coastal model simulated and observed water depths. The overall computed Root Mean Square (RMS) error is around 6 inches (0.5 feet). The RMS error between the simulated and observed USGS HWM at 11 locations within the study area is 3.6 inches (0.3 feet). The RMSE between the simulated and observed Stevens Institute of Technology HWM at 17 locations within the study area is around 7 inches (0.6 feet). Figure 4-3 shows the correlation coefficient (R^2) of 0.95 between model simulated and observed High Water Marks (HWM) data; where the orange dotted line shows the estimated errors in model and observed HWM data. As seen from these figures and tables, the overall RMS error produced by the MIKE 21 coastal hydrodynamic model within the study area are similar to other studies such as Blumberg et. al 2015 that are peer reviewed in the literature. Model results that have correlation coefficient (R^2) above 0.9 and overall RMSE less than 1.3 feet (0.4m) is considered as an acceptable model (USACE, 2015).

Table 4-3. Root Mean Square Error (RMSE) between Modeled and Observed High Water Mark (HWM)

High Water Marks	Source	Water depth above ground (m) - Observed	Water depth above ground (m) - Model	Difference in Water Depth (Model - Observed) (m)	Difference in Water Depth (Model - Observed) (feet)
		Observed (m)	Model (m)		
HWM-NJ-HUD-109	USGS	1.3	1.3	0.0	0.0
HWM-NJ-HUD-110	USGS	1.7	1.8	0.1	0.2
HWM-NJ-HUD-010	USGS	0.2	0.3	0.0	0.1
HWM-NJ-HUD-009	USGS	0.8	0.8	0.0	0.2
HWM-NJ-HUD-006	USGS	2.7	2.7	-0.1	-0.3
HWM-NJ-HUD-003	USGS	2.0	2.1	0.1	0.4
HWM-NJ-HUD-420	USGS	0.3	0.5	0.2	0.6

High Water Marks	Source	Water depth above ground (m) - Observed	Water depth above ground (m) - Model	Difference in Water Depth (Model - Observed) (m)	Difference in Water Depth (Model - Observed) (feet)
		Observed (m)	Model (m)		
HWM-NJ-HUD-008	USGS	0.8	0.8	0.0	0.1
USGS-503	USGS	0.3	0.3	0.0	0.0
USGS-036	USGS	0.8	0.7	-0.1	-0.3
USGS-037	USGS	0.3	0.5	0.1	0.4
Root Mean Square Error (RMSE)				**0.1 meter**	**0.3 feet**
WM11	Stevens Institute	0.6	0.6	0.0	-0.2
WM12	Stevens Institute	0.2	0.2	0.0	0.0
WM14	Stevens Institute	0.8	0.9	0.1	0.5
WM17	Stevens Institute	0.2	0.2	0.0	-0.1
WM18	Stevens Institute	0.2	0.2	0.0	0.1
WM20	Stevens Institute	1.5	1.3	-0.2	-0.6
WM21	Stevens Institute	0.9	0.7	-0.2	-0.6
WM22	Stevens Institute	2.2	2.2	0.0	0.0
WM23	Stevens Institute	0.4	0.4	0.0	0.0
WM24	Stevens Institute	0.3	0.1	-0.2	-0.6
WM25	Stevens Institute	0.3	0.8	0.5	1.7
WM26	Stevens Institute	0.5	0.4	-0.1	-0.5
WM27	Stevens Institute	0.6	0.4	-0.2	-0.8
WM28	Stevens Institute	0.3	0.3	0.0	0.1
WM29	Stevens Institute	1.7	1.5	-0.2	-0.6
WM30	Stevens Institute	1.3	1.2	-0.1	-0.2
WM31	Stevens Institute	1.7	1.6	-0.1	-0.4
Root Mean Square Error (RMSE)				**0.2 meter**	**0.6 feet**
Combined Root Mean Square Error (RMSE)				**0.1**	**0.5**
				meter	**feet**

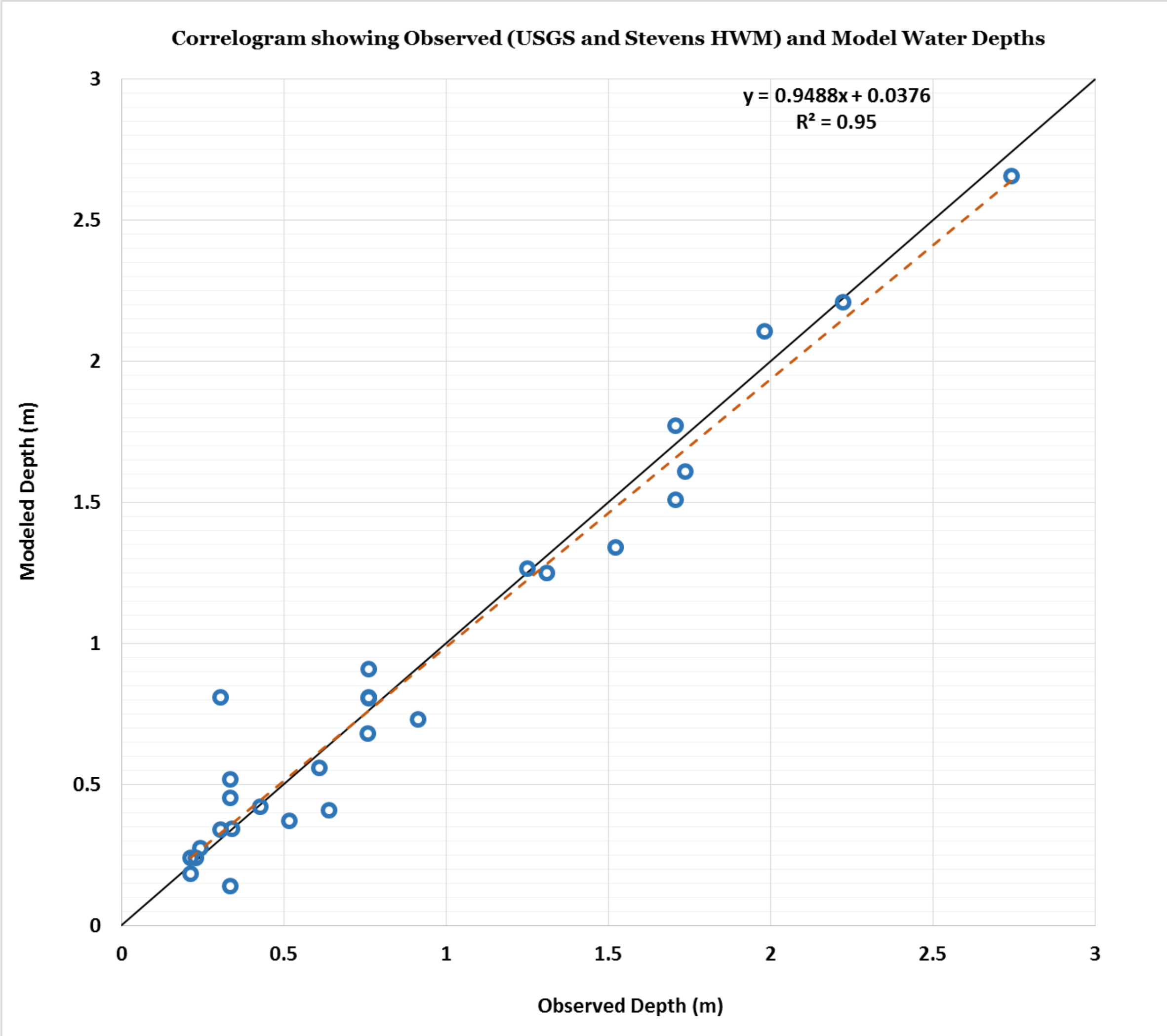


Figure 4-3. Correlogram showing Model and Observed High Water Mark Data

4.3 Superstorm Sandy Flood Inundation Results from Coastal Model

Water depth results were extracted from the MIKE 21 coastal hydrodynamic model at various time steps during the rise and fall of the Superstorm Sandy's coastal storm surge. Figure 4-4 to Figure 4-11 show the flood inundation areas and the maximum water depth simulated by the MIKE 21 coastal model between 5 pm to midnight on October 29th, 2012 within the study area.

On October 29th, 2012 at 5pm, when the water level in the Hudson River was about 5.5 feet-NAVD, NJ Transit's Hoboken Terminal started to flood, as shown in Figure 4-4. At this time, water from the Long Slip canal had just started to overtop the canal's bulkhead. At 6.30 pm when the water level in the Hudson River was around 7 feet-NAVD, the flood water completed overtopped Long Slip canal's bulkhead and simultaneously floodwater from the Hudson River flowed through NJ Transit's Hoboken Terminal towards Marin Boulevard. This floodwater then traveled west of the canal onto Marin Boulevard into Jersey City and Hoboken. Simultaneously, floodwater overtopped the existing walkway along Harbor Boulevard in the Weehawken Cove area and along the low lying waterfront walkway portions along 15th street in Hoboken. Refer to Figure 4-5 for the flow paths and flood inundation areas simulated by the MIKE 21 coastal model at 6.30 pm on October 29th, 2012.

Between 7 pm and 10 pm on October 29th, 2012, the water level in the Hudson River was between 8.6 feet-NAVD and 10.7 feet-NAVD, with the peak water level of 11.3 feet-NAVD occurring around 9.30 pm. During this time period, on the southern portion of the study area, water flowed through Long Slip canal and the NJ Transit rail yard onto Observer Highway and then into the western portions of Hoboken and portions of Jersey City along Grove Street and Jersey Avenue. Simultaneously, on the northern portion of the study area, floodwater flowed through Weehawken cove into areas east of Willow Avenue in Weehawken (area is also referred to as "Shades") and into western portions of Hoboken. Refer to Figure 4-6 to Figure 4-9 for the flow paths and flood inundation areas simulated by MIKE 21 coastal model between 7 pm and 10 pm.

Figure 4-10 and Figure 4-11 show the flood inundation areas after the peak of Superstorm Sandy's storm surge receded between 11pm and midnight on October 29th, 2012.

Figure 4-12 shows the maximum water depth simulated by the MIKE 21 coastal model during the entire Superstorm Sandy storm surge simulation.

Figure 4-12 shows that portions of Hoboken Housing Authority and critical facilities such as North Hudson Sewerage Authority (NHSA) located on the western portion of Hoboken were flooded with approximately 6-8 feet of water. In Hoboken, the flood inundation area covered the western portion starting from NJ Transit's Hudson Bergen Light Rail (HBLR) tracks and extended to portions of Garden Street/10th Street, then along Grand/Clinton Streets to 15th Street and Park Avenue. During the peak of Superstorm Sandy, small portions of the Hoboken waterfront along Maxwell Place and Hudson Street received floodwaters. On the Weehawken side, portions of Weehawken waterfront received approximately 3-4 feet of floodwaters while the Shades area of Weehawken received over 8 feet of water.

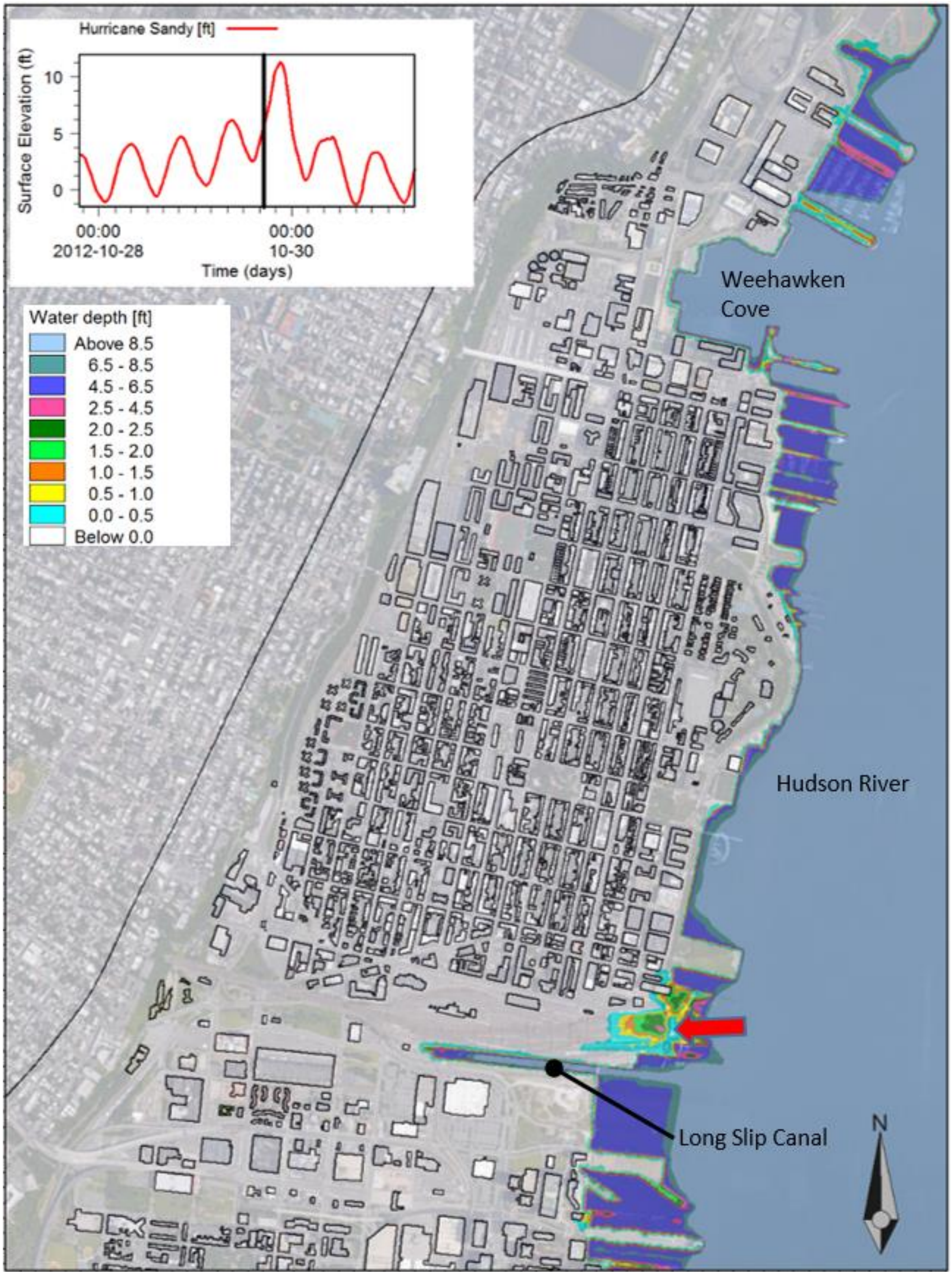


Figure 4-4. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 5.00 pm

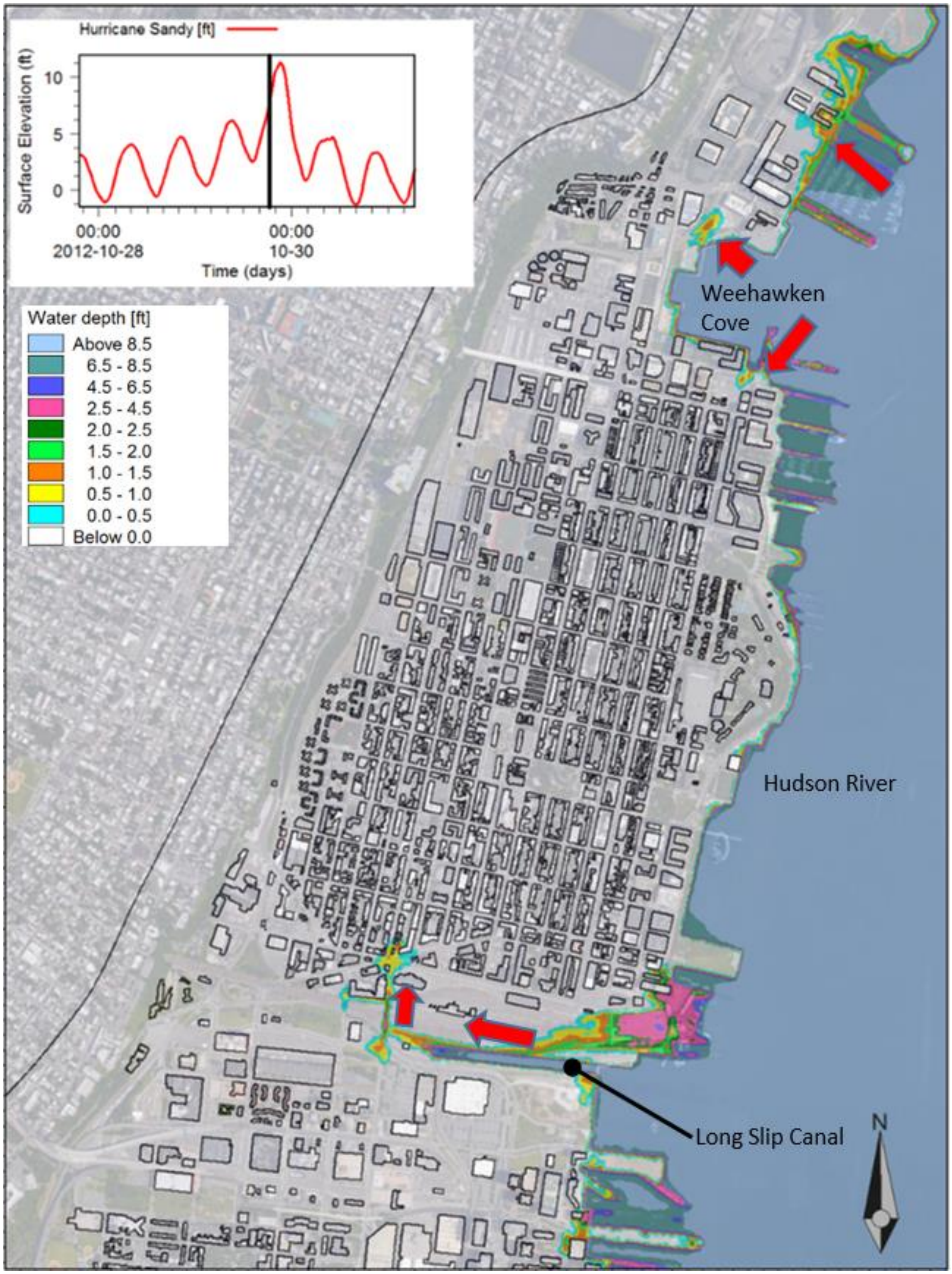


Figure 4-5. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 6.30 pm

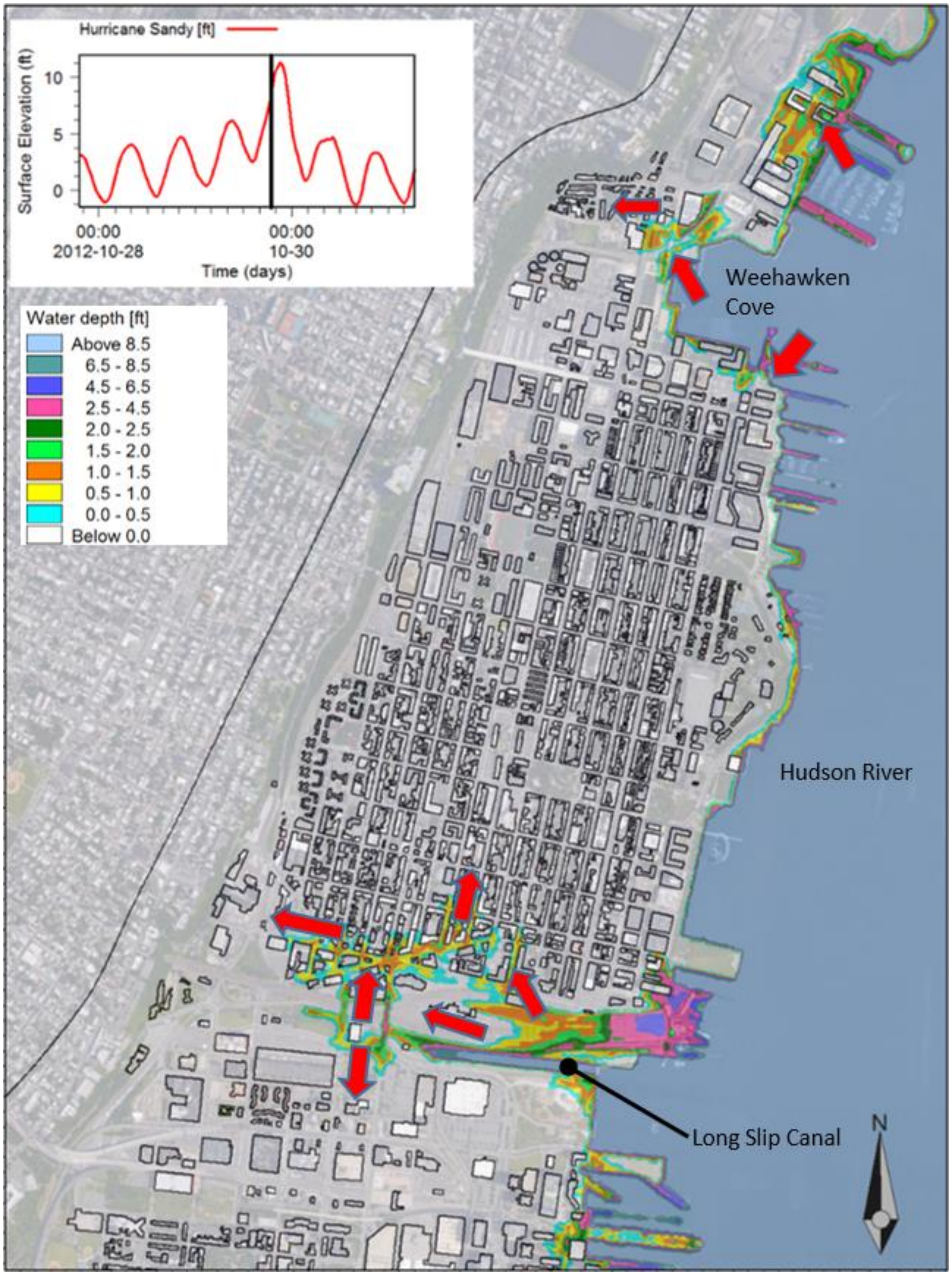


Figure 4-6. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 7.00 pm

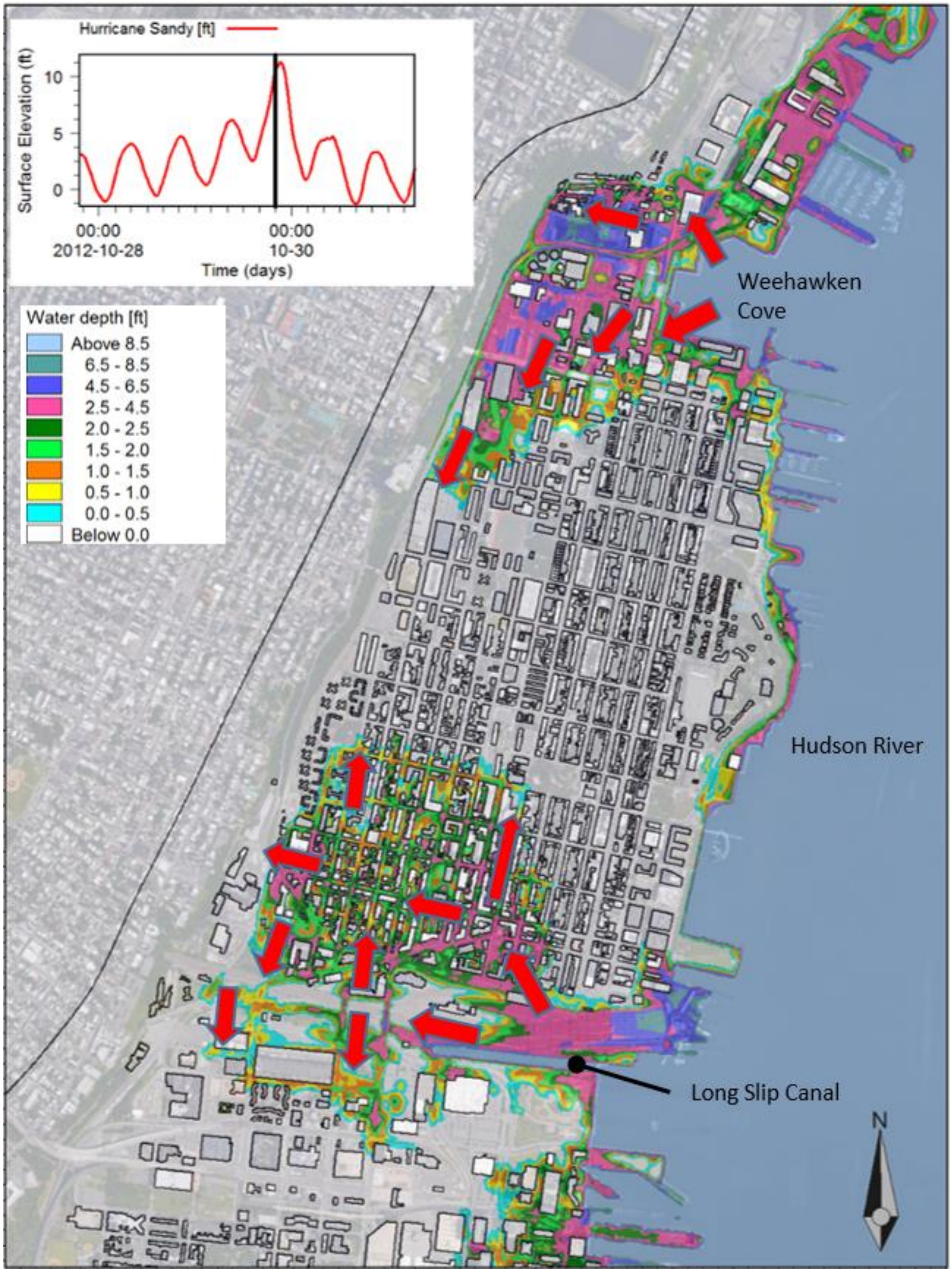


Figure 4-7. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 8.00 pm

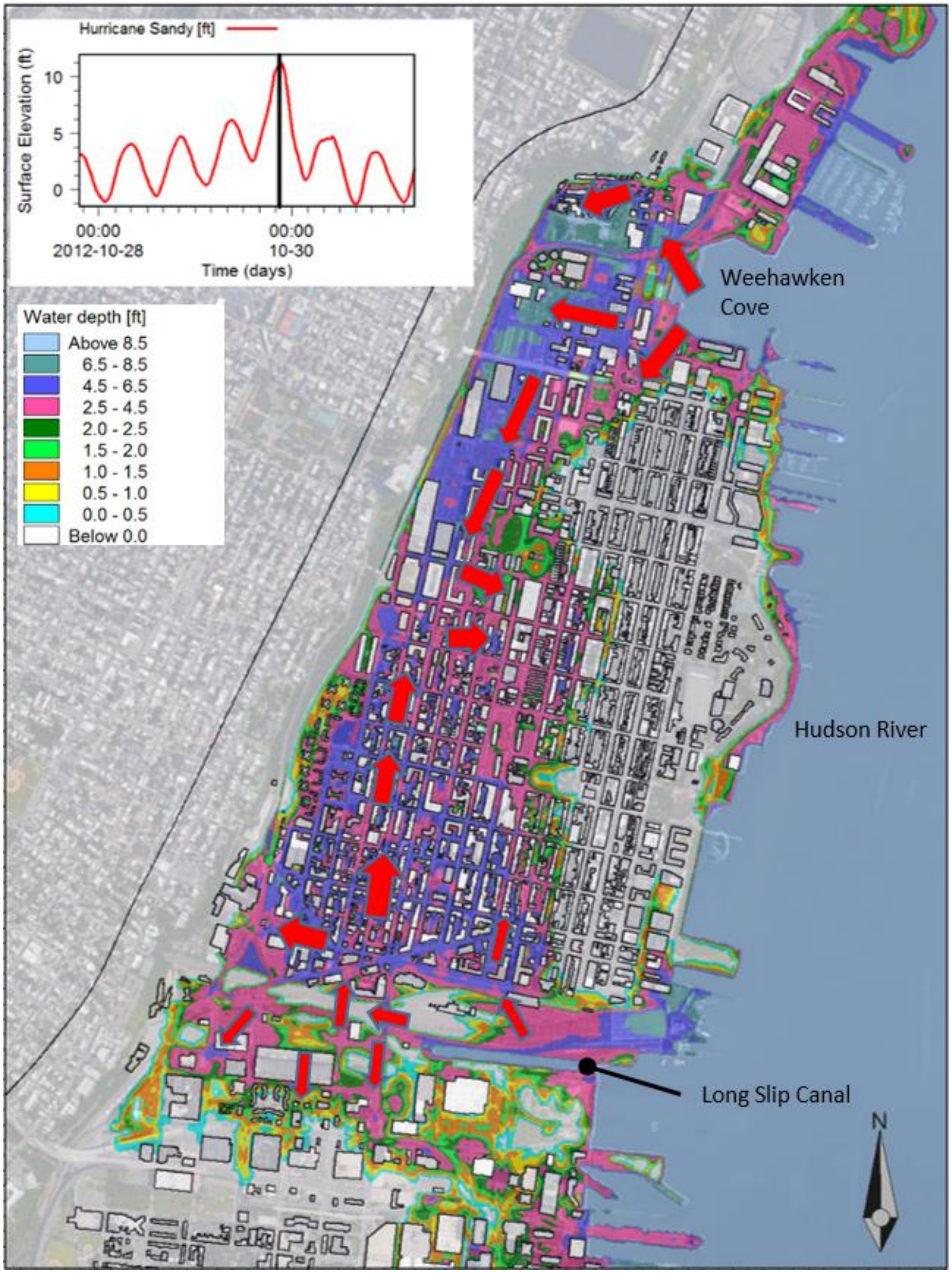


Figure 4-8. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 9.00 pm

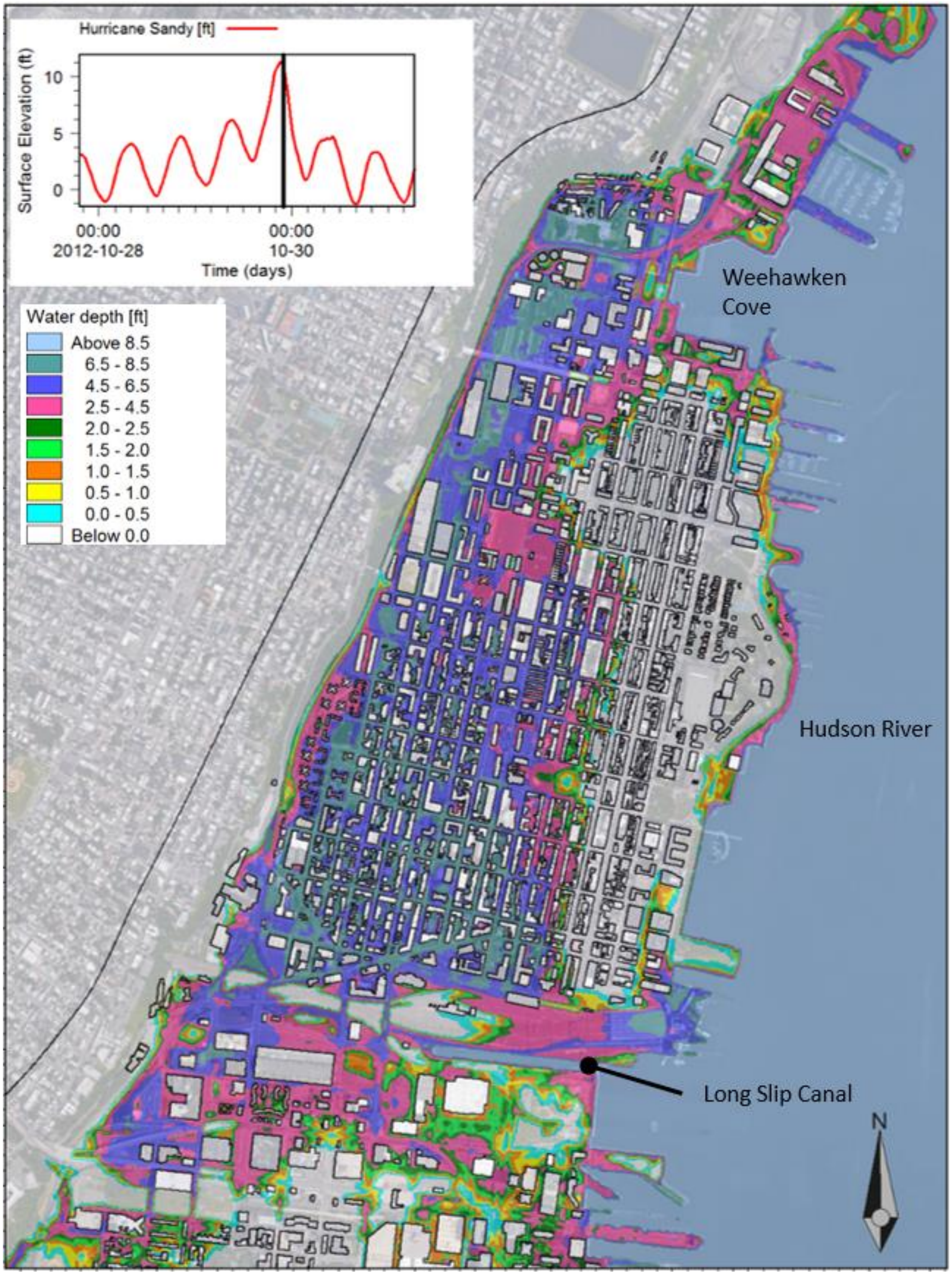


Figure 4-9. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 10.00 pm

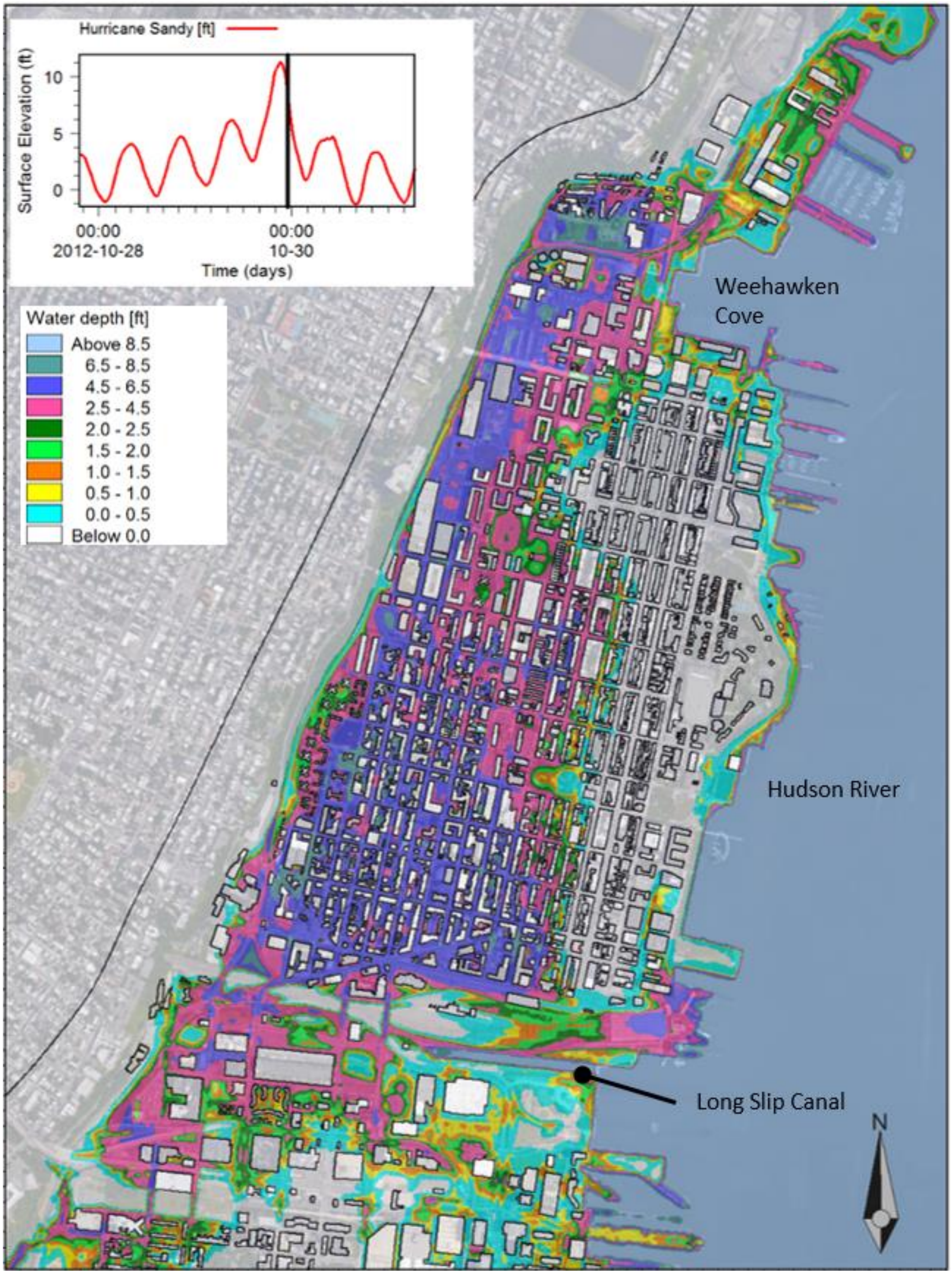


Figure 4-10. Water Depth (feet) in the Study Area on Oct 29th, 2012 at 11.00 pm

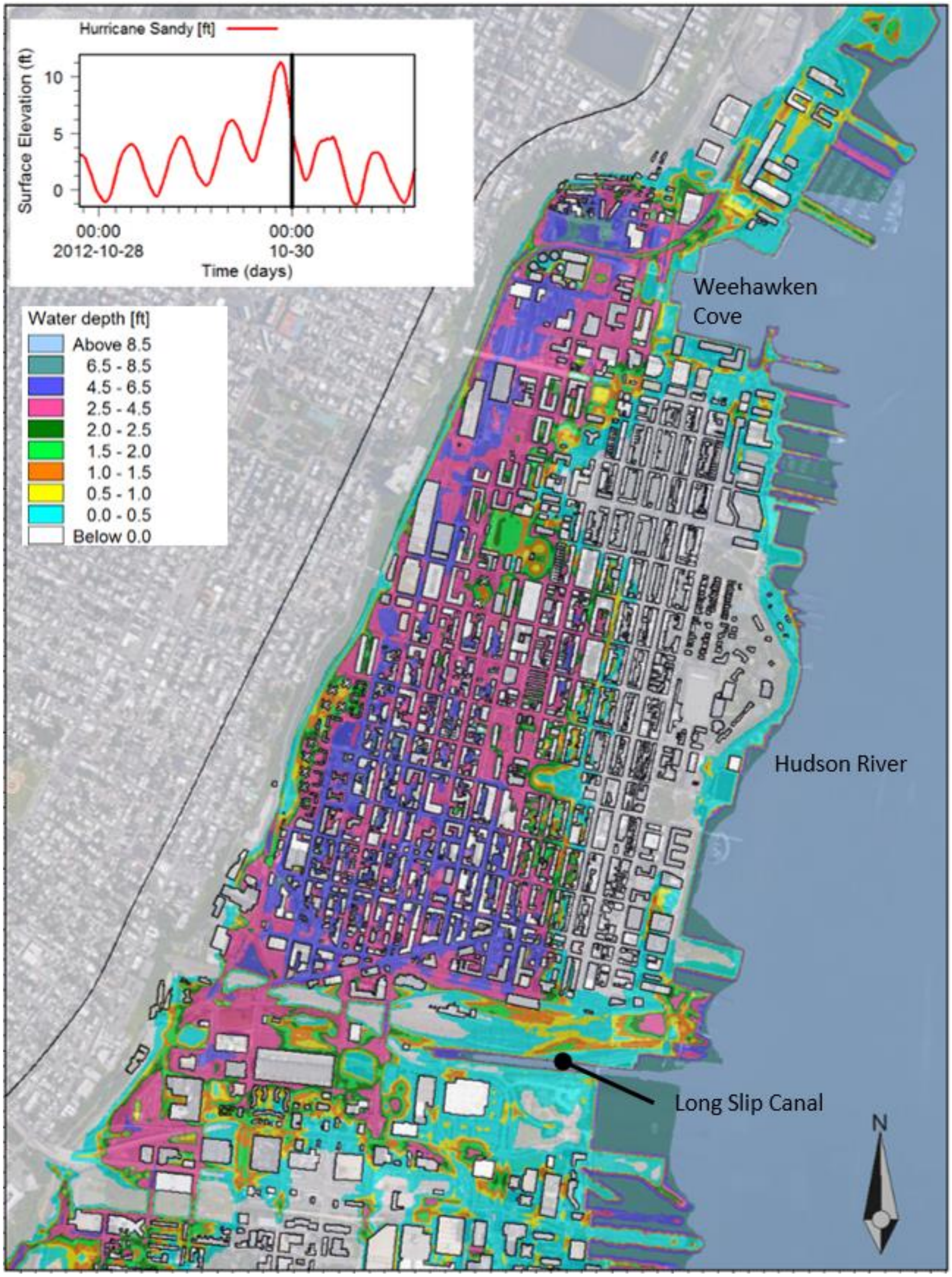


Figure 4-11. Water Depth (feet) in the Study Area on Oct 30th, 2012 at 12.00 am

Figure 4-12. Maximum Water Depth Simulated by MIKE 21 Coastal Model during Superstorm Sandy

4.4 Comparison of Validated Model with FEMA's Stillwater Elevations within Model Domain

The validated MIKE 21 coastal model was then used to simulate with FEMA's 2013 preliminary 1% annual chance event coastal storm surge event with forcing still-water elevation boundary for this event at the Battery. The intent of this model run was to compare the MIKE 21 model results with FEMA's 1% annual chance still water elevation (SWEL) within the model domain. Table 4-4 compares the MIKE 21 model results with FEMA's SWEL results for the 1% annual chance event at 7 locations within and outside the study area. As seen from Table 4-4, the RMS error between the MIKE 21 model and FEMA's values is around 0.20 feet (2 inches) with a maximum difference of around 0.29 feet (3.5 inches) at locations well beyond the study area boundary. The results indicate that even though MIKE model uses the FEMA's 1% still water elevation values at the Battery as forcing boundary conditions, the MIKE model simulates peak water levels within acceptable range when compared to FEMA's published 1% SWEL in the vicinity of the study area.

Table 4-4. Comparison of MIKE 21 and FEMA 1% Stillwater Elevations

Location (X and Y coordinates in NAD 1983 NJ State Plane feet)	FEMA 1% Annual Chance Event SWEL (feet-NAVD)	MIKE 21 1% Annual Chance Event SWEL (feet-NAVD)	Difference (feet)
Hoboken Light Rail Station (X – 622,311.85, Y – 692,708.341)	10.94	11.08	0.14
Lackwanna Station Parking (X – 623,950.740, Y - 696,041.710)	10.93	11.07	0.14
Hotel Sheraton Parking Lot, Weehawken (X – 624,134.981, Y – 701,458.178)	10.84	10.98	0.14
Harborside HBLR Station Parking (X – 621,533.040, Y - 687,834.865)	11.19	11.22	0.03
Hudson Club, West New York (X – 629,067.927, Y - 709,835.981)	10.52	10.77	0.25
Palisades Medical Center (X – 631,799.201, Y - 714,220.078)	10.32	10.61	0.29
Whole Foods Market, Edgewater (X – 638,117.407, Y - 726,104.210)	9.78	10.06	0.28
Root Mean Square Error (RMSE)			**0.20**

4.5 Additional Tide Validation Model Simulation

Additional model validation simulation was performed to ensure that the model replicates the observed tidal data and produces reasonable results. Observed tidal data was obtained for a period of 15 days starting from May 1st, 2016 at NOAA's Battery gage (as shown in Figure 4-13) and from Port Authority of New York and New Jersey's (PANYNJ)'s gage at Hudson River Square Park, NY location (as shown in Figure 4-14). It should be noted that this limited tidal validation simulation was performed within the vicinity of the study area boundary only and not in areas further upstream.

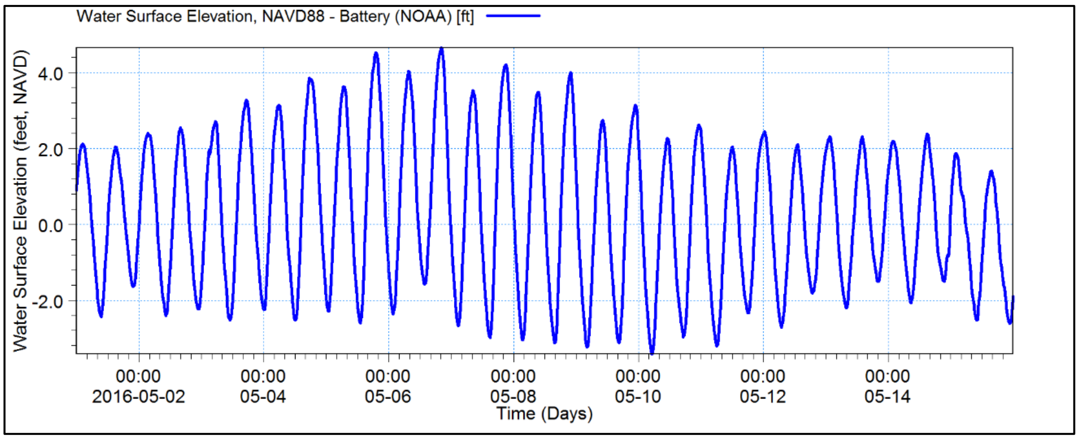


Figure 4-13. Time Series of Water Level at Battery between May 1st – May 15th 2016 (Source: NOAA)

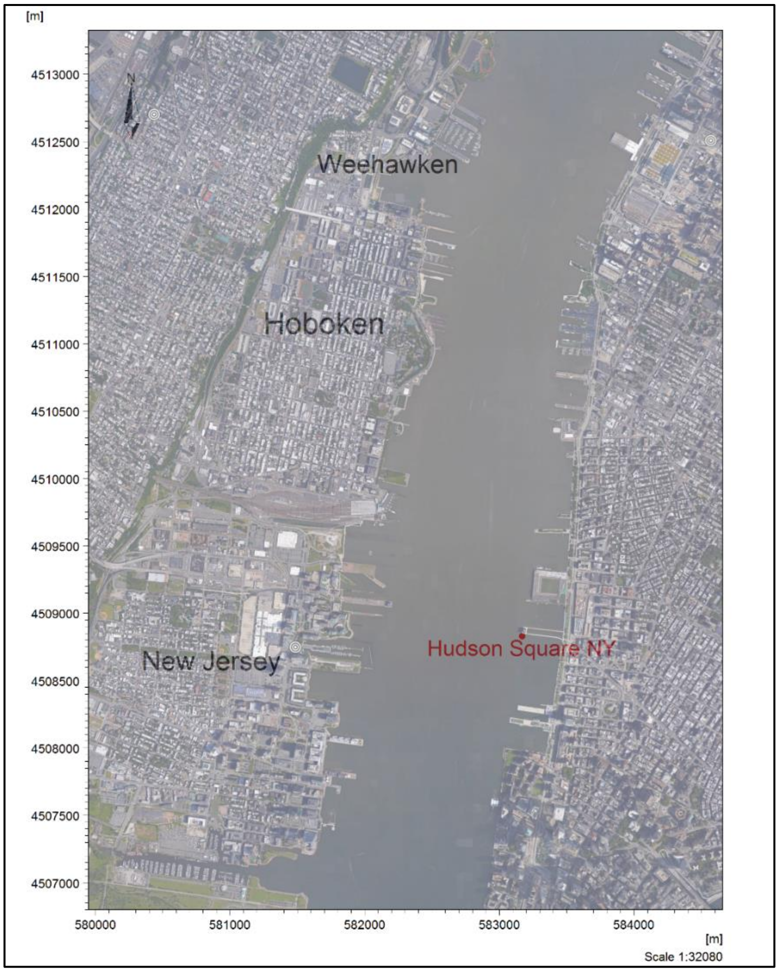


Figure 4-14. Location of PANYNJ's Gage at Hudson Square, NY

A 15-day tidal cycle condition was simulated using the MIKE 21 coastal model with the observed tidal boundary at the Battery and the simulated model results were compared with observed tidal data at PANYNJ's Hudson Square gage. Figure 4-15 shows the comparison of model simulated and observed tidal cycle between May 1st and May 15th, 2016 PANYNJ's Hudson Square gage. As seen from Figure 4-15, the MIKE 21 coastal model simulates the tidal amplitude and phase reasonably well with the observed gage data.

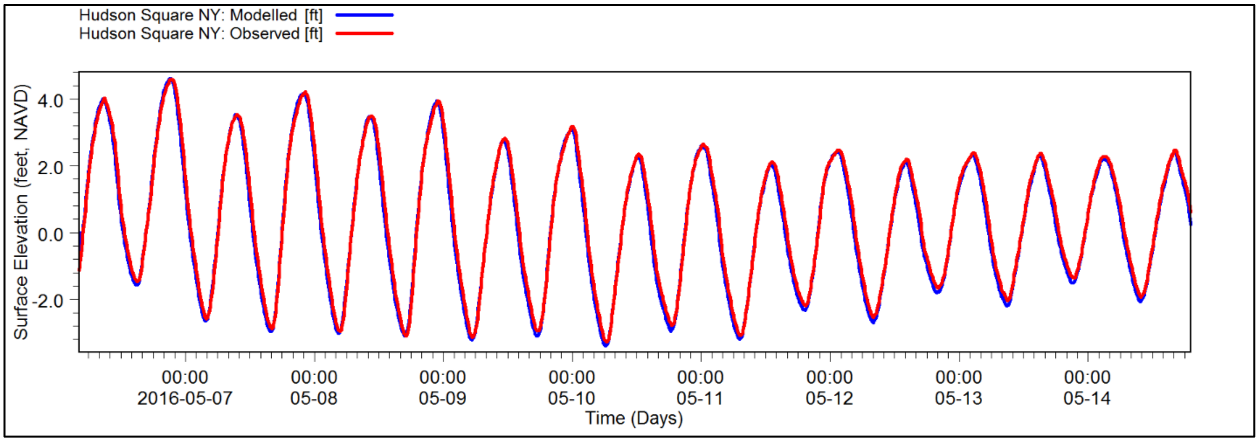


Figure 4-15. Comparison of Simulated (Blue) and Observed Tide (Red) Water Levels at Hudson Square, NY

4.6 Model Validation Results Discussion

As discussed in Sections 4.1– 4.4, the MIKE 21 coastal hydrodynamic model developed for the study area simulates the propagation of Superstorm Sandy's coastal storm surge within the study area with acceptable accuracy when compared to similar studies previously conducted in the study area (Blumberg et. al, 2015). The MIKE 21 coastal model shows that during Superstorm Sandy approximately 500 million gallons of floodwater flowed through NJ Transit yard and 185 million gallons of floodwater flowed through Weehawken Cove into the study area. Additionally, a meeting was held with Stevens on September 1, 2016 to discuss the coastal model. Key conclusions from that meeting can be found in Appendix C.

5 Evaluation of No-Action Alternative (NAA) for "Resist" Only

The No-Action Alternative (NAA) refers to an alternative with on-going or proposed/planned/ future projects except the Rebuild by Design-Hudson River project will be in place by year 2022 within the study area. The NAA represents the baseline conditions within the study area which will be used to compare the effectiveness of the proposed Rebuild by Design – Hudson River project's "Resist" alternatives within the study area under various coastal storm surge events (1%, 2% and 10% annual chance events). Section 3.8 provides a description of the water levels for various coastal storm events. The two primary projects as shown in Figure 5-1 that were included part of the "Resist" No-Action Alternative are as follows –

a. Long Slip Fill and Rail Enhancement Project by NJ Transit
b. Property development located between Long Slip Canal and 14th Street by Newport Associates

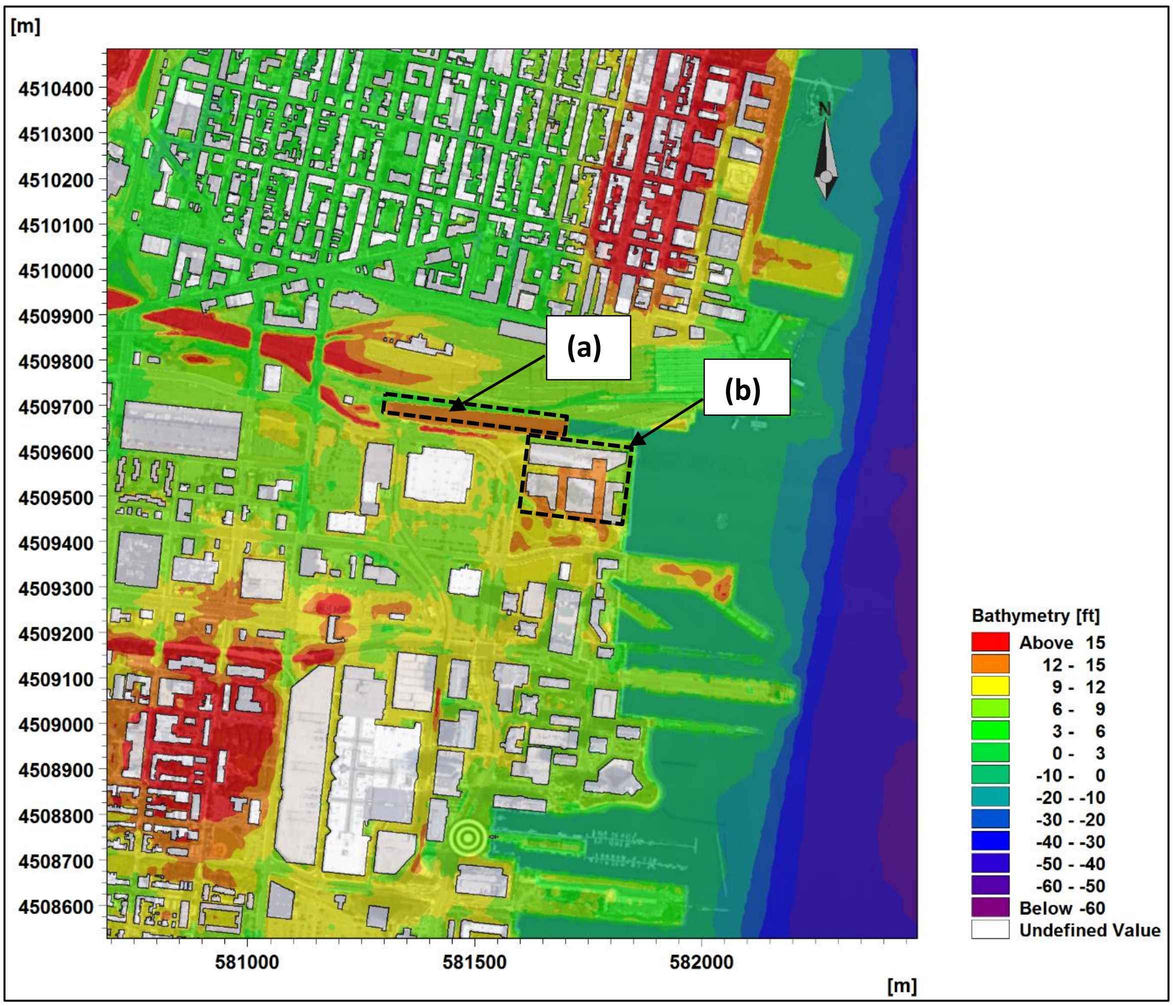


Figure 5-1. Projects included in the No-Action Alternative

NJ Transit provided the footprint and the proposed finished floor elevation of 14.5 feet-NAVD of the proposed Long Slip canal fill project. Newport Associates provided the proposed building footprints and roadway elevations within their proposed development area. The validated MIKE 21 model mesh was updated to reflect the footprint and proposed topographic elevations associated with these two major projects. During the course of the project, the City of Hoboken provided building footprint for the Hoboken Cove-Hudson Tea Building E located in the northern portion of the study area between Washington/Hudson Street and $14^{th}/15^{th}$ Streets. The building footprint of this on-going building project was included in the MIKE 21 model mesh for the NAA conditions.

The NAA conditions were simulated in the MIKE 21 coastal model by propagating the 10% (10-year), 2% (50-year) and 1% (100-year) - annual chance coastal storm surge event water levels from the Battery into the study area. Refer to Section 3.8 for the 10%, 2%, and 1 % annual chance coastal storm surge water levels. Figure 5-2 to Figure 5-4 shows the flood inundation extents and maximum water depths for the 10%-, 2%- and 1%-annual chance coastal storm surge events within the entire study area with focus on the north and southern portions of the study area.

As seen from Figure 5-2., during the peak of the 10% annual chance event (10-year), the coastal storm surge would flood portions of the Weehawken waterfront along Harbor Boulevard and NJ Transit's HBLR tracks in Weehawken. Simultaneously, the coastal storm surge travels through NJ Transit's Hoboken terminal and along the northern portion of the filled-in Long Slip canal onto Marin Boulevard into portions of Jersey City and Hoboken. The floodwaters travel along Observer Highway and Newark Avenue up to 1^{st} Street in Hoboken and along portions of Grove Street and Marin Boulevard in Jersey City.

As seen from Figure 5-3, during the peak of the 2% annual chance event (50-year), the coastal storm surge floods major portions of Hoboken, Weehawken and Jersey City. In the southern portion of the study area, the floodwaters travel through the NJ Transit yard with the filled in Long Slip canal in place into western portions of Hoboken and Jersey City. In the north portion of the study area, the floodwater travels through Weehawken Cove at two places – the walkway located along the Weehawken Cove waterfront and the walkway located along the Hoboken waterfront adjacent to the Harborside Lofts Condominiums near 15^{th} street. During the peak of the 2% annual chance coastal storm event (50-year), Hoboken Housing Authority and critical facilities such as North Hudson Sewerage Authority's (NHSA) waste water treatment plant located along the western edge of Hoboken is subject to approximately 4-6 feet of flooding as shown by the MIKE 21 coastal model simulation.

Figure 5-4 shows that during the peak of the 1% annual chance event (100-year) coastal storm surge floods major portions of Hoboken, Weehawken and Jersey City with slightly higher flood depths and extent than the 2% annual chance event (50-year). The flood pathways are similar to the 2% annual chance flood event but the flood extent and maximum flood depths for the 1% annual chance event (100-year) are similar to those simulated for Superstorm Sandy (the difference in maximum water level is less than 0.02 feet).

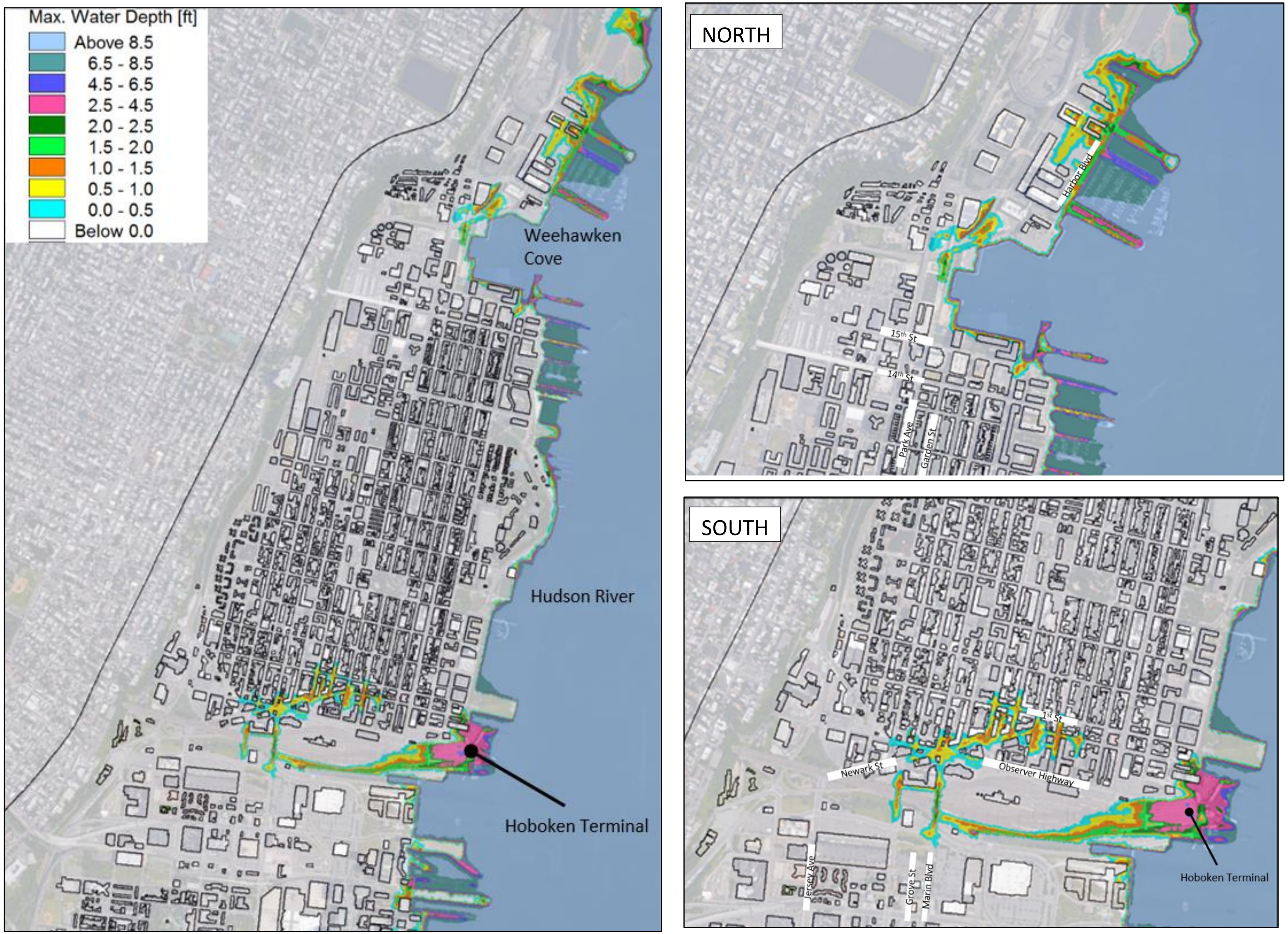


Figure 5-2. Flood Inundation and Maximum Water Depth in the Study Area during a 10% (10-year) Annual Chance Coastal Storm Surge Event

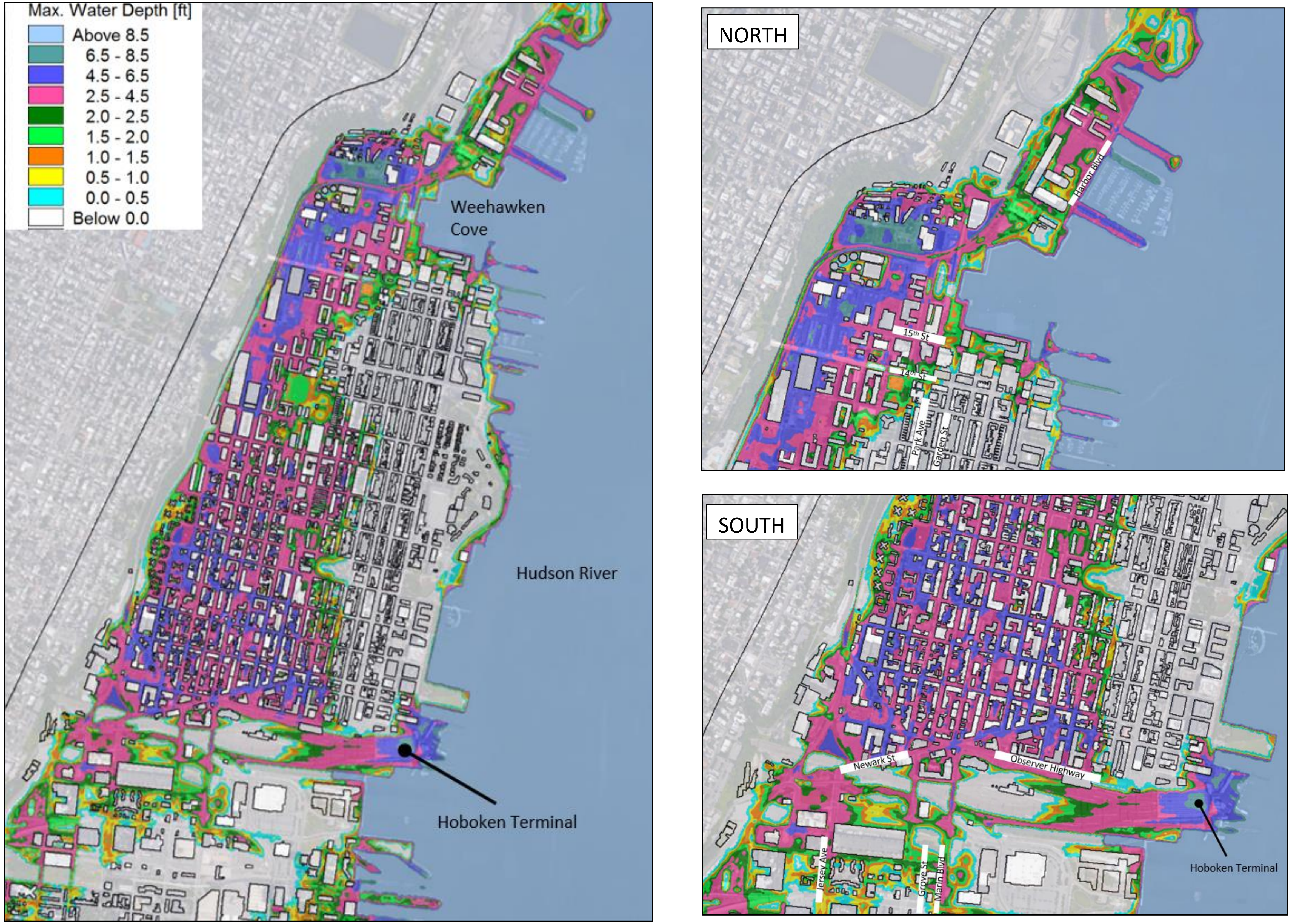


Figure 5-3. Flood Inundation and Maximum Water Depth in the Study Area during a 2% (50-year) Annual Chance Coastal Storm Surge Event

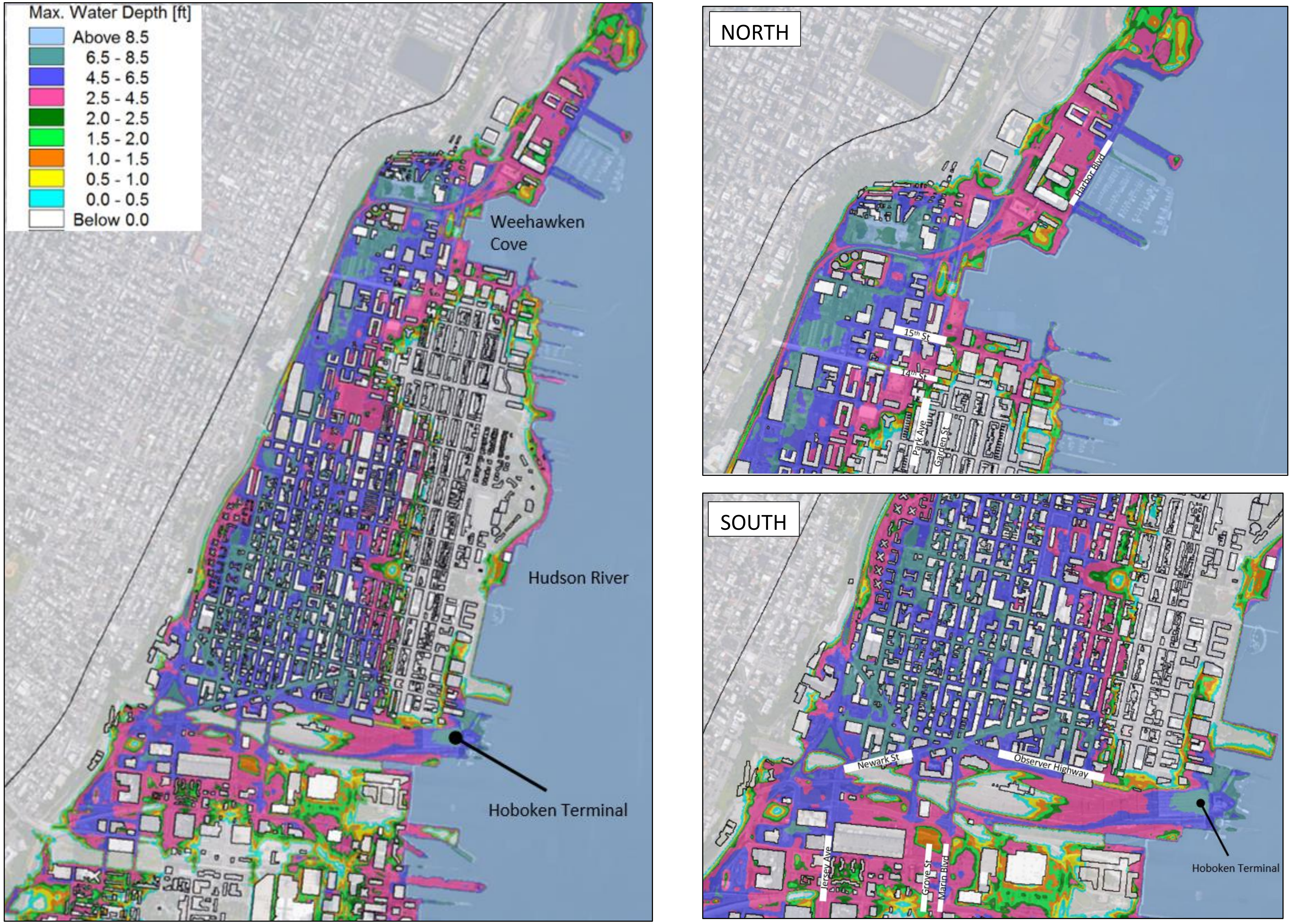


Figure 5-4. Flood Inundation and Maximum Water Depth in the Study Area during a 1% (100-year) Annual Chance Coastal Storm Surge Event

6 Evaluation of "Resist" Alternatives

The flood pathways in the No-Action Alternative (NAA) for various coastal storm surge events were analyzed and were used to recommended locations for "Resist" alignments within the study area. Three preliminary "Resist" alternatives were developed to provide varying levels of coastal flood risk reduction benefits and are described in detail in Task 5- Feasibility Assessment report. A preliminary evaluation for one out of the three proposed "Resist" alternatives was carried out to test the effectiveness of the alignments to provide flood risk reduction benefits and evaluate any potential residual flooding impacts from this alternative using the MIKE 21 coastal model. This preliminary evaluation was carried out on Alternative 3 only initially and the coastal model results from this alternative were used to inform any refinements to the three alternatives. During this preliminary evaluation, major potential residual flooding impacts were identified and solutions were developed to minimize these impacts. The three preliminary alternatives were updated with the proposed solutions and the final "Resist" alternatives were developed for further evaluation. Each of the three resist alternatives will be a combination of hard infrastructure and soft landscaping features that act as barriers along the coast during exceptionally high tide and/or storm surge events. A detailed description of the three final "Resist" alternatives is provided in the Task 5 – Feasibility Assessment report. It should be noted that for each alternative, there are two options along the NJ Transit rail yard – Option 1 that follows the proposed Hoboken Yards Redevelopment boundary and Option 2 that follows the existing property boundary of NJ Transit along the Observer Highway. For the evaluation purposes using the MIKE 21 coastal model, the Option 1 "Resist" alignment was considered as part of each alternative. Coastal model simulations were not performed with the Option 2 "Resist" alignment.

6.1 Modeling Methodology

The alignments were developed for each alternative using Geographic Information System (GIS) and Computer Aided Design (CAD) techniques. There are two modeling options to evaluate the effectiveness of "Resist" alignment in MIKE 21 coastal model –

Option 1 – Represent the alignment by modifying topography in the MIKE 21 coastal model mesh

Option 2 – Represent the alignment as a "dike" structure in MIKE 21

Both of these options would allow to evaluate the effectiveness of the "Resist" alignment to reduce flooding risks from coastal storm surge within the study area and inform potential residual flooding impacts within the study area. It should be noted that both these options have limitations to represent the exact size and configuration of the proposed "Resist" alignments. For example, Option 1 would require very detailed and fine cell size in the MIKE 21 model mesh to represent the "Resist" structures that are between 2-3 feet wide. Greater level of effort is required to represent structures that are not fully designed with the fine cell size and is not recommended to be used as the feasibility assessment stage of the project. Option 2 which requires the use of "dike" feature in MIKE 21 utilizes the cells in the model mesh that are located immediately on the dry side of the proposed “Resist” alignment. Figure 6-1 shows a representation of using Option 2 “dike” feature in MIKE 21 where the blue line is the actual centerline of the dike structure and the red line is the actual cell faces that are used in the model computation.

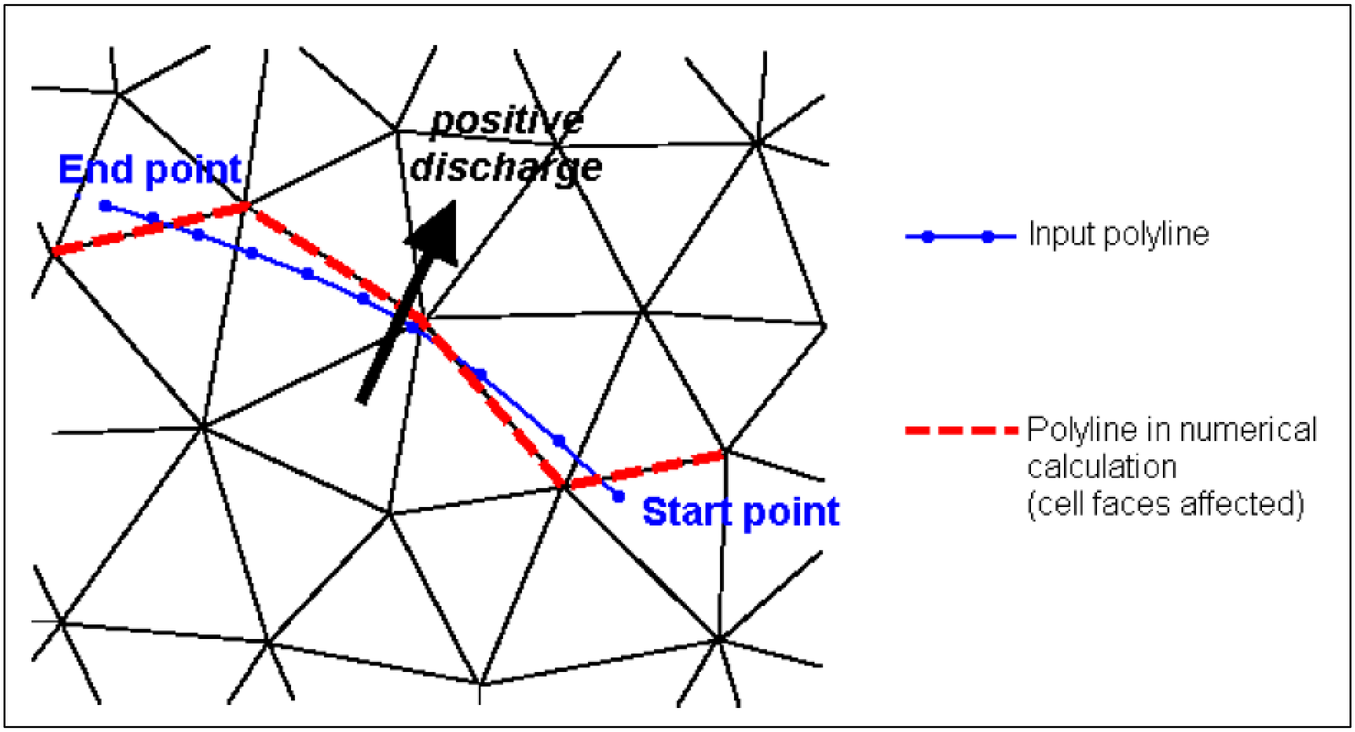


Figure 6-1. Representation of “Resist” Alignment in MIKE 21 Model using “Dike” Feature

As seen from Figure 6-1, some of the cells that are on the “dry” side of the alignment are considered as part of the dike and the MIKE 21 model shown them as “wet” during the model computations. However, the area that is considered “wet” in the model computation is extremely small and will not significantly affect the model results. The Option 2 technique is a faster way to evaluate the feasibility of multiple “Resist” alternatives. For the purposes of the feasibility study, Option 2 technique was utilized to evaluate the three “Resist” alternatives. However, it is recommended that during the design phase for the preferred alternative, Option 1 technique should be adopted to evaluate any potential residual flooding impacts from the preferred alternative.

A statistical analysis was performed to obtain the maximum water depths for various coastal storm surge events in the No-Action Alternative and “Resist” Alternative scenarios. Tools within DHI’s MIKE model program were used to subtract the “NAA” maximum water depths over the “Resist” maximum water depths to obtain the difference in the maximum water depths. A positive difference value that is over 0.04 feet (0.48 inches) is considered as a residual flooding impact per NJAC 7:13 regulations and any negative difference value (less than 0 feet) is considered as a flood risk reduction benefit. The potential residual flooding values were symbolized as pink color and flood risk reduction benefit values were symbolized as green color in the difference plots. It should be noted that the "interpolated" values option (shaded contour option) in the MIKE model was used to develop the maximum water depth and difference in water depth plots. The interpolated values provides a better representation of the flooding extents for display purposes only; however the "actual" values option (box contour option) provides the actual maximum water depth at specific locations within the model domain.

6.2 Evaluation of Preliminary "Resist" Alignment Alternatives

Figure 6-2 shows the preliminary alignment for the three proposed "Resist" alternatives – Alternative 1 (Waterfront), Alternative 2 (15th Street) and Alternative 3 (Alleyway). Each of these three alternatives were developed as part of the Task 5 – Feasibility Assessment and with significant input from the community.

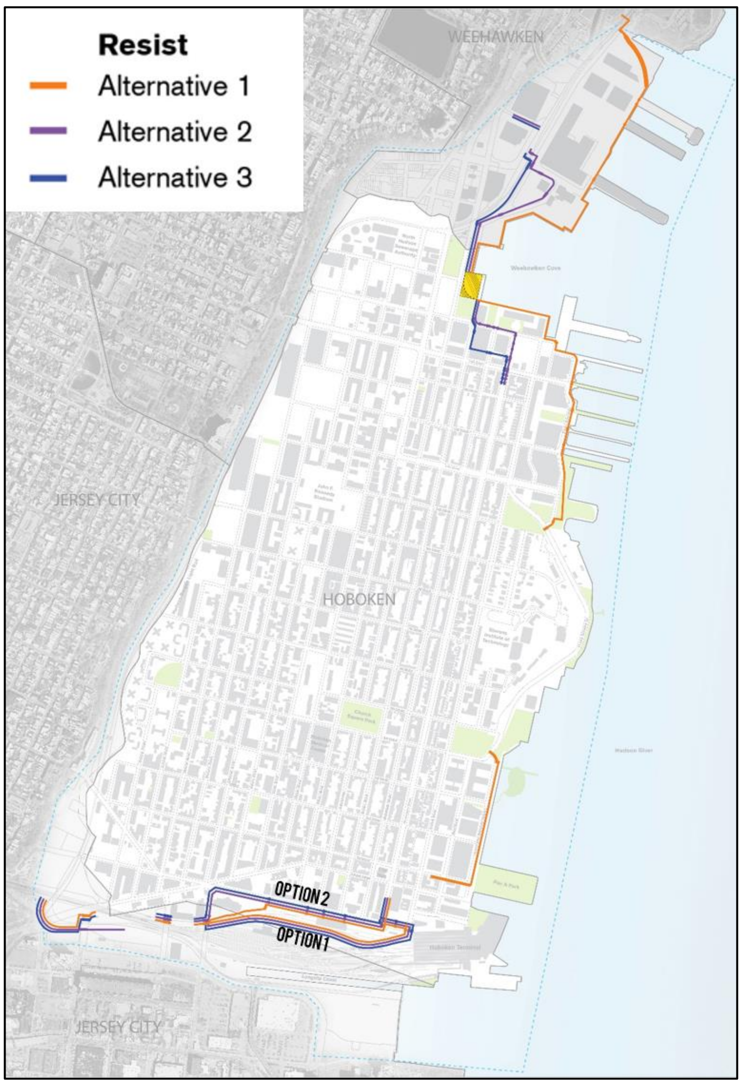


Figure 6-2. Proposed Preliminary Alignments for the Three "Resist" Alternatives

In order to evaluate effectiveness of the “Resist” alternative and any potential major residual flooding impacts, Alternative 3 as shown in Figure 6-3 which provides the least level of flood risk reduction benefits among the three alternatives and has highest number of properties on the unprotected side of the alignment was chosen to be evaluated first with the MIKE 21 coastal hydrodynamic model. Model simulations were performed to evaluate the effects of the 10%, 2% and 1% annual chance coastal storm surge events with the preliminary Alternative 3 (Alleyway) alignment in place and were compared it with the No-Action Alternative (NAA). These model results were then used to evaluate potential major residual flooding and the need for additional mitigation measures for Alternative 3 and its applicability to remaining two alternatives.

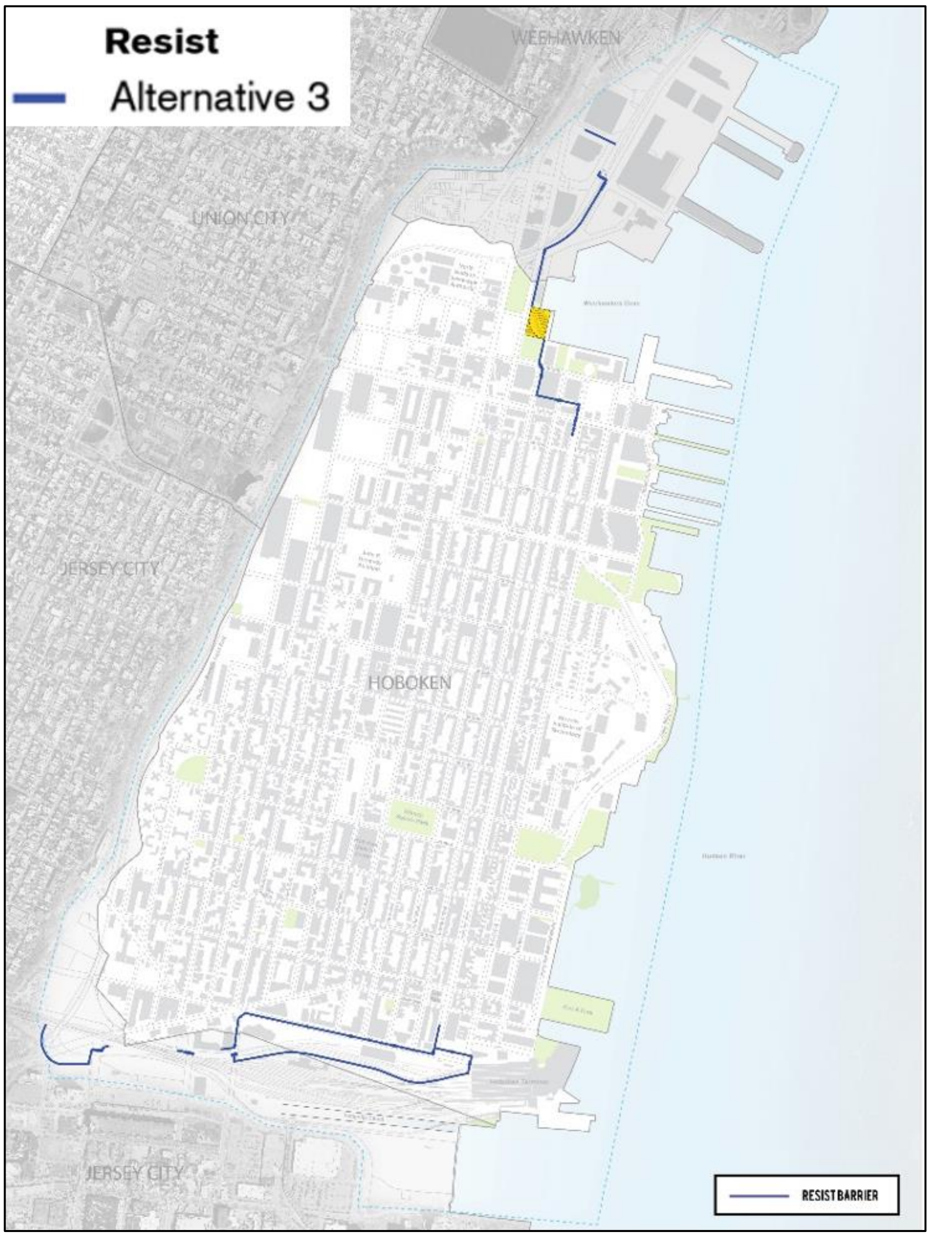


Figure 6-3. Proposed Preliminary Alignment for Alternative 3 (Alleyway)

Figure 6-4 compares the maximum flood extent for the 10% annual chance coastal storm surge event in the No-Action Alternative (NAA) and with the preliminary Alternative 3 (Alleyway). Figure 6-5 provides the difference in maximum water depth spatial plots between these two alternatives at the north and the south end of the study area. As seen from these figures, the MIKE 21 coastal model shows that the preliminary Alternative 3 (Alleyway) will result in residual flooding in portions of Jersey City and Weehawken; however at the same time it would provide flood risk reduction benefits to portions of Hoboken and Weehawken that are located on the dry side of the “Resist” alignment.

During the 10% annual chance coastal storm surge event and with the preliminary Alternative 3 (Alleyway) in place, the coastal storm surge will travel through NJ Transit yard onto Marin Boulevard but due to the “Resist” barrier located at Marin Boulevard, the model shows that coastal storm surge would reverse its path and instead flow into Jersey City along 18th street. During the No-Action Alternative and without a barrier in place along Marin Boulevard, this coastal storm surge would normally flow into Hoboken.

In the northern portion of the study area, during the 10% annual chance coastal storm surge event, the coastal storm surge would overtop the low-lying sections of the walkway located along Weehawken Cove, but due to the “Resist” barrier located parallel to the HBLR tracks, the model shows the coastal storm surge would reverse its path and instead flow along Harbor Boulevard and will result in residual flooding along the proposed ‘Resist” barrier under the Park Avenue bridge.

Figure 6-6 and Figure 6-7 show the maximum flood extent for the 2% annual chance coastal storm surge event and the difference in maximum water depth spatial plots between the NAA and the preliminary Alternative 3 (Alleyway), respectively. Similar to the 10% annual chance coastal storm surge event, for the 2% annual chance coastal storm surge event, the MIKE 21 coastal model shows that the preliminary Alternative 3 (Alleyway) will result in residual flooding in portions of Hoboken, Jersey City and Weehawken; however at the same time it would provide flood risk reduction benefits to portions of Hoboken, Jersey City and Weehawken that are located on the dry side of the “Resist” alignment.

Figure 6-8 and Figure 6-9 show the maximum flood extent for the 1% annual chance coastal storm surge event and the difference in maximum water depth spatial plots between the NAA and the preliminary Alternative 3 (Alleyway), respectively. As seen from Figure 6-9, in the 1% annual chance coastal storm event, the MIKE 21 coastal model shows no residual flooding in portions of Jersey City that previously were subject to residual flooding in the 10% and 2% annual chance coastal storm events. However, the model shows that portions of NJ Transit’s Hoboken terminal yard and portions of Weehawken Cove will be subject to residual flooding during the 1% annual chance coastal storm event.

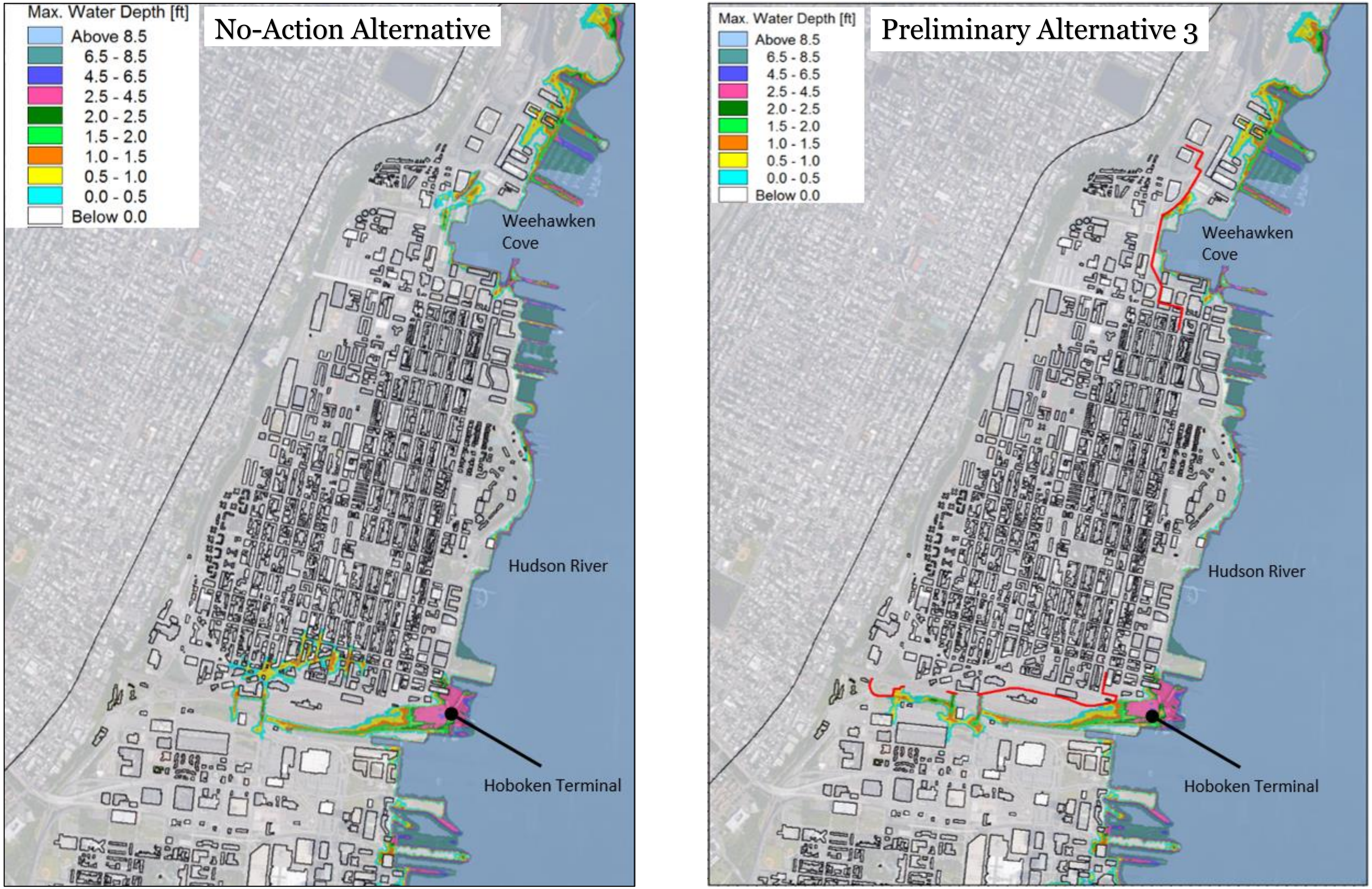


Figure 6-4. Comparison of the Flood Inundation and Maximum Water Depth in the Study Area during a 10% (10-year) Annual Chance Coastal Storm Surge Event

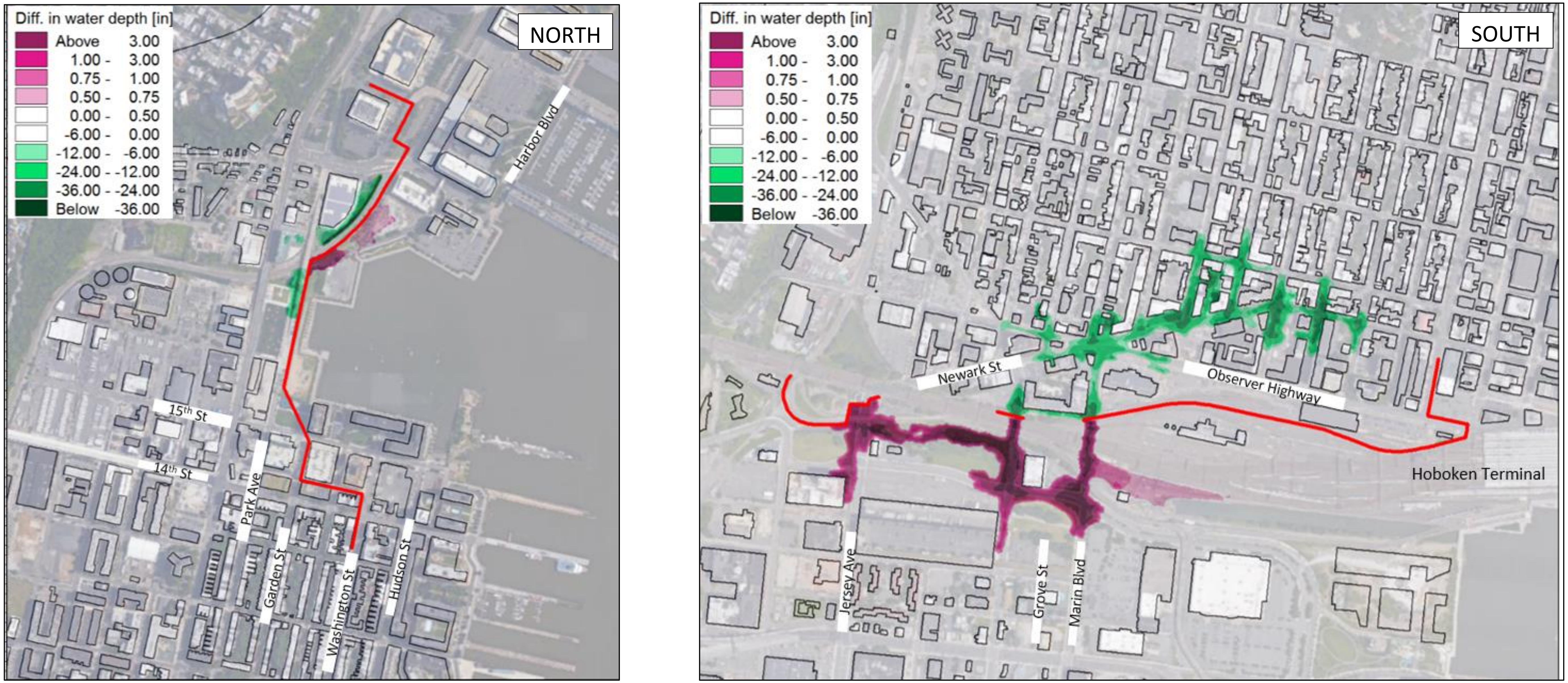


Figure 6-5. Difference Plots for the 10% (10-year) Annual Chance Coastal Surge Event

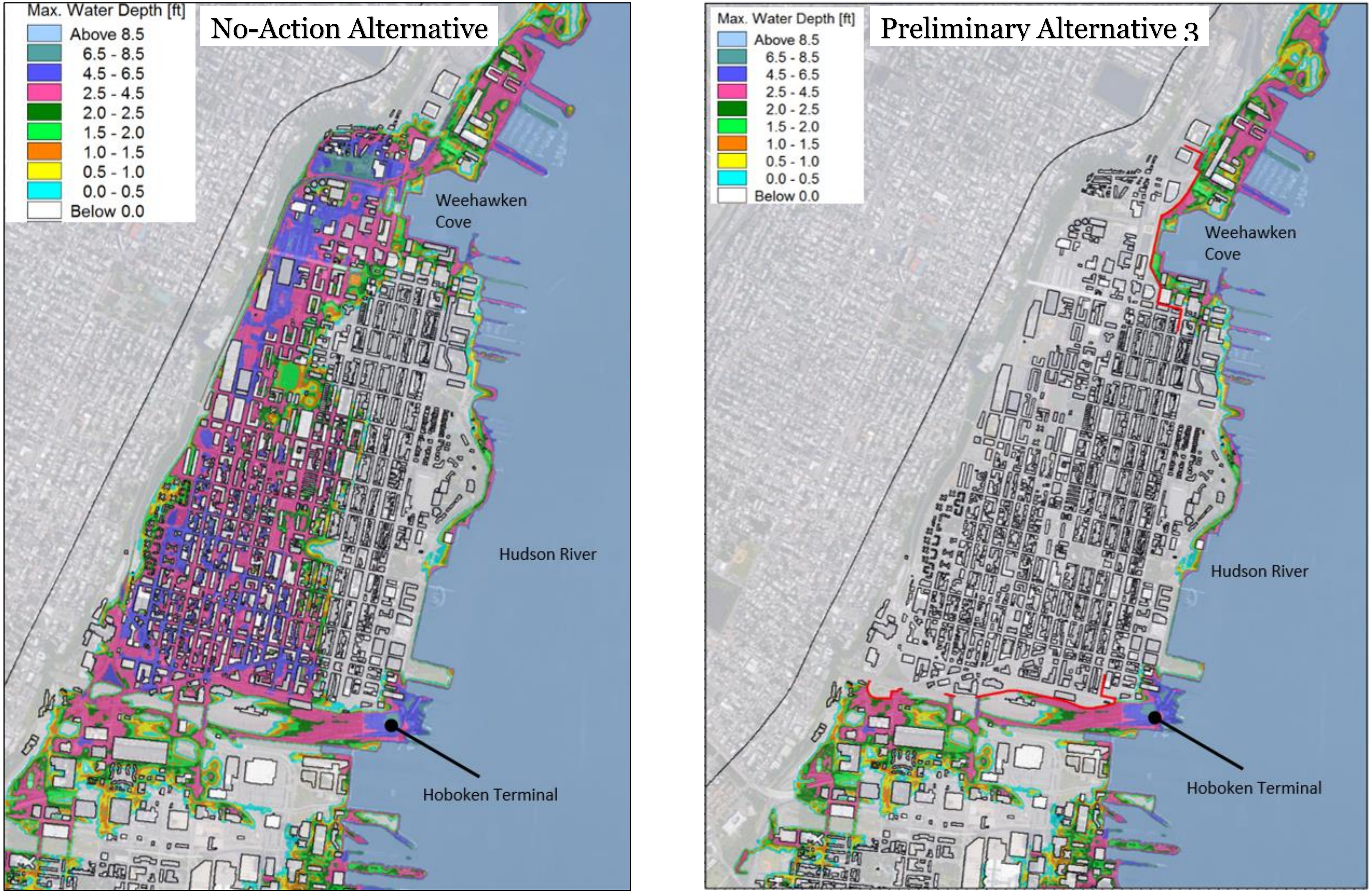
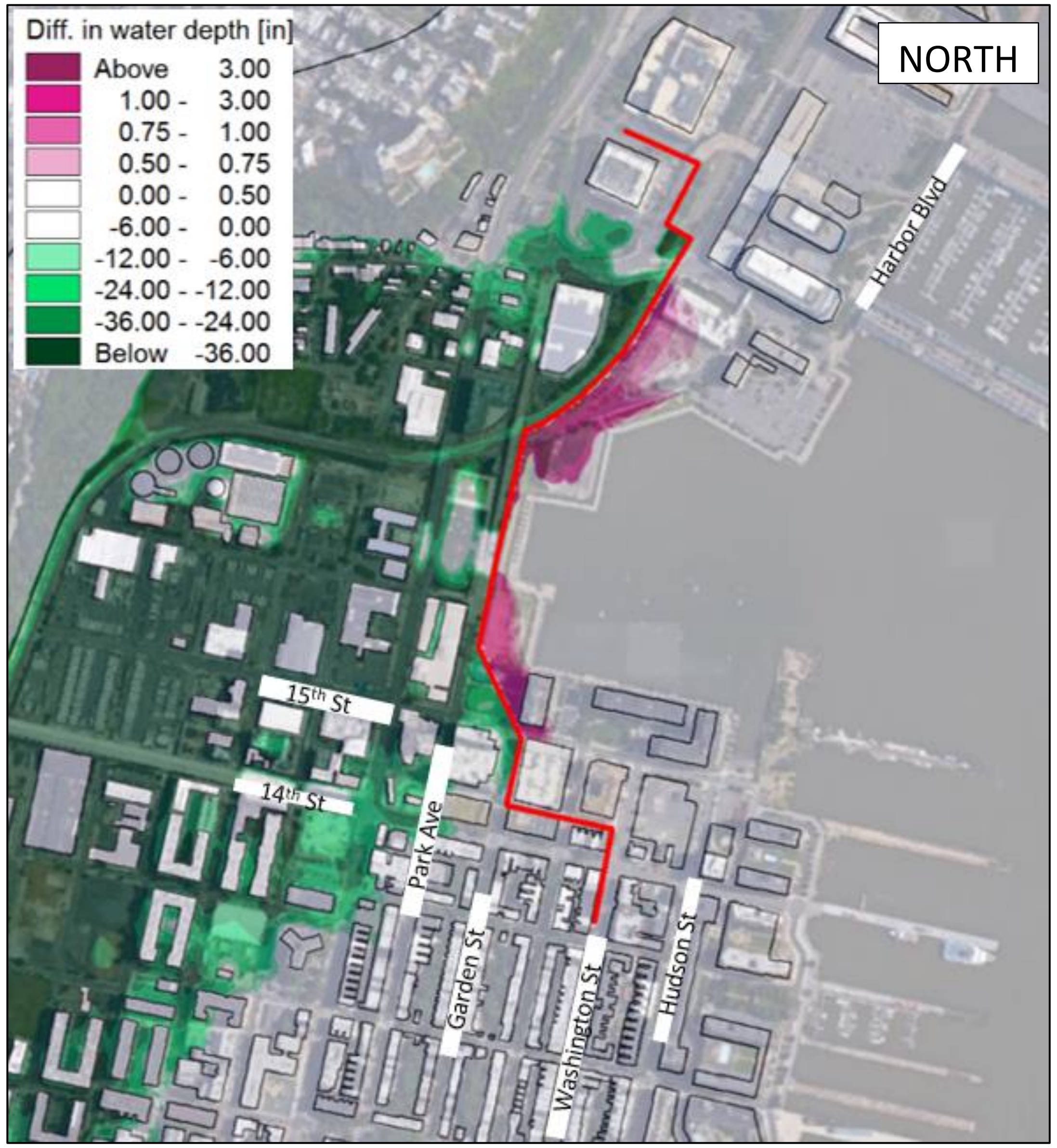


Figure 6-6. Comparison of the Flood Inundation and Maximum Water Depth in the Study Area during a 2% (50-year) Annual Chance Coastal Storm Surge Event



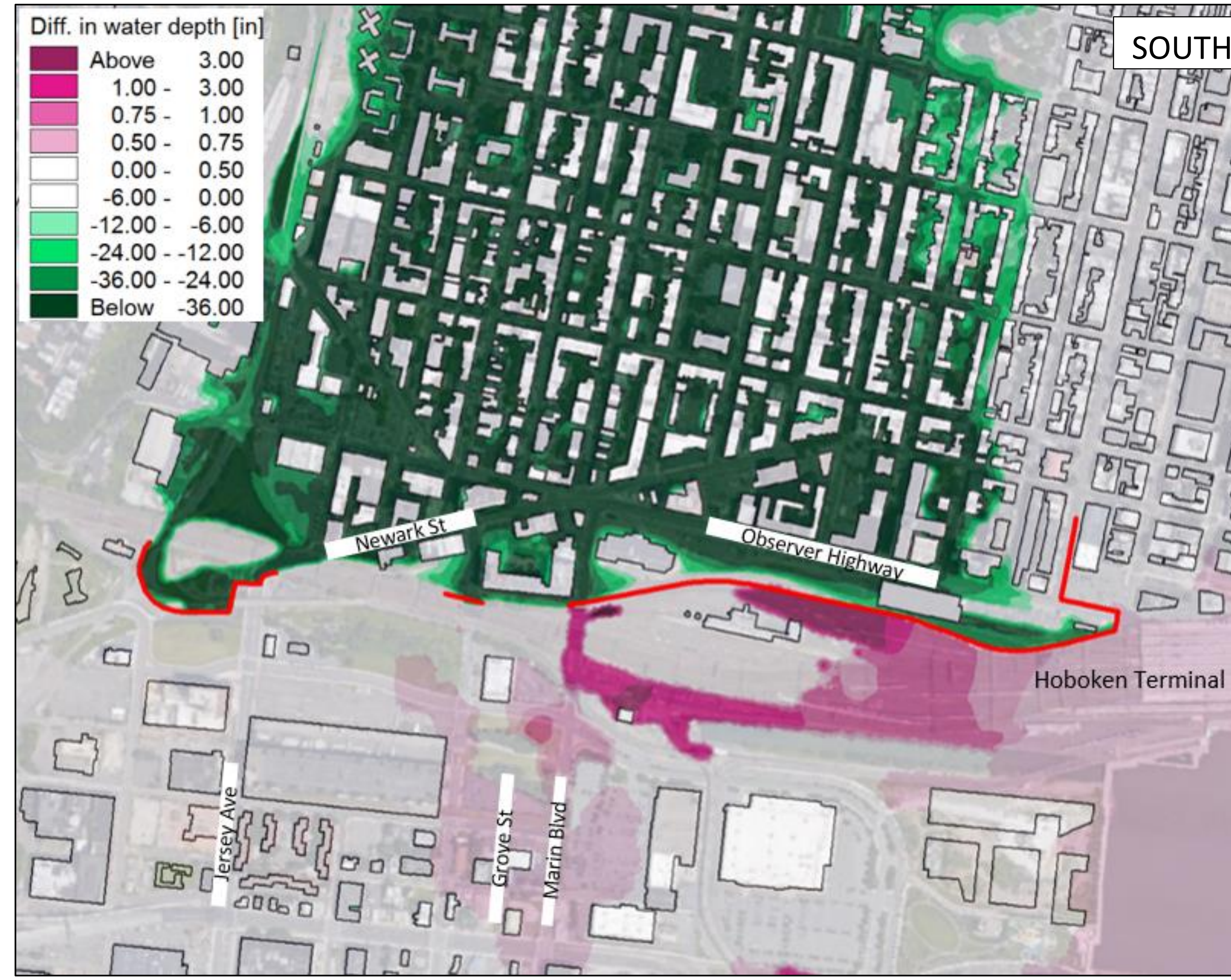


Figure 6-7. Difference Plots for the 2% (50-year) Annual Chance Coastal Surge Event

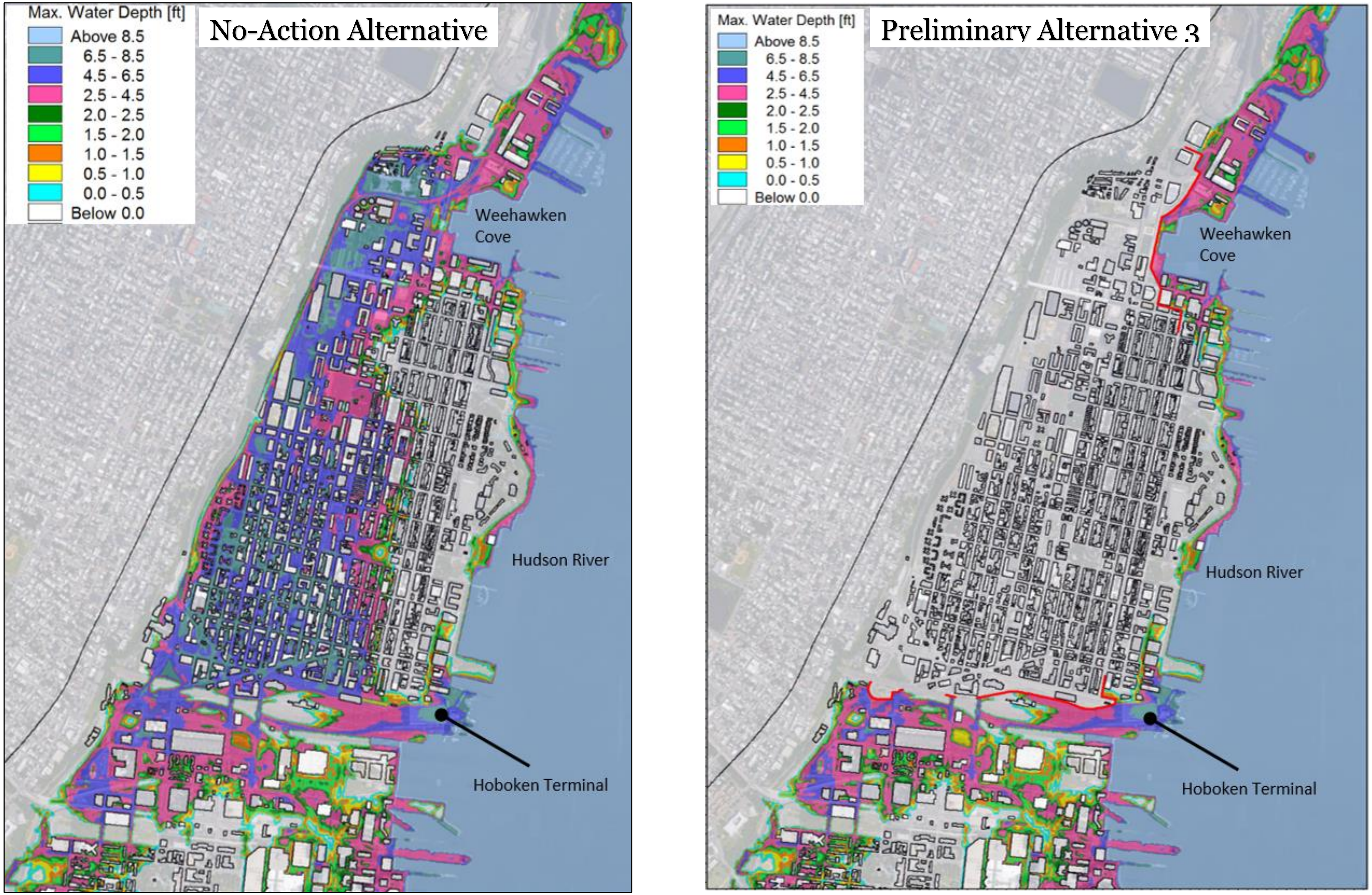


Figure 6-8. Comparison of the Flood Inundation and Maximum Water Depth in the Study Area during a 1% (100-year) Annual Chance Coastal Storm Surge Event

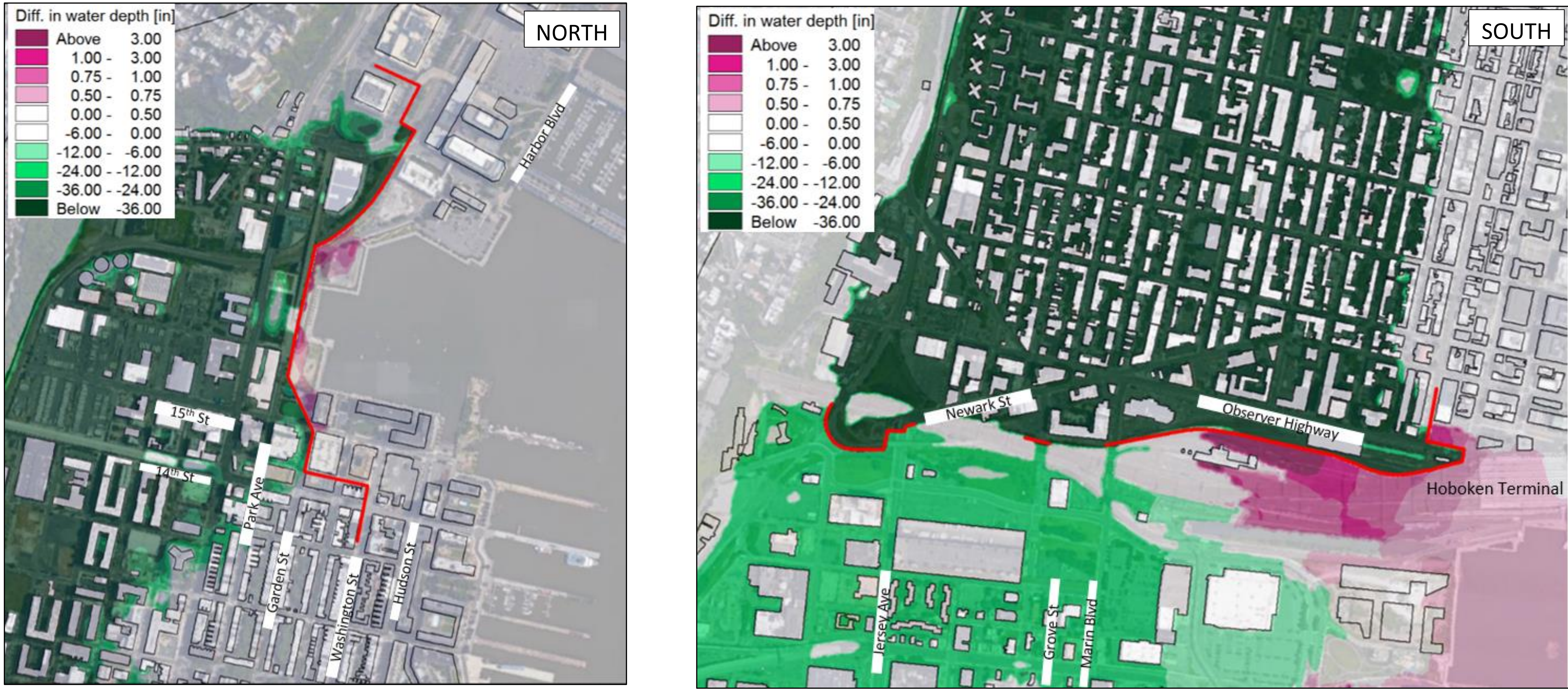


Figure 6-9. Difference Plots for the 1% (100-year) Annual Chance Coastal Surge Event

6.3 Recommendation for Additional "Resist" Components

Since the MIKE 21 model simulated significant residual flooding due to the preliminary "Resist" Alternative 3 (Alleyway) alignment, as shown in Figure 6-10, it was recommended to consider the following additional "Resist" components to mitigate these significant residual flooding increases –

- Barrier on Marin Boulevard along the NJ Transit's property boundary
- Barrier on 18th Street along the NJ Transit's property boundary
- Elevate the low-lying sections of the walkway in Weehawken Cove to an approximate elevation of 9' NAVD (only applicable for Alternative 2 and 3)

These additional "Resist" components were included as applicable to all the three alternatives as shown in Figure 6-11. The effectiveness of these three final alternatives to provide flood risk reduction benefits and to minimize the potential residual flooding risks from various coastal storm surge events were then evaluated using the MIKE 21 coastal model.

Figure 6-10. Location of the Three Additional Components (Shown in Green Boxes) for Alternative 3

Figure 6-11. Plan showing Alignments for the Final Three "Resist" Alternatives

6.4 Evaluation of Final “Resist” Alternative 1

Alternative 1 (Waterfront) alignment’s resist structure generally follows the waterfront from the Lincoln Tunnel in Weehawken south to Weehawken Cove where it is envisioned that a boathouse (alternatively funded) will be incorporated into the structure. In addition, a bermed and terraced Cove Park could be incorporated into the southwest corner of Weehawken Cove. This would include existing undeveloped land as well as the currently-developed Cove Park (adjacent to Harborside Lofts at 1500 Garden Street). Potential amenities at this park may include playgrounds, lawn areas, game courts, and a viewing deck overlooking Weehawken Cove. The alignment continues around the waterside of the Tea Building and heads south in front of Maxwell Place. The Resist structure continues south along the waterfront to the intersection of Sinatra Drive North and Frank Sinatra Drive, just south of Maxwell Place Park where the ground elevation begins to rise, and the wall tapers down to meet high ground. There will be a series of gates along the waterfront to allow access onto piers and across road intersections during non-flood conditions. Possible designs for the Resist structure in this area include an elevated promenade north of the Tea Building, raised terraced parks adjacent to Shipyard Park, and bermed/terraced park areas at the location of the existing Maxwell Place Park.

The Resist structure also has a component along Sinatra Drive from 4th Street to 1st Street, in southern Hoboken, where the design may consist of an elevated walkway and park space that ties into a deployable system running east/west on 1st Street. In the southern portion of the Study Area, two options were analyzed: Option 1 features an alignment south of Observer Highway, within the rail yard (south of the proposed Hoboken Yard Redevelopment Area). Option 2 includes an alignment along Observer Highway from Washington Street to Marin Boulevard, on an alignment that runs behind NJ Transit offices. The alignment includes gates for access at various locations including the Marin Boulevard, Grove Street and Newark Avenue underpasses beneath the rail lines, as well as protection where the HBLR tracks pass below the NJ Transit overpass in the southwest corner of the study area. Urban amenities in these areas include lighting, murals, seating, plantings and wayfinding/signage.

The effectiveness of the final Alternative 1 alignment to provide flood risk reduction benefits and evaluate any potential residual flooding was performed using the MIKE 21 coastal model for the 10%- , 2%-, and 1% annual chance coastal storm surge events. Figure 6-12 and Figure 6-13 show the maximum flood extent and maximum flood depths for the 10% annual chance coastal storm surge event with the “Resist” Alternative 1 and difference in maximum water depth spatial plots between the NAA and the final Alternative 1 (Waterfront) in north and south portions of the study area, respectively.

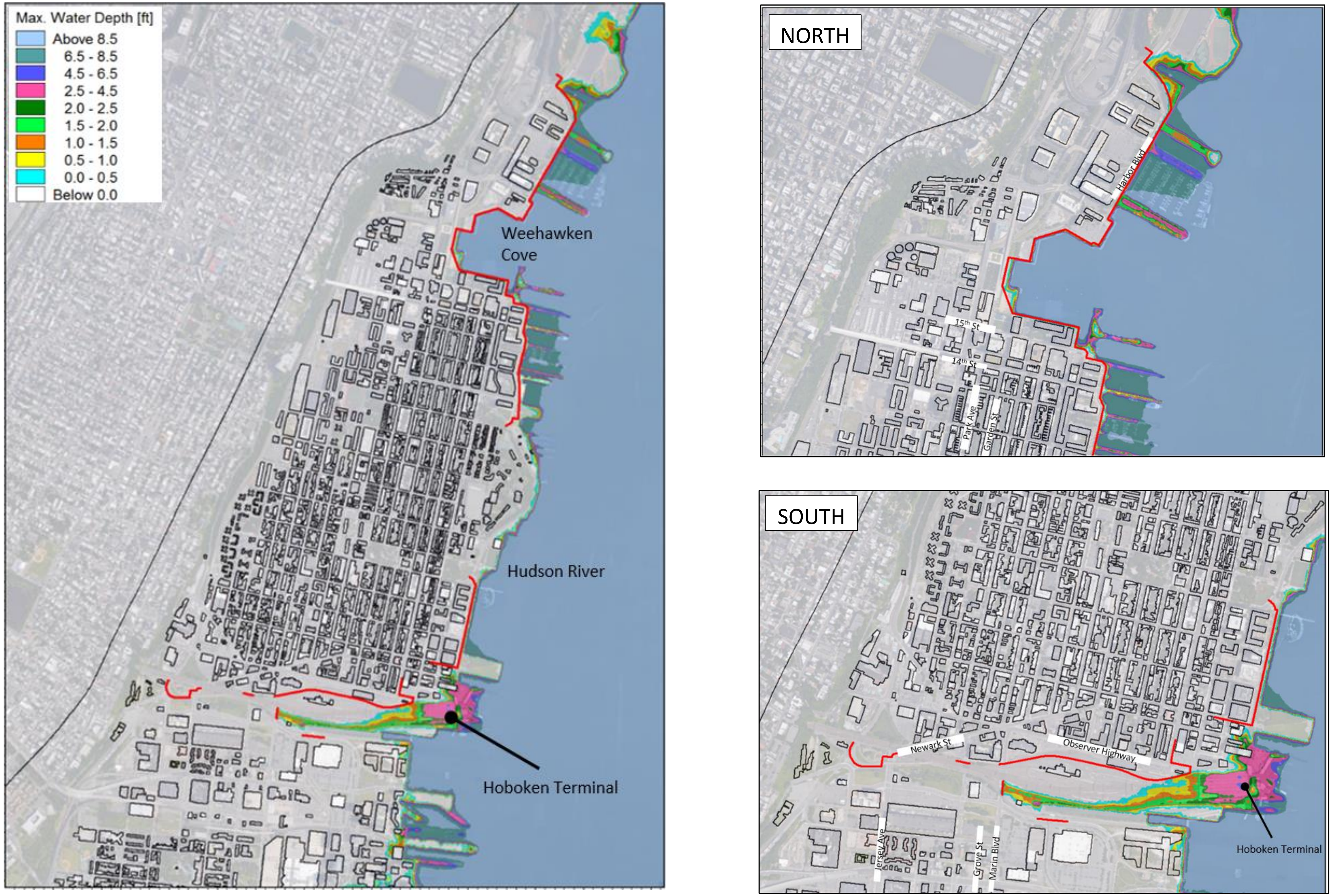


Figure 6-12. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 10% Annual Chance Coastal Storm Surge Event (10-Year) with Alternative 1 (Waterfront)

Figure 6-13. Difference in Maximum Water Depths between NAA and Alternative 1 for 10% Annual Chance Storm Surge (10-Year) Event in Northern and Southern Portions of Study Area

As seen from Figure 6-13, the green color shows the flood risk reduction benefits whereas the pink color shows the potential residual flooding impacts due to Alternative 1's "Resist" alignment. Alternative 1 provides flood risk reduction benefits for the study area with potential residual flooding impacts in the NJ Transit yard. Due to the additional "Resist" components, the coastal storm surge during a 10% annual chance event does not travel outside the NJ Transit yard, thus providing flood risk reduction benefits to portions of Jersey City. As seen from Figure 6-12, this alternative provides flood risk reduction benefits in southern and northern portions of Hoboken along with portions of Weehawken in the northern portion of the study area that were previously subject to flooding with water depths ranging approximately from 0 – 2 feet in the NAA during a 10% annual chance event.

Figure 6-14 and Figure 6-15 shows the maximum flood extent and maximum flood depths for the 2% annual chance coastal storm surge event (50-year) with the "Resist" Alternative 1 and difference in maximum water depth spatial plots between the NAA and the final Alternative 1 (Waterfront) in north and south portions of the study area, respectively. As seen from Figure 6-14, this alternative provides flood risk reduction benefits for western, southern and northern portions of Hoboken,; western portions of Weehawken and portions of Jersey City located within the study area that were previously subject to flooding with water depths ranging approximately from 0 – 7 feet in the NAA during a 2% annual chance event.

Figure 6-16 and Figure 6-17 shows the maximum flood extent and maximum flood depths for the 1% annual chance coastal storm surge event (100-year) with the "Resist" Alternative 1 and difference in maximum water depth spatial plots between the NAA and the final Alternative 1 (Waterfront) in north and south portions of the study area, respectively. As seen from Figure 6-16, this alternative provides flood risk reduction benefits for western, southern and northern portions of Hoboken,; western portions of Weehawken and portions of Jersey City located within the study area that were previously subject to flooding with water depths ranging approximately from 0 – 8 feet in the NAA during a 2% annual chance event.

As seen from Figure 6-13 to Figure 6-17, Alternative 1 provides the flood risk reduction benefits from all the three coastal storm events for a majority of the study area that includes most of Hoboken with the exception of a small portion of waterfront between 5th Street and 10th Street; and portions of Weehawken and Jersey City that are located within the study area boundary.

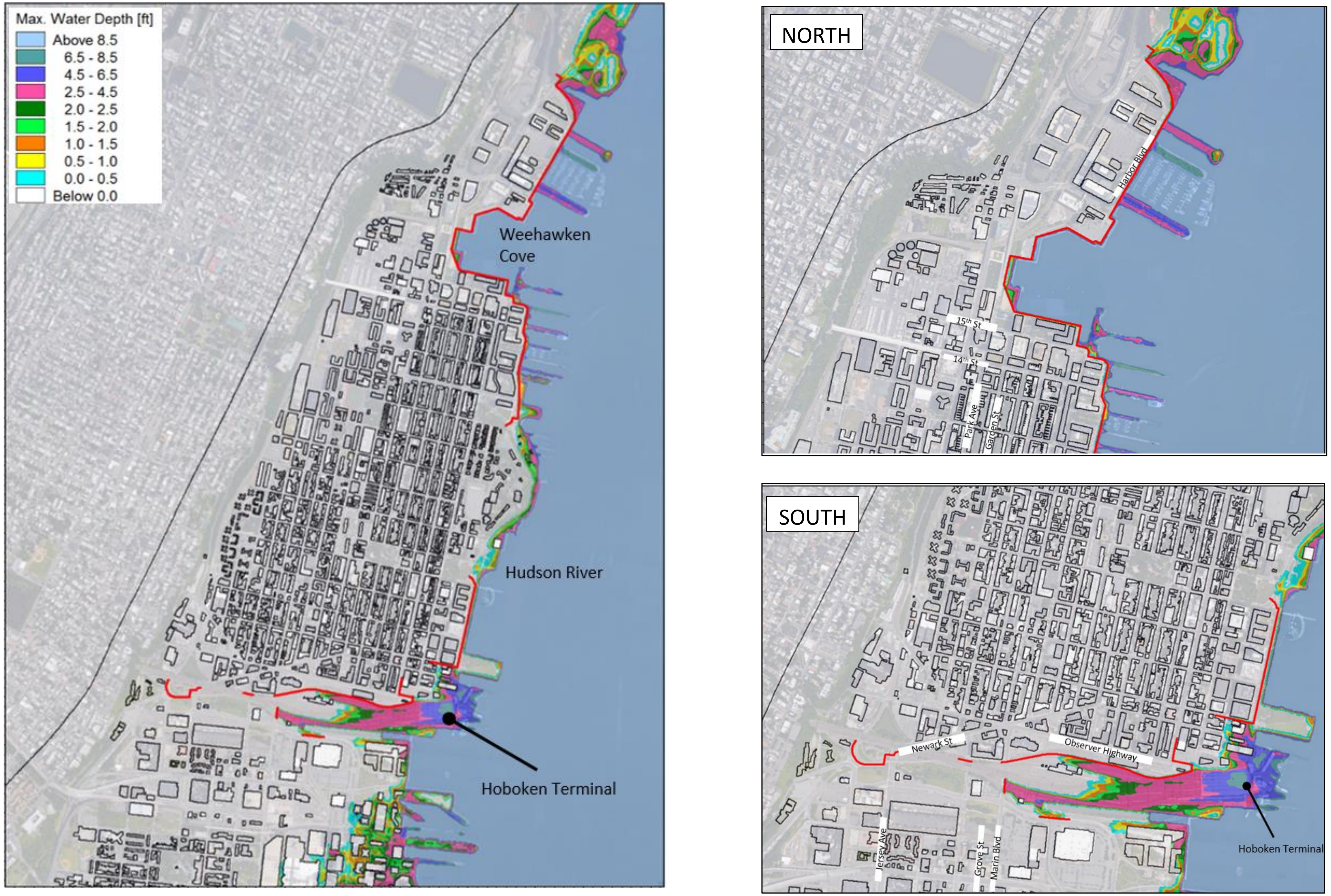


Figure 6-14. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 2% Annual Chance Coastal Storm Surge Event (50-Year) with Alternative 1 (Waterfront)

Figure 6-15. Difference in Maximum Water Depths between NAA and Alternative 1 for 2% Annual Chance Storm Surge (50-Year) Event in Northern and Southern Portions of Study Area

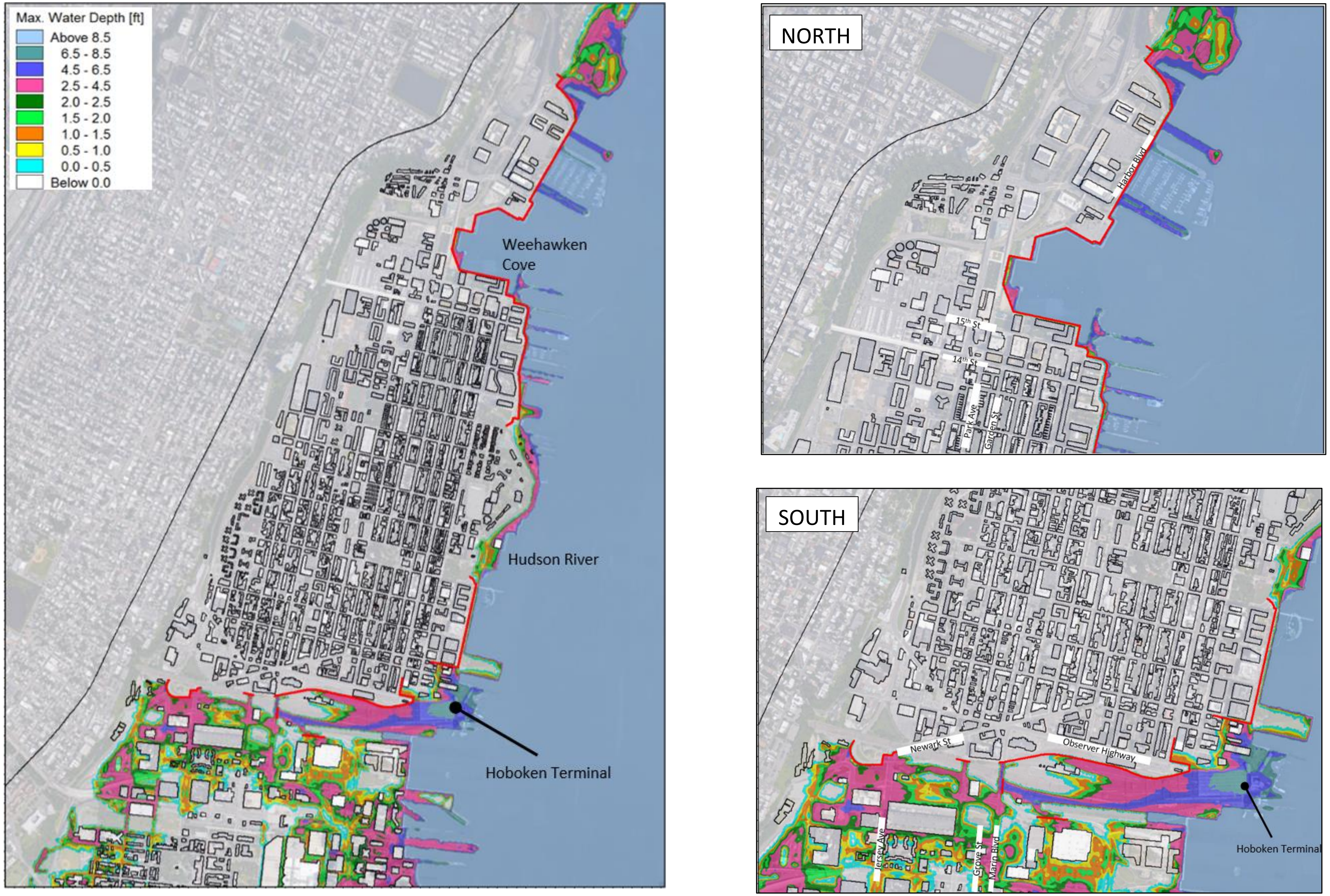


Figure 6-16. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 1% Annual Chance Coastal Storm Surge Event (100-Year) with Alternative 1 (Waterfront)

Figure 6-17. Difference in Maximum Water Depths between NAA and Alternative 1 for 1% Annual Chance Storm Surge (100-Year) Event in Northern and Southern Portions of Study Area

6.5 Evaluation of Final "Resist" Alternative 2

Alternative 2 (15^{th} Street)'s resist structure begins near the HBLR Lincoln Harbor station at Waterfront Terrace traveling south towards Harbor Boulevard. Opportunities for urban enhancement in the northern portion of the Study Area under Alternative 2 are limited due to siting conditions and include lighting, murals and seating. The Resist features then run south along Weehawken Cove where it is envisioned that a boathouse (alternatively funded) will be incorporated into the structure. In addition, a bermed and terraced Cove Park will be incorporated into the southwest corner of the Weehawken Cove. This would include existing undeveloped land as well as the currently-developed Cove Park (adjacent to Harborside Lofts at 1500 Garden Street). Potential amenities at this park may include playgrounds, lawn areas, game courts, and a viewing deck overlooking Weehawken Cove.

The structure continues to 15th Street, and travels east along 15th Street from the northern end of Garden to Washington Streets. Urban amenities in this area may include a bermed park long 15th Street in front of the Tea Building. The Resist feature then continues south along Washington Street, tapering in height between 14th and 13th Streets. Street crossings will feature gates to allow for access during non-flood conditions. Consideration will be given to adapting the use of structures in a way to provide urban amenities and landscape enhancements, including elevated walkways and pocket parks, plantings and/or seating areas along Washington Street.

There will then be two options in the south, along the Hoboken Terminal rail yard: Option 1 will feature an alignment south of Observer Highway, within the rail yard (south of the proposed Hoboken Yard Redevelopment Area). Option 2 will include an alignment along Observer Highway from Washington Street directly to Marin Boulevard. The alignment includes gates for access at various locations including the Marin Boulevard, Grove Street and Newark Avenue underpasses beneath the rail lines, as well as protection where HBLR tracks pass below the NJ Transit overpass in the southwest corner of the study area. Urban amenities in these areas include lighting, murals, seating, plantings and wayfinding/signage.

The effectiveness of the final Alternative 2 alignment to provide flood risk reduction benefits and evaluate any potential residual flooding was performed using the MIKE 21 coastal model for the 10%- , 2%-, and 1% annual chance coastal storm surge events. Figure 6-18 and Figure 6-19 shows the maximum flood extent and maximum flood depths for the 10% annual chance coastal storm surge event with the "Resist" Alternative 2 and difference in maximum water depth spatial plots between the NAA and the final Alternative 2 (15^{th} Street) in north and south portions of the study area, respectively.

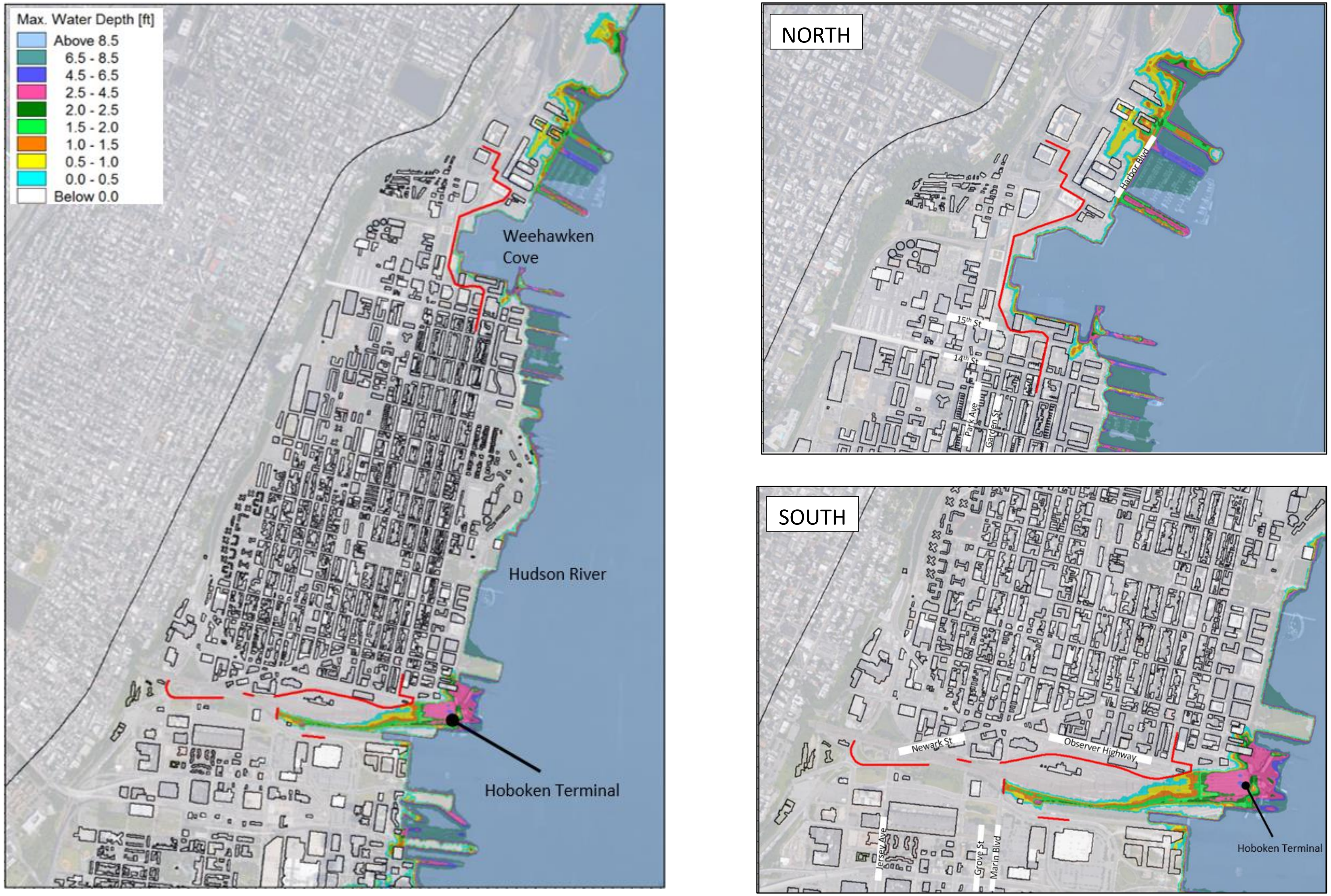


Figure 6-18. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 10% Annual Chance Coastal Storm Surge Event (10-Year) with Alternative 2 (15th Street)

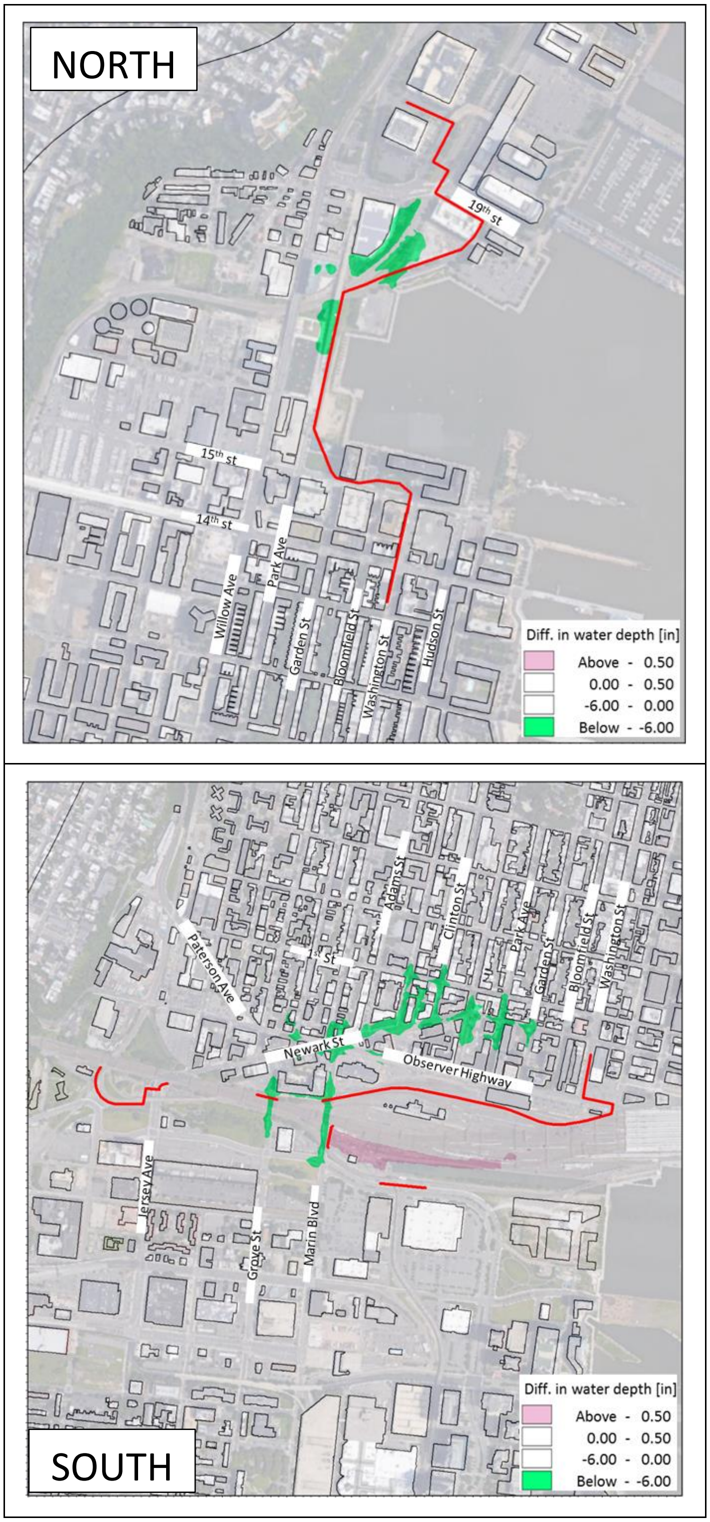


Figure 6-19. Difference in Maximum Water Depths between NAA and Alternative 2 for 10% Annual Chance Storm Surge (10-Year) Event in Northern and Southern Portions of Study Area

As seen from Figure 6-19, the green color shows the flood risk reduction benefits whereas the pink color shows the potential residual flooding impacts due to Alternative 2's "Resist" alignment. Alternative 2 provides flood risk reduction benefits for the study area with minor potential residual flooding impacts in the NJ Transit yard. Due to the additional "Resist" components, the coastal storm surge during a 10% annual chance event does not travel outside the NJ Transit yard, thus providing flood risk reduction benefits to portions of Jersey City. As seen from Figure 6-18, this alternative provides flood risk reduction benefits in southern and northern portions of Hoboken along with portions of Weehawken in the northern portion of the study area that were previously subject to flooding with water depths ranging approximately from 0 – 2 feet in the NAA during a 10% annual chance event.

Figure 6-20 and Figure 6-21 shows the maximum flood extent and maximum flood depths for the 2% annual chance (50-year) coastal storm surge event with the "Resist" Alternative 2 and difference in maximum water depth spatial plots between the NAA and the final Alternative 2 (15th Street) in north and south portions of the study area, respectively. During the peak of the 2% annual chance (50-year) coastal storm surge event, the areas flooded in Jersey City (within the study area) in the No-Action Alternative scenario would not receive any overland coastal storm surge flooding with the Alternative 2 in place. However, the MIKE 21 coastal model shows that portions of the NJ Transit yard and parking lot near the intersection of Washington Street and Observer Highway in the south; portions of the walkway near the Harborside Lofts building in Hoboken; and two parcels located along the waterfront in Weehawken could potentially see minor increases in the maximum flood depths due to Alternative 2 alignment. As seen from Figure 6-20, this alternative provides flood risk reduction benefits for western, southern and northern portions of Hoboken,; western portions of Weehawken and portions of Jersey City located within the study area that were previously subject to flooding with water depths ranging approximately from 0 – 7 feet in the NAA during a 2% annual chance event.

Figure 6-22 and Figure 6-23 shows the maximum flood extent and maximum flood depths for the 1% annual chance coastal storm surge event (100-year) with the "Resist" Alternative 2 and difference in maximum water depth spatial plots between the NAA and the final Alternative 2 (15th Street) in north and south portions of the study area, respectively. As seen from Figure 6-22, this alternative provides flood risk reduction benefits for western, southern and northern portions of Hoboken,; western portions of Weehawken and portions of Jersey City located within the study area that were previously subject to flooding with water depths ranging approximately from 0 – 8 feet in the NAA during a 1% annual chance event.

As seen from Figure 6-18 to Figure 6-23, Alternative 2 provides the flood risk reduction benefits for majority of the study area that includes most of Hoboken with the exception of a portion of waterfront located between 5th Street and 10th Street and areas located east of Garden Street/15th Street and Washington Street/14th Street in the north; and major portions of Weehawken and Jersey City that are located within the study area.

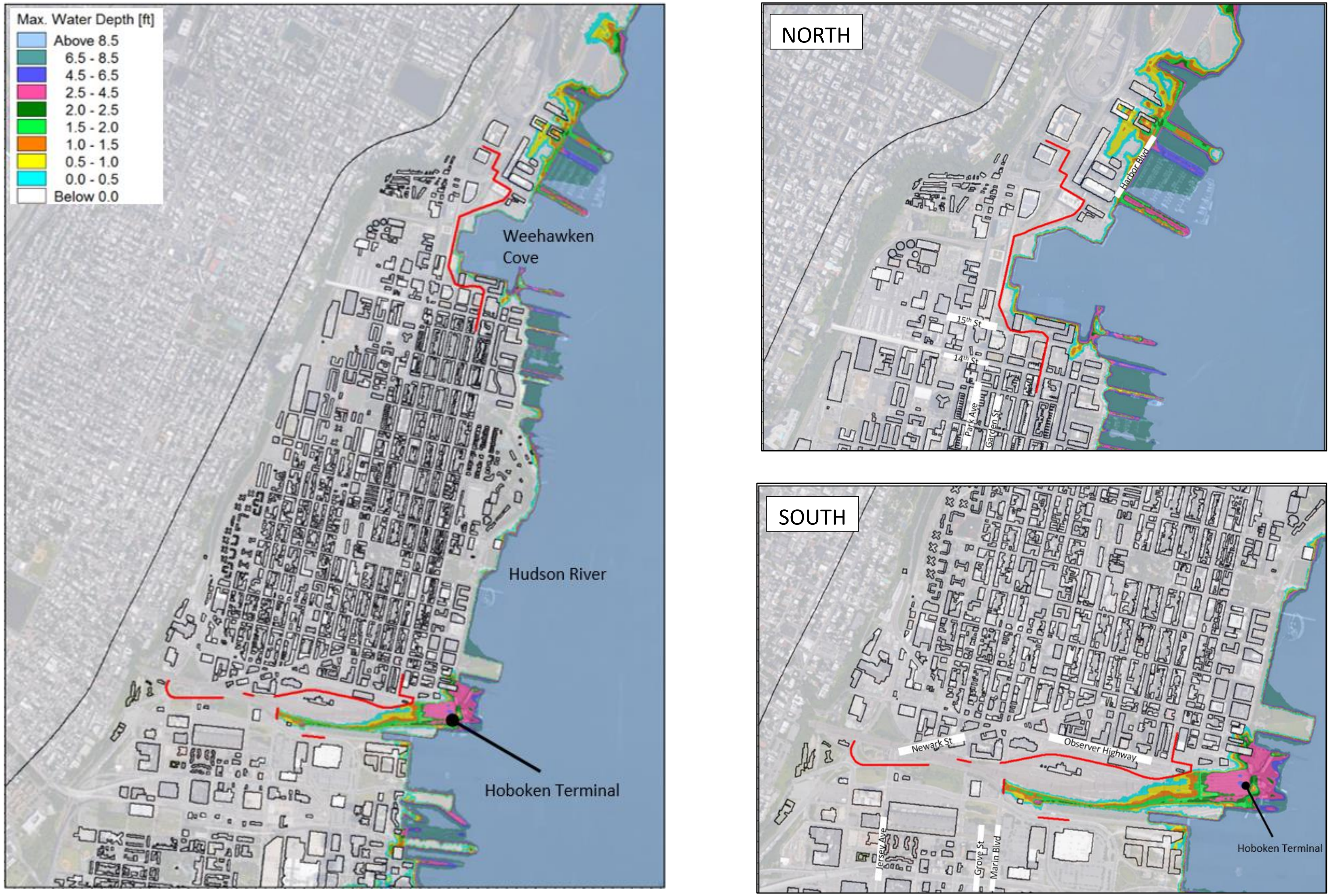


Figure 6-20. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 2% Annual Chance Coastal Storm Surge Event (50-Year) with Alternative 2 (15th Street)

Figure 6-21. Difference in Maximum Water Depths between NAA and Alternative 2 for 2% Annual Chance Storm Surge (50-Year) Event in Northern and Southern Portions of Study Area

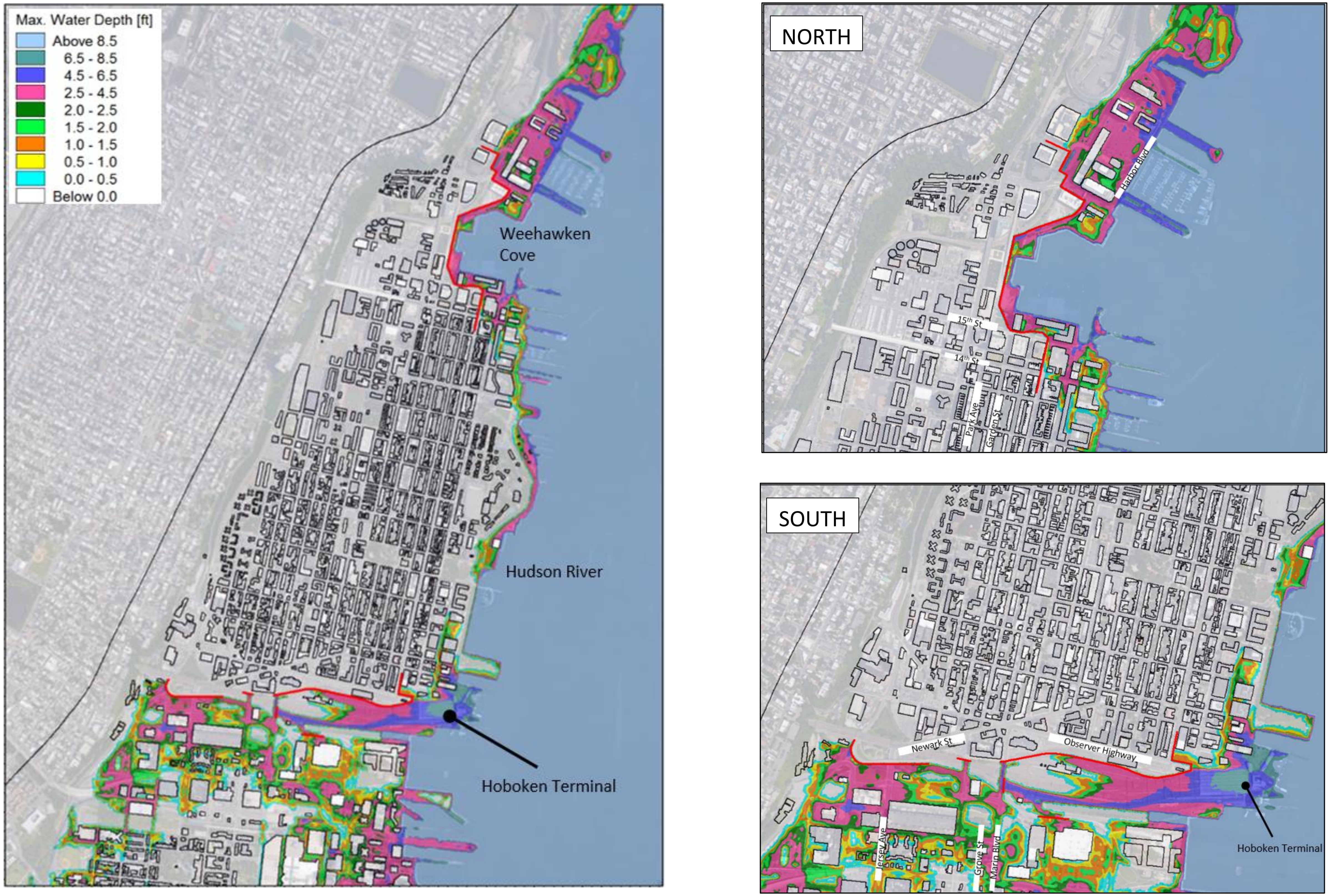


Figure 6-22. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 1% Annual Chance Coastal Storm Surge Event (100-Year) with Alternative 2 (15th Street)

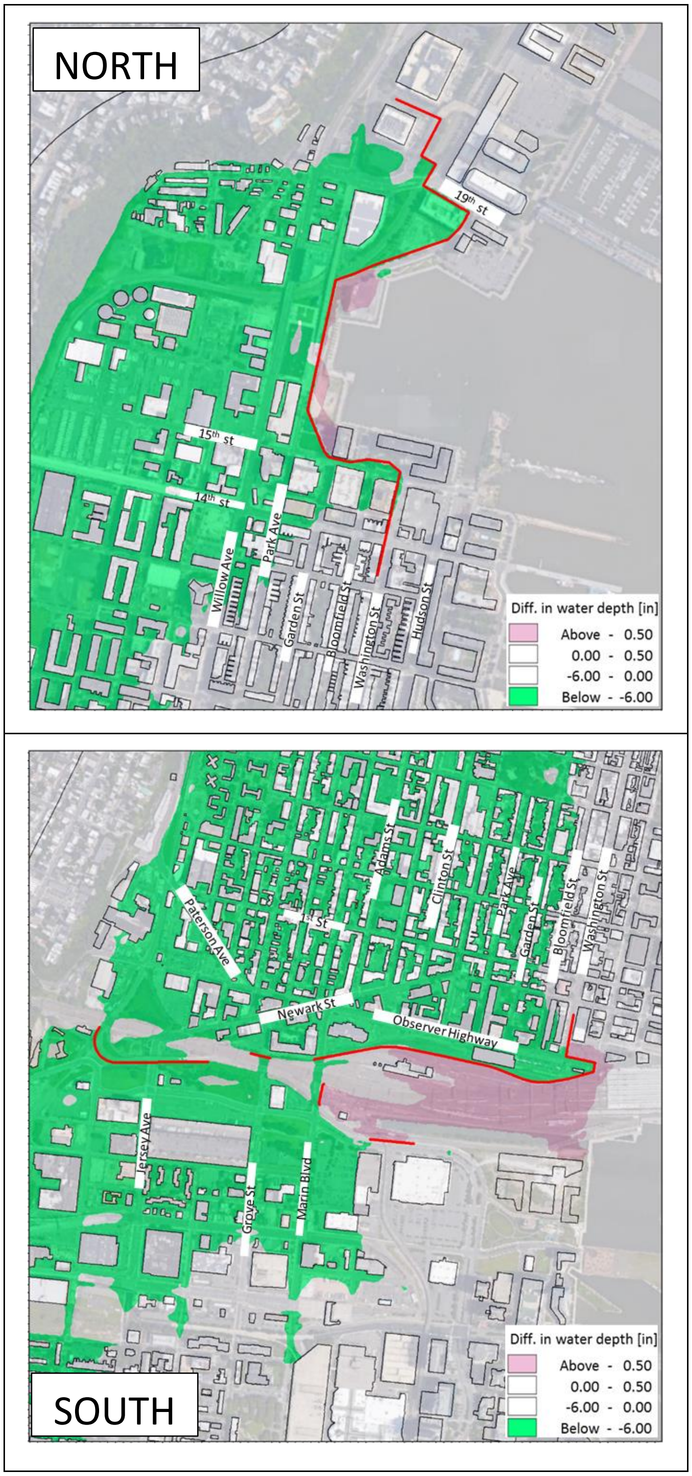


Figure 6-23. Difference in Maximum Water Depths between NAA and Alternative 2 for 1% Annual Chance Storm Surge (100-Year) Event in Northern and Southern Portions of Study Area

6.6 Evaluation of Final "Resist" Alternative 3

This alternative's Resist structure begins near the HBLR Lincoln Harbor station at Waterfront Terrace, traveling south along HBLR and then continuing south along Weehawken Cove towards Garden Street. Opportunities for urban enhancement in the northern portion of the Study Area under Alternative 3 are limited due to siting conditions and include lighting, murals and seating. It is envisioned that a boathouse (alternatively funded) will be incorporated into the structure. In addition, a bermed and terraced Cove Park will be incorporated into the southwest corner of the Weehawken Cove. This would include existing undeveloped land as well as the currently-developed Cove Park (adjacent to Harborside Lofts at 1500 Garden Street). Potential amenities at this park may include playgrounds, lawn areas, game courts, and a viewing deck overlooking Weehawken Cove.

A barrier structure would then travel down the east side of Garden Street adjacent to the west of the Hudson Tea Parking Garage; the structure along Garden Street may consist of an elevated planter with seating. The structure would then continue down the alleyway midway between 15th and 14th Streets from Garden to Washington Streets. Urban amenities within the alleyway could include planters. The structure would then travel south along Washington Street ending between 14th and 13th Streets. Street crossings will feature gates to allow for access during non-flood conditions. Consideration will be given to adapting the use of structures in a way to provide urban amenities and landscape enhancements.

There will then be two options: Option 1 will include an alignment south of Observer Highway, within the rail yard (south of the proposed Hoboken Yard Redevelopment Area). Option 2 will feature an alignment along Observer Highway from Washington Street directly to Marin Boulevard. The alignment includes gates for access at various locations including at the Marin Boulevard, Grove Street and Newark Avenue underpasses beneath the rail lines, as well as protection where HBLR tracks pass below the NJ Transit overpass in the southwest corner of the study area. Urban amenities in these areas include lighting, murals, seating, plantings, and wayfinding/signage.

The effectiveness of the final Alternative 3 alignment to provide flood risk reduction benefits and evaluate any potential residual flooding was performed using the MIKE 21 coastal model for the 10%- , 2%-, and 1% annual chance coastal storm surge events. Figure 6-24 and Figure 6-25 shows the maximum flood extent and maximum flood depths for the 10% annual chance coastal storm surge event with the "Resist" Alternative 3 and difference in maximum water depth spatial plots between the NAA and the final Alternative 3 (Alleyway) in north and south portions of the study area, respectively.

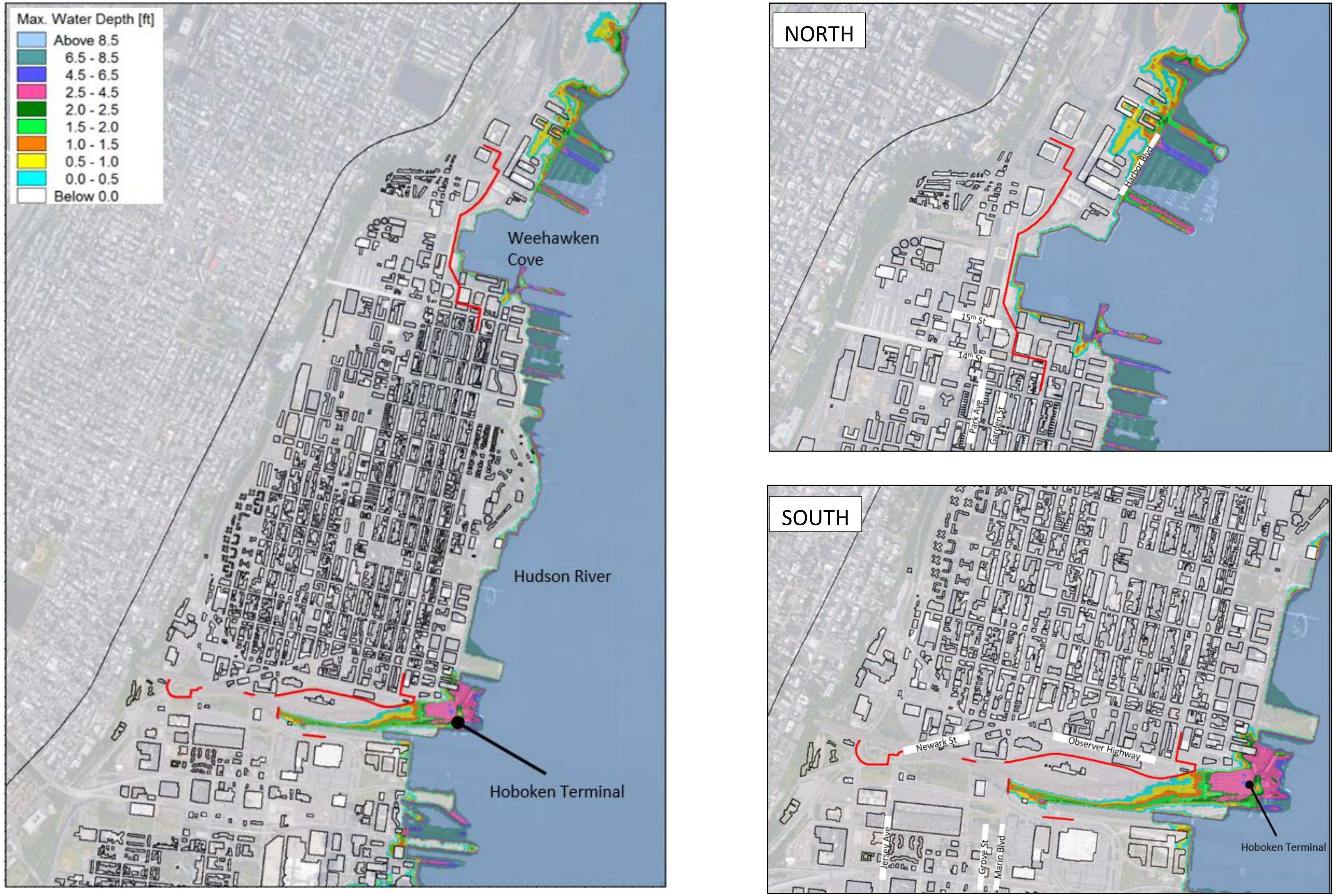


Figure 6-24. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 10% Annual Chance Coastal Storm Surge Event (10-Year) with Alternative 3 (Alleyway)

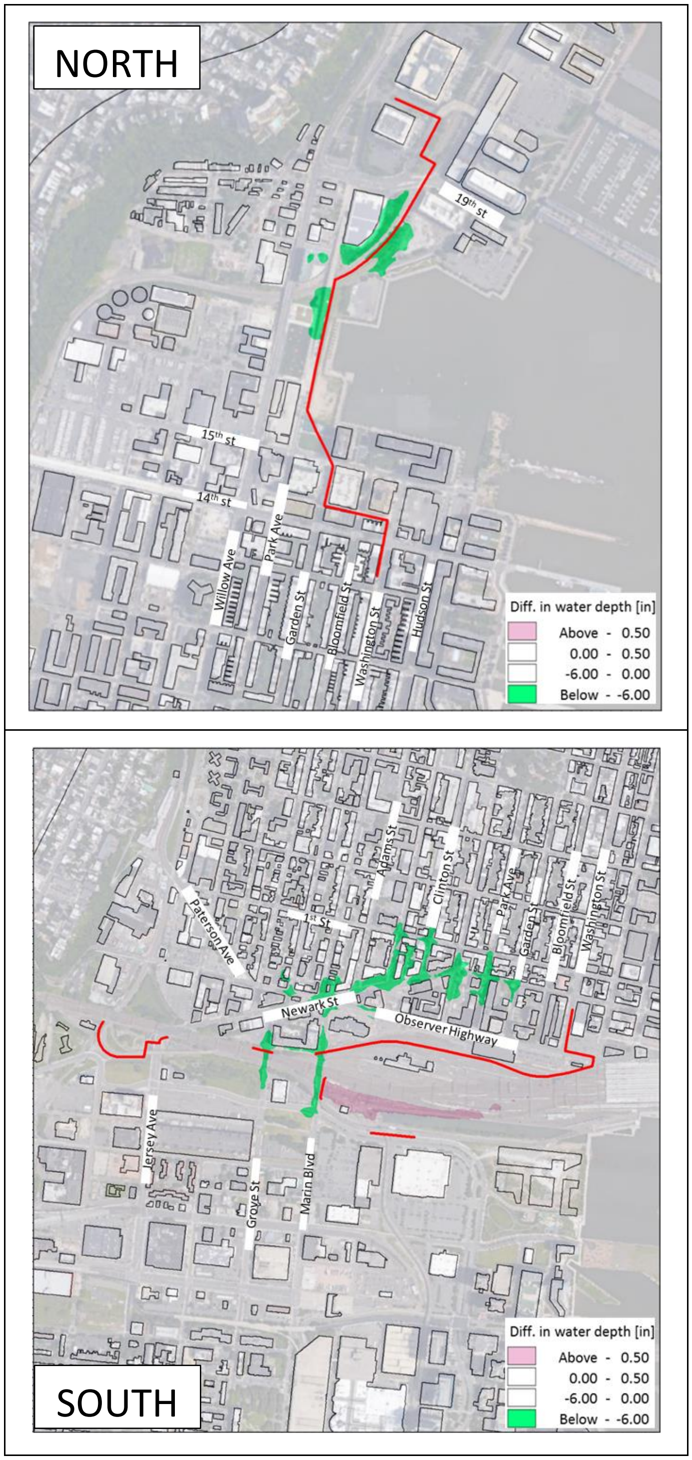


Figure 6-25. Difference in Maximum Water Depths between NAA and Alternative 3 for 10% Annual Chance Storm Surge (10-Year) Event in Northern and Southern Portions of Study Area

As seen from Figure 6-25, the green color shows the flood risk reduction benefits whereas the pink color shows the potential residual flooding impacts due to Alternative 3's "Resist" alignment. Alternative 3 provides flood risk reduction benefits for the study area with minor potential residual flooding impacts in the NJ Transit yard. Due to the additional "Resist" components, the coastal storm surge during a 10% annual chance event does not travel outside the NJ Transit yard, thus providing flood risk reduction benefits to portions of Jersey City.

Figure 6-26 and Figure 6-27 shows the maximum flood extent and maximum flood depths for the 2% annual chance (50-year) coastal storm surge event with the "Resist" Alternative 3 and difference in maximum water depth spatial plots between the NAA and the final Alternative 3 (Alleyway) in north and south portions of the study area, respectively. During the peak of the 2% annual chance (50-year) coastal storm surge event, the areas flooded in Jersey City (within the study area) in the No-Action Alternative scenario would not receive any overland coastal storm surge flooding with Alternative 3 in place. However, the MIKE 21 coastal model shows that portions of the NJ Transit yard and parking lot near the intersection of Washington Street and Observer Highway in the south; portions of the walkway near the Harborside Lofts building in Hoboken; and two parcels located along the waterfront in Weehawken could potentially see minor increases in the maximum flood depths due to the Alternative 3 alignment.

Figure 6-28 and Figure 6-29 shows the maximum flood extent and maximum flood depths for the 1% annual chance coastal storm surge event (100-year) with the "Resist" Alternative 3 and difference in maximum water depth spatial plots between the NAA and the final Alternative 3 (Alleyway) in north and south portions of the study area, respectively. The MIKE 21 coastal model shows areas subject to potential residual flooding similar to the 2% annual chance (50-year) coastal storm surge event with about 1 inch of potential increase in the maximum water depth along the walkway near Harborside Lofts building with Alternative 3. The model also shows that NJ Transit yard could potentially get maximum increase of 6 inches in the water depth over the water depth in NAA during the peak of the 1% annual chance storm event with Alternative 3. In the NJ Transit yard, these increases in water depth are at highest in areas adjacent to Alternative 3's "Resist" alignment and gradually decreases to less than 0.04 feet closer to the Hoboken Terminal and Hudson River.

As seen from Figure 6-24 to Figure 6-29, Alternative 3 provides the flood risk reduction benefits for majority of the study area that includes most of Hoboken with the exception of a portion of waterfront located between 5th Street and 10th Street and areas located east of Garden Street/Alleyway and Washington Streets/14th street in the north; and major portions of Weehawken and Jersey City that are located within the study area. Alternative 3 provides flood risk reduction benefits for western, southern and northern portions of Hoboken,; western portions of Weehawken and portions of Jersey City located within the study area that were previously subject to flooding with water depths ranging approximately from 0 – 8 feet in the NAA during a 1% annual chance event.

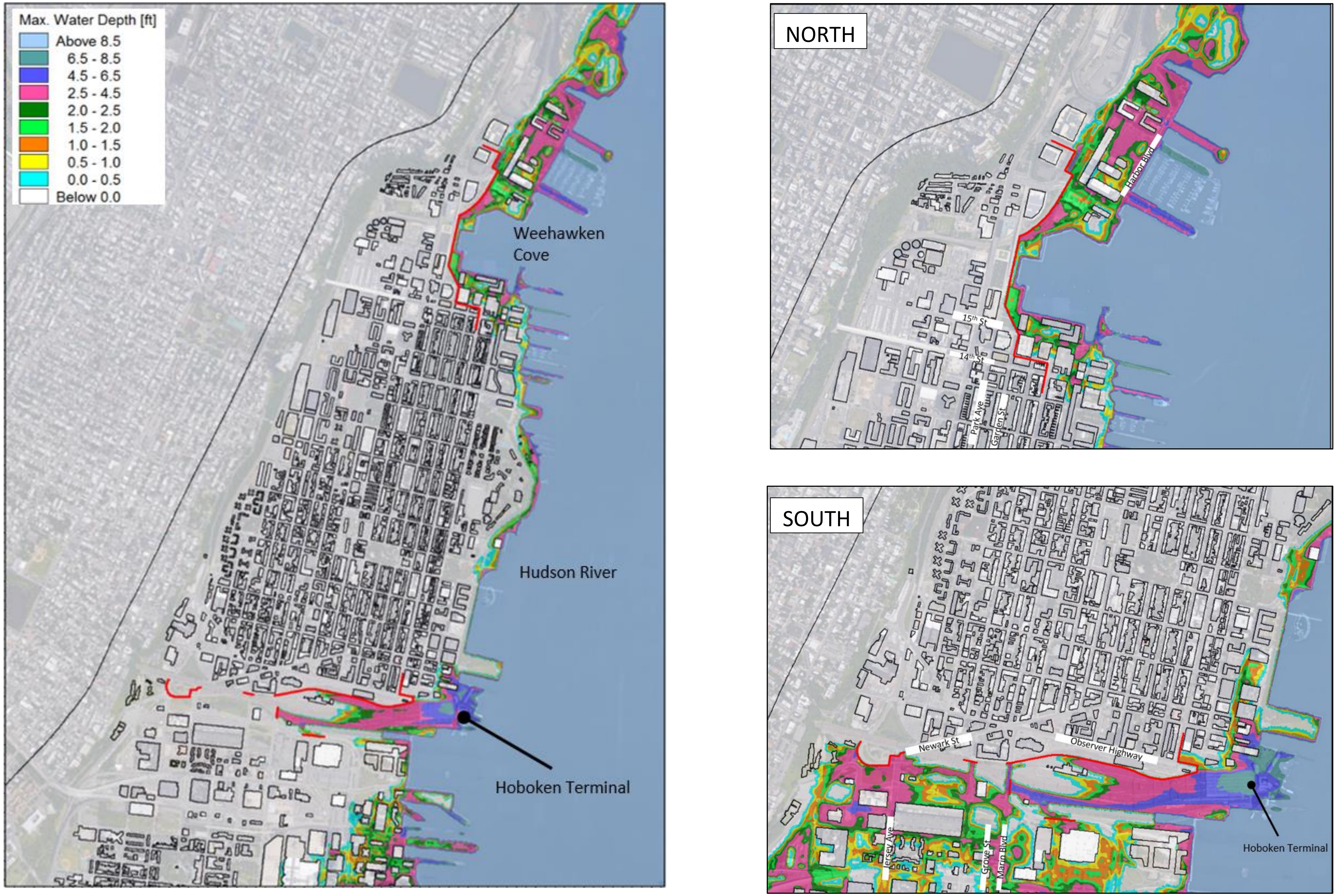


Figure 6-26. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 2% Annual Chance Coastal Storm Surge Event (50-Year) with Alternative 3 (Alleyway)

Figure 6-27. Difference in Maximum Water Depths between NAA and Alternative 3 for 2% Annual Chance Storm Surge (50-Year) Event in Northern and Southern Portions of Study Area

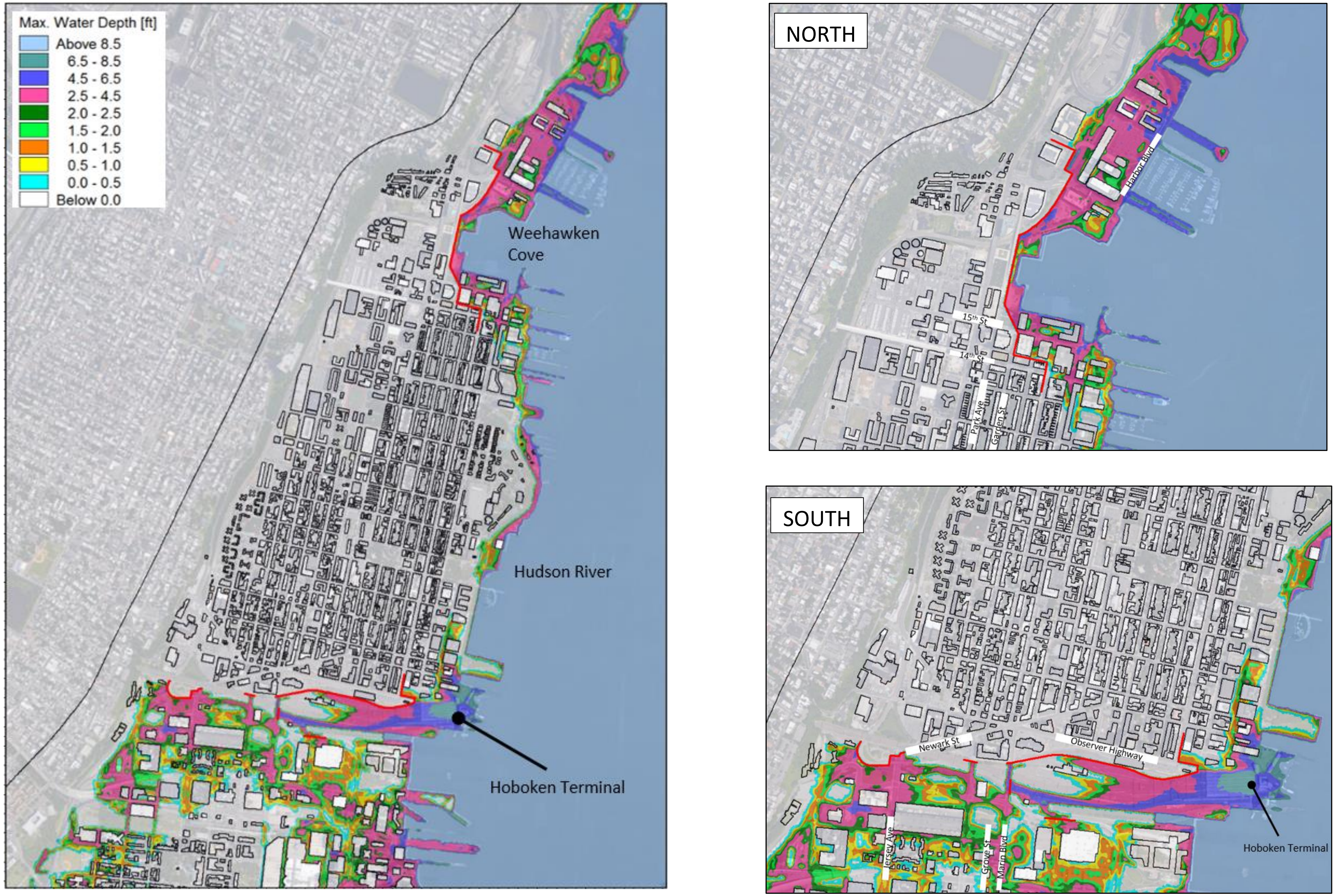


Figure 6-28. Spatial Plot Showing Maximum Flood Depths and Inundation Extents for the 1% Annual Chance Coastal Storm Surge Event (100-Year) with Alternative 3 (Alleyway)

Figure 6-29. Difference in Maximum Water Depths between NAA and Alternative 3 for 1% Annual Chance Storm Surge (100-Year) Event in Northern and Southern Portions of Study Area

6.7 Coastal Model Results Discussion

The MIKE 21 coastal model shows that all the three alternative would provide varying levels of flood risk reduction benefits for the study area with minimal residual flood impacts. Alternative 1 (Waterfront) provides the maximum flood risk reduction benefits followed by Alternative 2 (15th Street) and Alternative 3 (Alleyway) respectively (See Tables 6-1 through 6-3). Alternative 1 potentially has the least number of properties impacted by residual flooding whereas both Alternative 2 and Alternative 3 have potentially five (5) properties that would be impacted by residual flooding during the peak of the 1% annual chance coastal storm surge event.

It should be noted that although the coastal model shows that each alternative would prevent the flow of overland coastal storm surge into portions of Jersey City, the coastal model does not take into account any potential flow of coastal storm surge through existing subsurface utilities that could intrude into portions of Jersey City located within the study area. It is possible that the coastal storm surge could travel through existing utilities that are located outside of the study area into portions of the study area. The volume of coastal storm surge traveling through utilities is dependent on the duration of inundation and the hydraulic gradient of the utility system. Based on the qualitative assessment, the volume of water traveling through the subsurface utilities would be significantly less than the overland flow of coastal storm surge.

GIS techniques were used to develop quantitative estimates for coastal food risk reduction benefits provided by each alternative in the 10% -, 2% - and 1% -annual chance coastal storm events as shown in Table 6-1 – Table 6-3. These flood risk reduction benefits parameters include population, buildings, and inundation area. It should be noted that these flood risk reduction benefit estimates are approximate. Additionally, the 2015 FEMA's preliminary floodplain maps was utilized to estimate the percentage population based on the 2010 US Census Bureau currently located within FEMA's 1% annual chance floodplain that would receive flood risk reduction benefits from each alternative as shown in Table 6-4.

Table 6-1. Flood Risk Reduction Benefits from Alternative 1 (Waterfront)

Storm Events	Scenario	Inundation Area		Affected Buildings		Affected Population	
		Total Land Area = 1,018 Acre		Total No. of Buildings = 4,243		Total Population = 51,802	
		Acres	% Difference	No. of Buildings	% Difference	Population	% Difference
10% (10yr)	NAA	83	35%	124	90%	9,886	62%
	Alternative 1	54		13		3,770	
2% (50-yr)	NAA	489	83%	2,238	99%	38,821	90%
	Alternative 1	82		25		3,848	
1% (100-yr)	NAA	545	80%	2,603	98%	41,838	89%
	Alternative 1	109		44		4,485	

Table 6-2. Flood Risk Reduction Benefits from Alternative 2 (15th Street)

Storm Events	Scenario	Inundation Area: Total Land Area = 1,018 Acre		Affected Buildings: Total No. of Buildings = 4,243		Affected Population: Total Population = 51,802	
		Acres	% Difference	No. of Buildings	% Difference	Population	% Difference
10% (10yr)	NAA	83	22%	124	83%	9,886	62%
	Alternative 2	65		21		3,770	
2% (50-yr)	NAA	489	75%	2,238	98%	38,821	87%
	Alternative 2	122		54		5,085	
1% (100-yr)	NAA	545	71%	2,603	97%	41,838	82%
	Alternative 2	157		83		7,694	

Table 6-3. Flood Risk Reduction Benefits from Alternative 3 (Alleyway)

Storm Events	Scenario	Inundation Area: Total Land Area = 1,018 Acre		Affected Buildings: Total No. of Buildings = 4,243		Affected Population: Total Population = 51,802	
		Acres	% Difference	No. of Buildings	% Difference	Population	% Difference
10% (10yr)	NAA	83	22%	124	83%	9,886	62%
	Alternative 3	65		21		3,770	
2% (50-yr)	NAA	489	74%	2,238	97%	38,821	87%
	Alternative 3	126		57		5,085	
1% (100-yr)	NAA	545	70%	2,603	97%	41,838	82%
	Alternative 3	163		89		7,694	

Table 6-4. Population within the 2015 Preliminary FEMA 1% Annual Chance (100-year) Floodplain Receiving Flood Risk Reduction Benefits from Each Alternative

Population in 100-year FEMA Floodplain	Flood Risk Reduction	Alternative 1		Alternative 2		Alternative 3	
		Population	%	Population	%	Population	%
39,901	Flood Risk Reduced	39,205	98.3%	34,230	85.8%	34,084	85.4%
	Flood Risk Not Reduced	696	1.7%	5,671	14.2%	5,817	14.6%

As an example to demonstrate potential residual flooding impacts, as per State of New Jersey's permit regulations, the maximum water depths were extracted from the MIKE 21 coastal model at three (3) locations around the Harborside Lofts building in Hoboken for the 10%, 2% and 1% annual chance events in the NAA and Alternative 3. Figure 6-30 shows the locations for the three points whereas Table 6-5 shows the maximum water depths and the difference in the maximum water depths between NAA and Alternative 3 at these three locations.

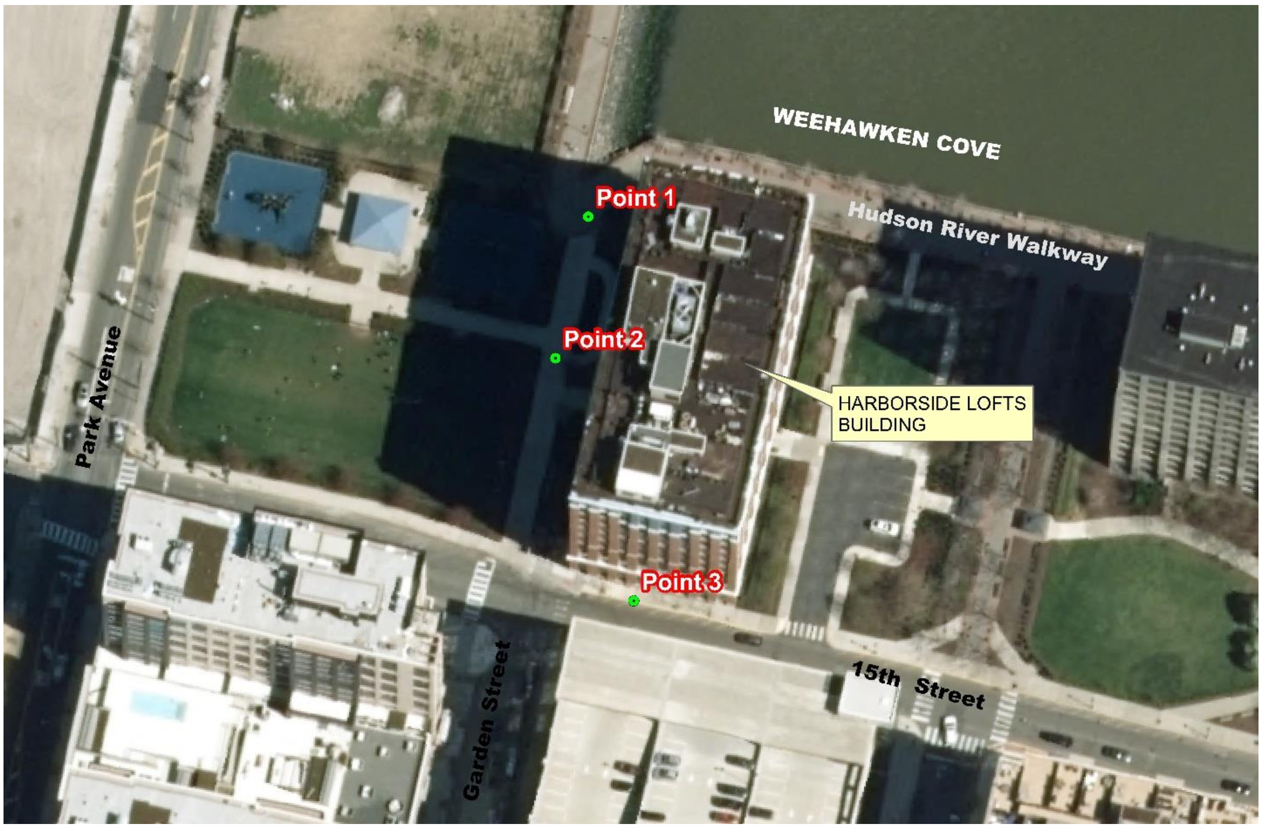


Figure 6-30. Location Map of three points adjacent to Harbor Side Lofts for Comparison of Maximum Water Depths

As seen from Table 6-5, during a 1% annual chance coastal storm surge event, among the three locations the maximum water depth is at Point 1 with 49.5 inches (4.13 feet) in No-Action Alternative (NAA) and 50.1 inches (4.18 feet) in Alternative 3. The difference in the maximum water depth at Point 1 between the NAA and Alternative 1 is 0.6 inches (0.05 feet). However, during the 1% annual chance coastal storm surge event, the maximum difference is approximately 0.8 inches at Point 3. It should be noted that Point 3 would have about 3.5 feet of water in NAA scenario and the MIKE 21 coastal model results shows that an additional 0.8 inches would be added over the 3.5 feet of water with Alternative 3 in place. Similar to this example of potential residual flooding impacts, it is anticipated that NJDEP would coordinate with the other four affected property owners to demonstrate the minor increases in maximum flood depths shown by the MIKE 21 coastal model. Appendix D provides a map and table with maximum water depth for various locations within the study area in the NAA and all three alternatives.

Table 6-5. Maximum Water Depths in NAA and Alternative 3 at three locations around Harborside Lofts Building

Coastal Storm Event	Scenario	Maximum Water Depth in Inches		
		Point 1	Point 2	Point 3
10% annual chance (10-year)	NAA	7.3	0.0	0.0
	Alternative 3	7.3	0.0	0.0
	Difference in Water Depth	0.0	0.0	0.0
2% annual chance (50-year)	NAA	35.3	16.6	28.4
	Alternative 3	36.4	18.0	29.7
	Difference in Water Depth	1.1	1.4	1.2
1% annual chance (100-year)	NAA	49.5	31.0	42.6
	Alternative 3	50.1	31.8	43.4
	Difference in Water Depth	0.6	0.7	0.8

Table 6-6 through Table 6-8 shows the properties that would experience residual flooding as a result of each of the three Resist alternatives. In order for the project to be compliant with applicable state laws, either an easement on these properties must be acquired, or written permission must be secured from the affected property owner to authorize the projected increase in flooding.

Table 6-6. Properties impacted by Residual Flooding under Alternative 1

BLOCK	LOT	OWNER	EXISTING CONDITIONS
7302	1	NJ TRANSIT	NJ TRANSIT property near Long Slip Canal containing multiple rail tracks
210, 210.01	1-6, 26-29	Washington-Hudson Assoc.	Existing parking lot on Observer Hwy. and Washington St.

Table 6-7. Properties impacted by Residual Flooding under Alternative 2

BLOCK	LOT	OWNER	EXISTING CONDITIONS
7302	1	NJ TRANSIT	NJ TRANSIT property near Long Slip Canal containing multiple rail tracks
210, 210.01	1-6, 26-29	Washington-Hudson Assoc.	Existing parking lot on Observer Hwy. and Washington St.
268.01	1	1500 Garden St.	Harborside Lofts. Existing residential building
34.03	1.01 & 1.02	BDLJ Associates	Vacant properties.
34.03	4.01	HARTZ	Existing parking lot.

Table 6-8. Properties impacted by Residual Flooding under Alternative 3

BLOCK	LOT	OWNER	EXISTING CONDITIONS
7302	1	NJ TRANSIT	NJ TRANSIT property near Long Slip Canal containing multiple rail tracks
210, 210.01	1-6, 26-29	Washington-Hudson Assoc.	Existing parking lot on Observer Hwy. and Washington St.
268.01	1	1500 Garden St.	Harborside Lofts. Existing residential building
34.03	1.01 & 1.02	BDLJ Associates	Vacant properties.
34.03	4.01	HARTZ	Existing parking lot.

7 Stormwater Modeling Methodology

7.1 Stormwater Model Study Area Overview

The Delay, Store, Discharge (DSD) components of this project are located entirely within the City of Hoboken and do not extend into portions of Weehawken and Jersey City. Hence, for the purposes of this study, the drainage network impacted by the proposed Delay, Store and Discharge components that are located within the City of Hoboken limits are considered as part of the stormwater model domain. However, there are areas beyond City of Hoboken limits such as the Palisades (in Jersey City and Union City) that drains into NJ Transit's HBLR's drainage canal. Additionally, Hudson County owned drainage system also drains portions of Palisades and 14th street viaduct through City of Hoboken. These additional areas that are located outside of City of Hoboken limits but that drain into City of Hoboken limits were considered as part of the stormwater model domain.

Topographically, the City of Hoboken resembles a bowl with a depressed center and higher edges along its borders. Higher elevations are observed along Castle Point and Hudson River to the east and the Palisades cliffs to the west. To the north and south are manmade structures including the Hoboken Rail Yard and Hudson Bergen Light Rail tracks and embankments higher than the center of the City (Hoboken Strategic Recovery Planning Report, 2014).

The North Hudson Sewerage Authority (NHSA) owns and operates Adams Street Wastewater Treatment Plant (WWTP) that is located within the north western corner of the City of Hoboken limits. The storm-sewer collection system serviced by the WWTP covers the entire city of Hoboken, Weehawken and portions of Union City. The stormwater model domain area includes the storm-sewer collection system located within the City of Hoboken and small portions of Jersey City, Union City and Weehawken located immediately adjacent to the City of Hoboken limits. Figure 7-1 shows the extent of the project study area (in red), the WWTP service area (in black) and the approximate stormwater model domain area (light blue hatch). The model domain area differs from the project study area because portions of the waterfront sheetflow directly to the Hudson and do not drain into the City's storm sewer system.

The total stormwater model domain area is approximately 1.95 sq. miles. This includes the entire City of Hoboken, excluding the waterfront area, which has its own separate storm system that flows directly into the Hudson River; parts of Weehawken, and Jersey City. Parts of Weehawken and Jersey City that would naturally drain to drainage features within the City were included after due consideration to the existing hydraulic characteristics.

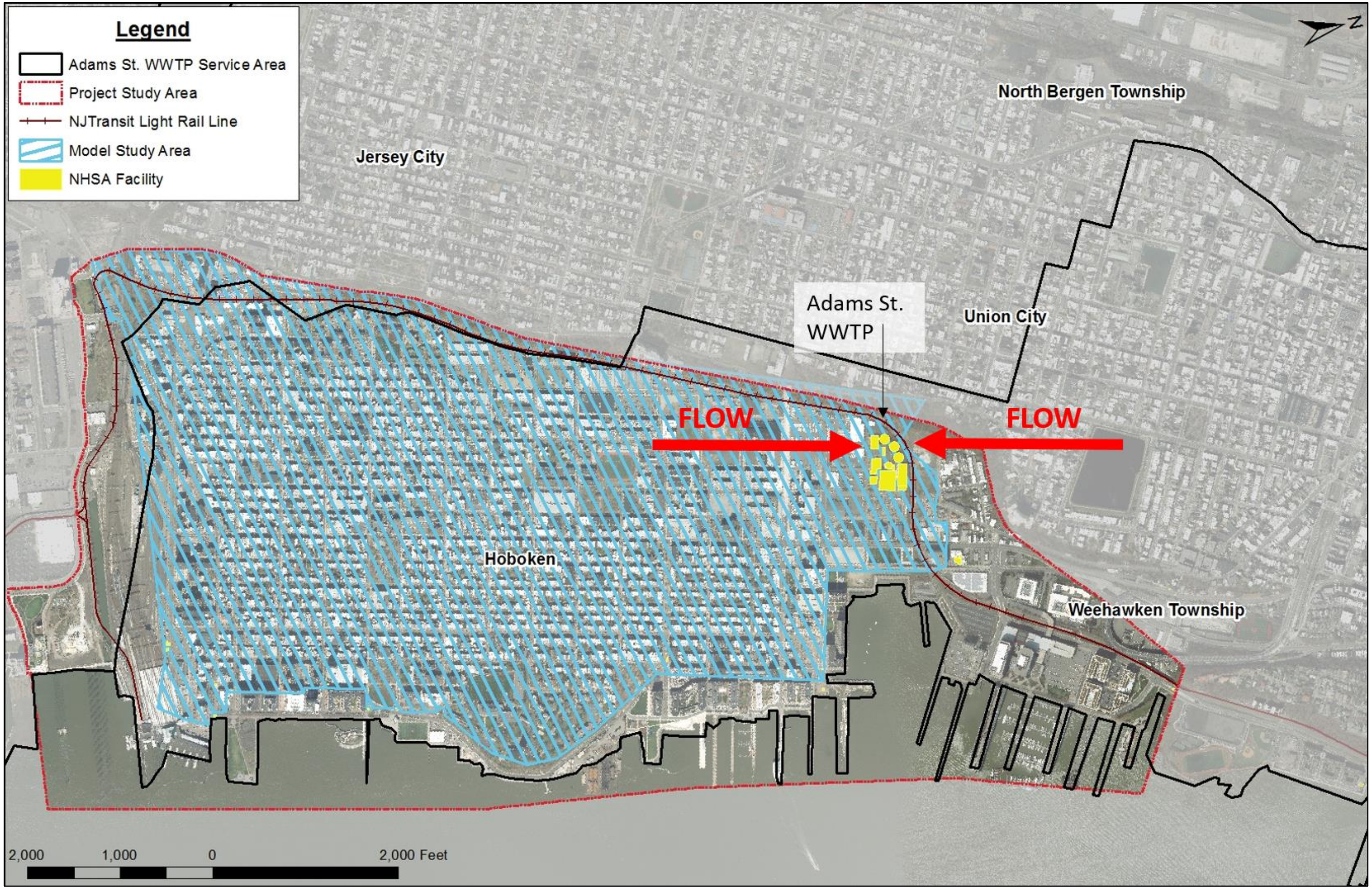


Figure 7-1. Adams Street WWTP Service Area and Stormwater Model Domain Area

7.2 North Hudson Sewerage Authority (NHSA) Network

The combined sewer system (CSS) serving the City of Hoboken is part of NHSA's WWTP collection system service area. The CSS was originally designed to convey sewage and storm water (collectively referred to as "wastewater") directly to the Hudson River. A majority of the sewer system components were constructed during two main time periods – 1850's and between 1920's to 1940's. The Adam's Street WWTP was constructed in 1958 to treat the wastewater before discharging into the Hudson. At this time, a system of interceptors and pump stations were constructed to direct the City of Hoboken's combined wastewater to the WWTP for treatment. Since the collection system is a Combined Sewer Overflow (CSO) system and the Adam's Street WWTP was originally designed to handle dry weather flows (sewer only) and a small portion of the wet weather (stormwater and sewer) flows, a system of regulators was constructed to convey the excess stormwater directly into the Hudson River (NHSA Annual Report, 2011). As per the NJPDES Permit No. NJ0026085, Adams Street WWTP has a permitted plant flow of 20.8 million gallons per day (MGD) with the design flow for the plant at 24 MGD. The WWTP has a capacity to handle a wet weather flow of 36 MGD at full operating capacity. Based on discussions with NHSA, the Adams Street WWTP typically gets the following average dry weather sewer flow distribution -48% from Hoboken, 40% from Union City and 12% from Weehawken. Monthly average influent flow at Adams Street WWTP varied between 10 and 16 MGD between 2009 and 2013 (NHSA, 2014).

The City of Hoboken's high percentage of impervious areas combined with increasing frequency of high intensity rainfall storm events and over a century old collection system poses significant challenges to address the frequently occurring flash flooding within the City. As of 2014, the Adams Street WWTP was overburdened by stormwater flows, on average, five times per month leading to combined sewer overflow issues. Hurricanes Irene and Sandy worsened the situation due to unprecedented flood levels causing widespread damage to public infrastructure and private property (Green Infrastructure Strategic Plan, 2014).

The City of Hoboken's sewer system comprises of multiple sewersheds within the City with interconnections to allow stormwater flow from one sewershed to another. Increased stormwater flows from one sewershed might aggravate flooding potential in the downstream / receiving connected sewershed due to undersized drainage infrastructure already overburdened by the flows from its contributing drainage area. Figure 7-4 shows the major sewersheds within the study area draining into the City's CSO system. Figure 7-5 shows the various components of the Combined Sewer System (CSS) systems located within the study area. Gravity sewer lines capture and route the stormwater runoff and wastewater (dry weather flow from the residential and commercial facilities within the City) to a system of interceptor pipes, force main pipes and pumps and finally through an inverted siphon into the Adams Street WWTP.

Interceptors are gravity sewers that collect wastewater flows from the regulators. Within Hoboken, the South interceptor conveys flows from drainage areas H1, H2, H3, and H4 to the 5th Street Pump Station and the North interceptor conveys flows from drainage areas H5, H6, and H7 to the 11th Street Pump Station. The 5th Street pump station discharges via forces mains and gravity sewer to a chamber adjacent to the 11th Street pump station, which in turn discharges directly into the same chamber. The outlet from this chamber is a 36-inch diameter depressed sewer, or siphon, that conveys the flows to the Adams Street Wastewater Treatment Plant.

Regulators within Hoboken consist of three sections for influent, diversion, and tide gate. Influent section includes an influent chamber and conveyance channel. The diversion section consists of overflow weirs or regulator float gates to ensure dry weather flows are directed into the interceptor and excess wet weather flows directly into the Hudson River. The tide gate section comprises of screens for debris removal prior to discharge into the river and tide gates to prevent backflow into the collection system. A schematic depicting a typical regulator layout can be seen in Figure 7-2(Emnet, 2011).The 5th Street pump station receives wastewater (wet and dry weather) flows from regulators H1, H2, H3 and H4 in southern two-thirds of Hoboken. The 11th Street pump station collects flow from H5, H6 and H7 in the northern portion of Hoboken. Following Hurricane Irene in 2011, a wet weather pump station called as H1 Wet Weather Pump Station (WWPS) was constructed at the intersection of Observer Highway and Washington Street to pump excess stormwater overflow from H1 sewershed to the Hudson River. Figure 7-3 shows the schematics of the conveyance of storm-sewer flows from City of Hoboken into the Adams Street WWTP.

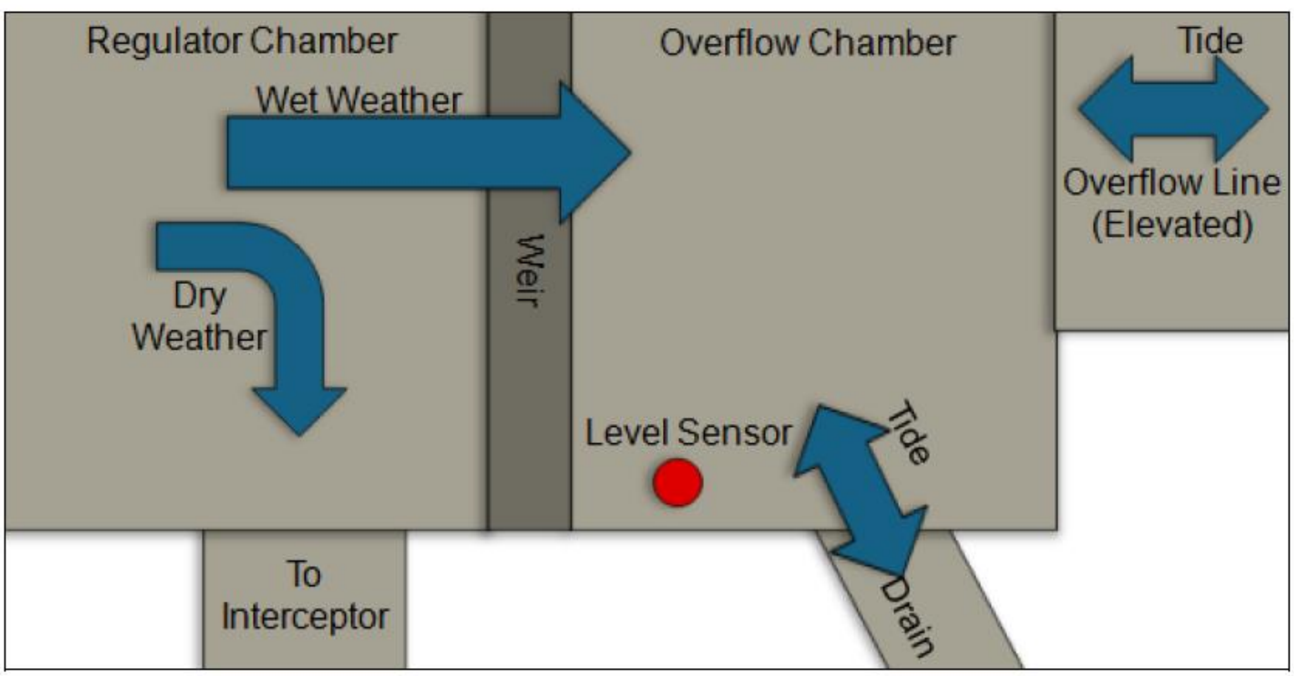


Figure 7-2. Schematics showing Typical Regulator Layout (Source: EmNet, 2011)

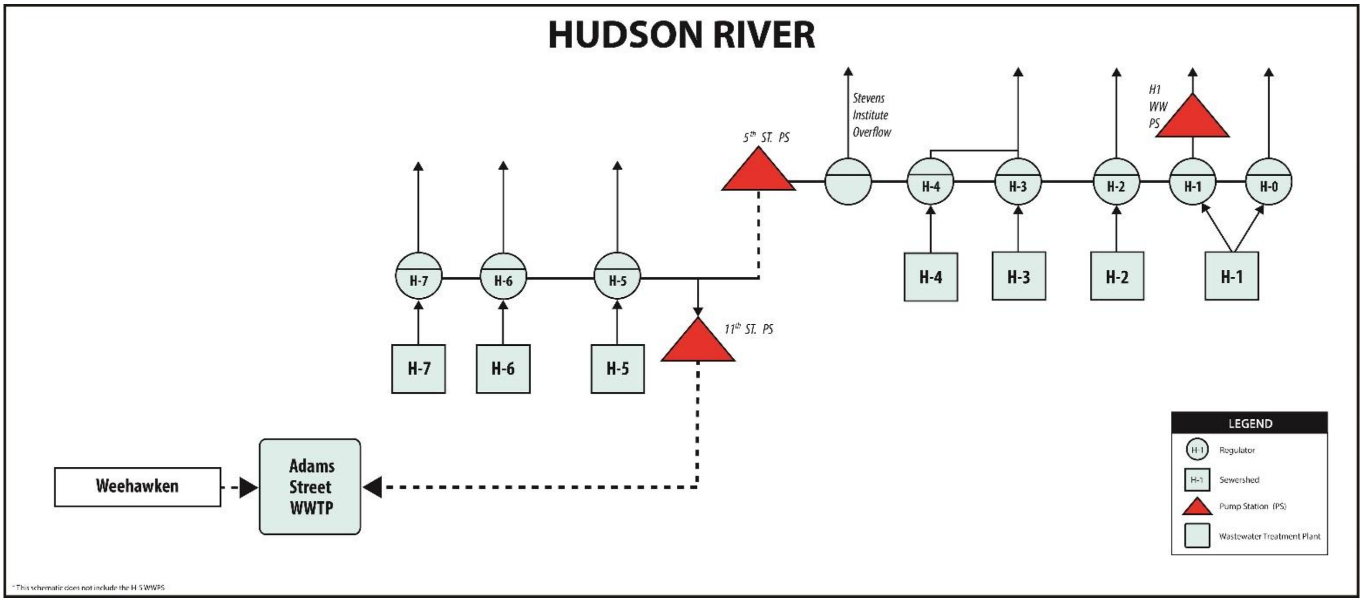


Figure 7-3. Schematics showing Adams Street WWTP Collection System in City of Hoboken

In 2016, NHSA and City Hoboken began construction of the H5 Wet Weather Pump Station at the intersection of 11th Street and Frank Sinatra Drive North to pump excess stormwater overflow primarily from the H5 sewershed to the Hudson River. Table 7-1 provides an approximate summary of the various storm-sewer components that exist within NHSA's collection system primarily in the study area.

Table 7-1. Summary of NHSA's Storm-Sewer System

Feature	Unit	Quantity
Gravity Sewer Pipes	Linear Feet	159,754
Interceptor and Force Mains	Linear Feet	9,445
Regulators	Each	7
Pump Station - Sewage	Each	2
Pump Station - Wet Weather	Each	2
Combined Sewer Overflow Outfalls	Each	9

Figure 7-4. Sewersheds within Study Area

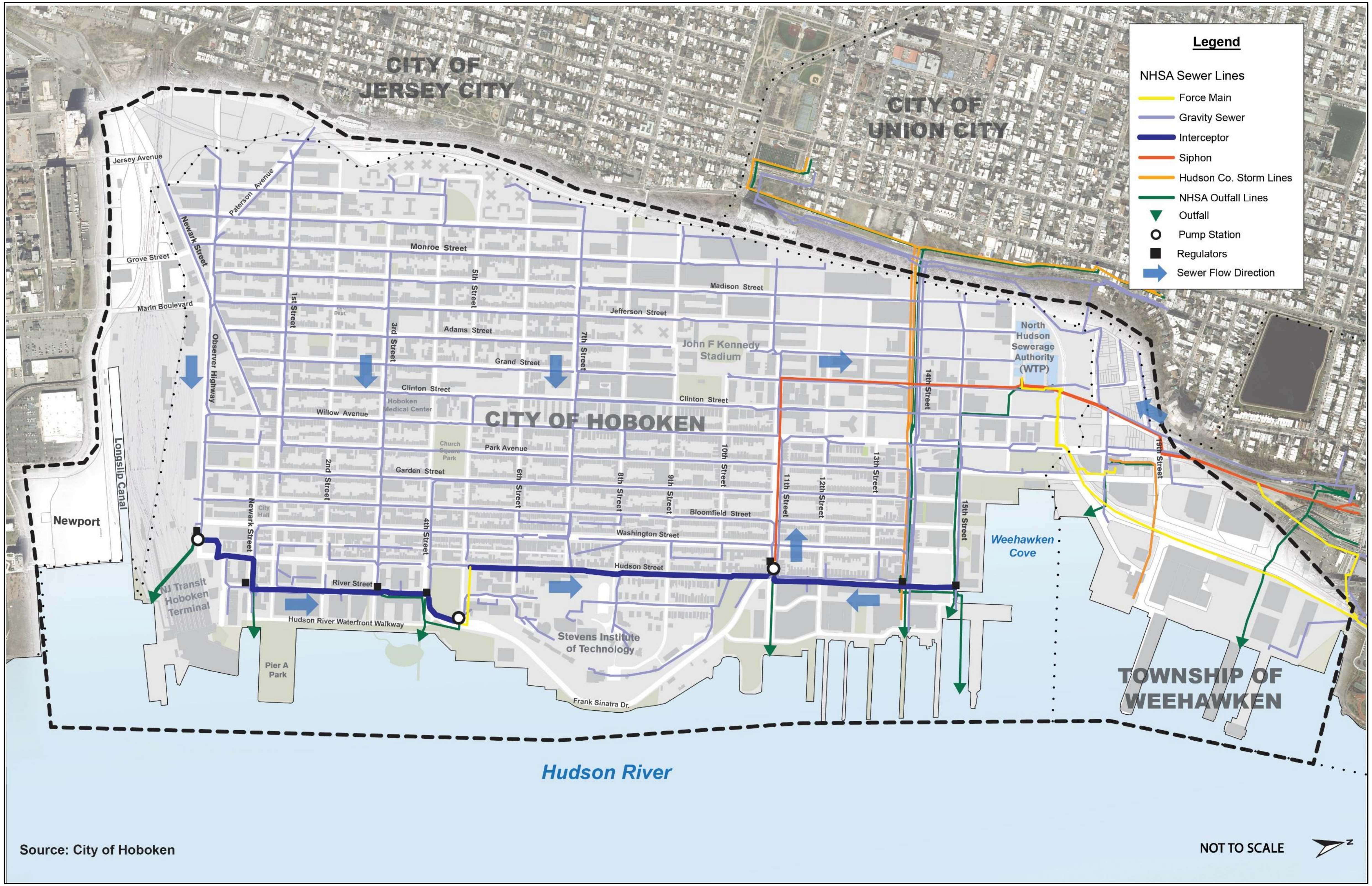


Figure 7-5. Existing Drainage Infrastructure within the Study Area

7.3 Stormwater Model Setup

The main goal of the stormwater model is to identify potential areas subject to flooding under various rainfall events in the No-Action Alternative (NAA) or the baseline conditions and then use the model to evaluate the effectiveness of the proposed Delay, Store, Discharge (DSD) components to reduce areas that are flooded in the NAA conditions. Another goal is to perform interior drainage analysis that follows 44 CFR 65.10 requirements for FEMA levee certification. Dewberry discussed the appropriate interior drainage analysis methodology with FEMA Region 2. Based on these discussions, the storm-sewer system was analyzed with two coastal conditions – one with a constant low tide and other with a constant high tide. During a constant low-tide, all the outfalls are open and can discharge freely into the Hudson River whereas with a constant high tide condition, all the outfalls are closed and only the pumps can discharge into the Hudson River. This methodology allows to demonstrate the range of areas subject to flooding under each rainfall event/tide combination scenario. It is our understanding that the results from this type of analysis can be used to satisfy the interior drainage requirements for the FEMA levee certification.

An integrated one- and two-dimensional hydrologic and hydraulic model was developed to simulate the conveyance of rainfall runoff within the City of Hoboken limits. The integrated stormwater and coastal model was developed using Danish Hydraulic Institute's (DHI) MIKE URBAN model and MIKE FLOOD module Version 2014 Service Pack 3. The MIKE URBAN and MIKE FLOOD modules are approved by FEMA to perform hydrologic and hydraulic analysis of a storm-sewer system.

7.3.1 MIKE URBAN Model and MIKE FLOOD Module Description

MIKE URBAN is a flexible hydrodynamic model to simulate conveyance of collection systems for wastewater and stormwater using the MOUSE engine. The MOUSE hydrology model utilizes the unit hydrograph method to calculate the excess rainfall runoff by using U.S. Soil Conservation Service (SCS) curve number and SCS hydrograph methods. The MOUSE pipe flow hydraulic model solves the complete Saint Venant (dynamic flow) equations throughout the drainage network (looped and dendritic), which allows to simulate backwater effects, flow reversal, surcharges in manholes, free surface and pressure flow, tidal outfalls and storage basins. The MOUSE engine is designed to handle any type of pipe network with alternating free surface and pressurized flows as well as open channel network and pipes and storage basins of any shape and geometry. The MIKE URBAN framework provides robust features for modeling pumps, weirs, orifices, inverted siphons, etc., and was therefore chosen as an appropriate model for use in this study.

The computational scheme uses an implicit, finite-difference numerical solution of the Saint Venant flow equations which ensure conservation of mass and energy/momentum. The numerical algorithm uses a self-adapting time-step, which provides efficient and accurate solutions in multiple connected branched and looped pipe networks. This computational scheme is applicable to unsteady flow conditions that commonly occur in pipes ranging from small-profile collectors for detailed urban drainage, to low-lying, often pressurized, sewer mains affected by varying outlet water levels. Both sub-critical and super-critical flows are treated by means of the same computational scheme that adapts to the local flow conditions. In addition, flow phenomena including backwater effects and surcharges are precisely simulated.

MIKE FLOOD is a module that integrates the one-dimensional model such as MIKE URBAN with MOUSE engine with a two dimensional model such as MIKE 21 into a single, dynamically coupled modeling system. The flow in the subsurface pipe system is simulated using the one-dimensional MIKE URBAN with MOUSE engine and the overland flow from the surcharged pipe system is simulated using the two-dimensional MIKE 21 overland flow model that represents the topography above the pipe system. The MIKE FLOOD module allows to simulate the conveyance and surcharge of a storm sewer system under various rainfall/tide combinations over the actual topography; thus providing a better result visualization of the areas subject to flooding. Additionally, it provides a more accurate calculation of the interaction of surcharged flows with the different parts of the drainage system.

It should be noted that MIKE URBAN and MIKE FLOOD model uses SI system units.

7.3.2 Hydrologic Model Setup

Hydrologic analysis was performed using the Unit Hydrograph Method (UHM) method in MIKE URBAN's MOUSE runoff module. The hydrologic analysis provides the sewer flow from the buildings and the rainfall runoff flow volume that enters the NHSA's storm-sewer network during the rainfall event. The hydrologic model requires the following input datasets –

- Subcatchment drainage areas
- Average daily sewer flow
- Curve Number (CN)
- Time of Concentration
- Rainfall depth, duration and distribution

NHSA provided the sewershed drainage areas within the City of Hoboken as shown in Figure 7-4. New York City Department of Environmental Protection (NYCDEP)'s catchment delineation techniques were utilized within each of NHSA's sewershed boundaries as shown in Figure 7-4. Within each sewershed, a detailed subcatchment delineation was developed using topography, building foot print data, roadway ROW, and location of drainage infrastructure (pipe, channels, manholes, etc.). Figure 7-6 shows the individual subcatchments within the entire study area used in the MIKE URBAN model; however a full-scale map showing each subcatchment labeled with identifying ID for the existing conditions (part of validation simulation) can be found in the Appendix E. Table 7-2 shows the number of subcatchments by each sewershed identified by NHSA in existing conditions. It should be noted that adjustments were made to these existing conditions subcatchments in the No-Action Alternative (NAA) and with proposed DSD alternative scenarios. Hence, the number of catchments will be slightly different in the NAA and the proposed DSD alternative scenarios.

Table 7-2. Summary of Modeled Catchments by Sewershed in Existing Conditions

NHSA Sewershed Name	Number of Catchments	Drainage Area (ha)
14VO	15	6.0
H1	532	110.5
H2	123	13.2
H3	164	25.5
H4	217	39.4
H5	263	57.9
H6	71	10.6
H7	147	29.6
HSI	16	4.0
NJ Transit	8	16.4
Jersey City	4	158.5
TOTAL	**1,560**	**471.5**

Sewer flows from each contributing subcatchment were incorporated into the MIKE URBAN model as "additional flow" for each modeled scenario. Sewer (dry weather) flows were determined using NYCDEP Sewer Design Manual (April 2000) methodology. Population density within each subcatchment was determined using Hoboken Zoning map and NYCDEP zoning criteria. Average domestic sewer flow in residential areas was assumed to be 150 gallons per capita per day. For commercial, and industrial areas, average sewage flows of 5,000 and 10,000 gallons per acre per day were assumed, respectively. A peak factor of 2 was assumed for industrial areas and 1 for the South Waterfront redevelopment plan area. The following formulas were used to estimate dry weather flow for various types of zones.

$$Dry\ Weather\ Flow, Residential = \frac{Pop.\ Density\ \left(\frac{person}{acre}\right) * Area\ (acre) * 150\ \left(\frac{\frac{gal}{person}}{day}\right)}{7.48 * 86400}$$

$$Dry\ Weather\ Flow, Commercial = \frac{Commercial\left(\frac{\frac{gal}{acre}}{day}\right) * Area\ (acre) * Factor}{7.48 * 86400}$$

$$Dry\ Weather\ Flow, Industrial = \frac{Ind.\ Waste\ Flow\left(\frac{\frac{gal}{acre}}{day}\right) * Area\ (acre) * Factor}{7.48 * 86400}$$

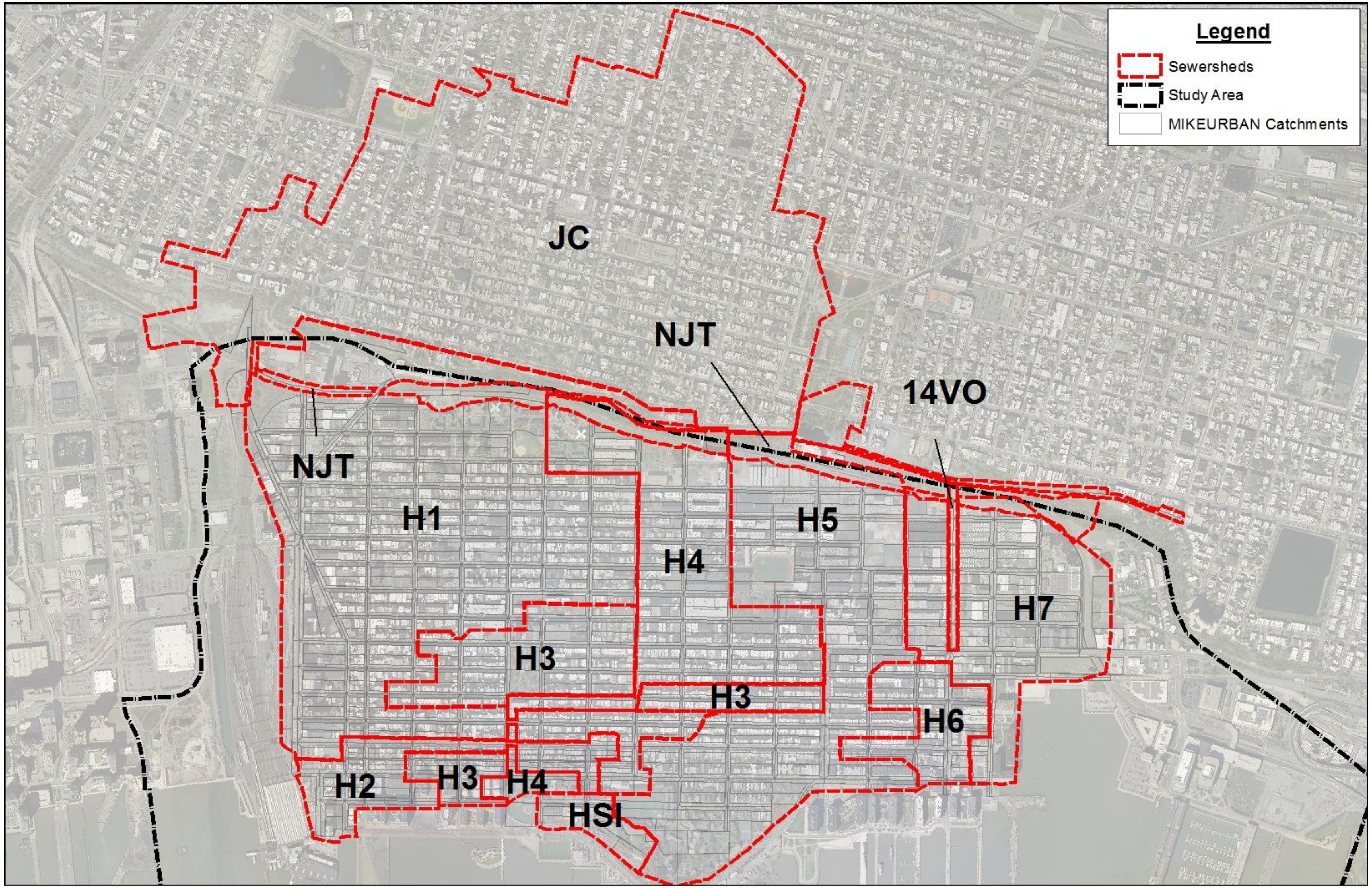


Figure 7-6. Subcatchments with Study Area's Sewersheds

Table 7-3 provides a breakdown of the various zones and the associated dry weather flows within each zone. GIS techniques were utilized to estimate the areas covered by each zone within NHSA's major sewersheds. Further analysis allowed to estimate the average daily sewer flow within each major sewershed. Additionally, since the zoning districts within the study area also included portions of the Hudson River, the dry weather flows were adjusted for each sewershed to deduct these areas. See Figure 7-7 which shows the zoning overlaid on the sewersheds. These adjustments resulted in a reduction of the total dry weather flow from 9.83 MGD to 7.2 MGD. The average daily sewer flow were then distributed for each subcatchment based on their area within each sewershed. Detailed dry weather flow calculations are included in Appendix F.

Table 7-3. Dry Weather Flows for each Zone within City of Hoboken

Zone	Type (per Hoboken Zoning Map)	**Assumed NYCDEP Zoning	Pop. Density (persons/acre)	Area (acres)	Factor	Avg. Flow (cfs)	Flow (mgd)
R-1	Residential - Conservation	R1-1	15	224	N/A	0.78	0.50
R-2	Residential - Stabilization	R2	35	132	N/A	1.07	0.69
R-3	Residential - Revitalization	R3	50	110	N/A	1.28	0.83
I-1	Industrial District	M1-2	N/A	125	2	3.87	2.50
I-2	Mixed Use	M1-2	N/A	70	2	2.17	1.40
I-1 (W)	Waterfront Sub-District	M1-2	N/A	147	2	4.55	2.94
W (RDV)	South Waterfront Redev Plan	C8-1	N/A	113	1	0.87	0.57
CBD	Central Business District	C7	N/A	40	2	0.62	0.40
			Total =	961		Total =	9.83

**Based on NYCDEP Sewer Design Manual, revised April 2000

The UHM method was chosen to simulate runoff from single storm events from the various subcatchments, by calculating the excess rainfall (precipitation), using the SCS curve number method for quantifying infiltration losses. Excess rainfall was routed by the UHM method using SCS dimensionless unit hydrographs corresponding to the total rainfall depth (inches) / intensity (mm/hr) for each modeled event. Precipitation time series based on rainfall intensity was input into the model, and the model calculates the rain intensity for each time step. Runoff computation considers all hydrological losses and composite runoff hydrographs for each subcatchment are routed to the nearest receiving manhole through catchment connections defined within the model based on data from NHSA.

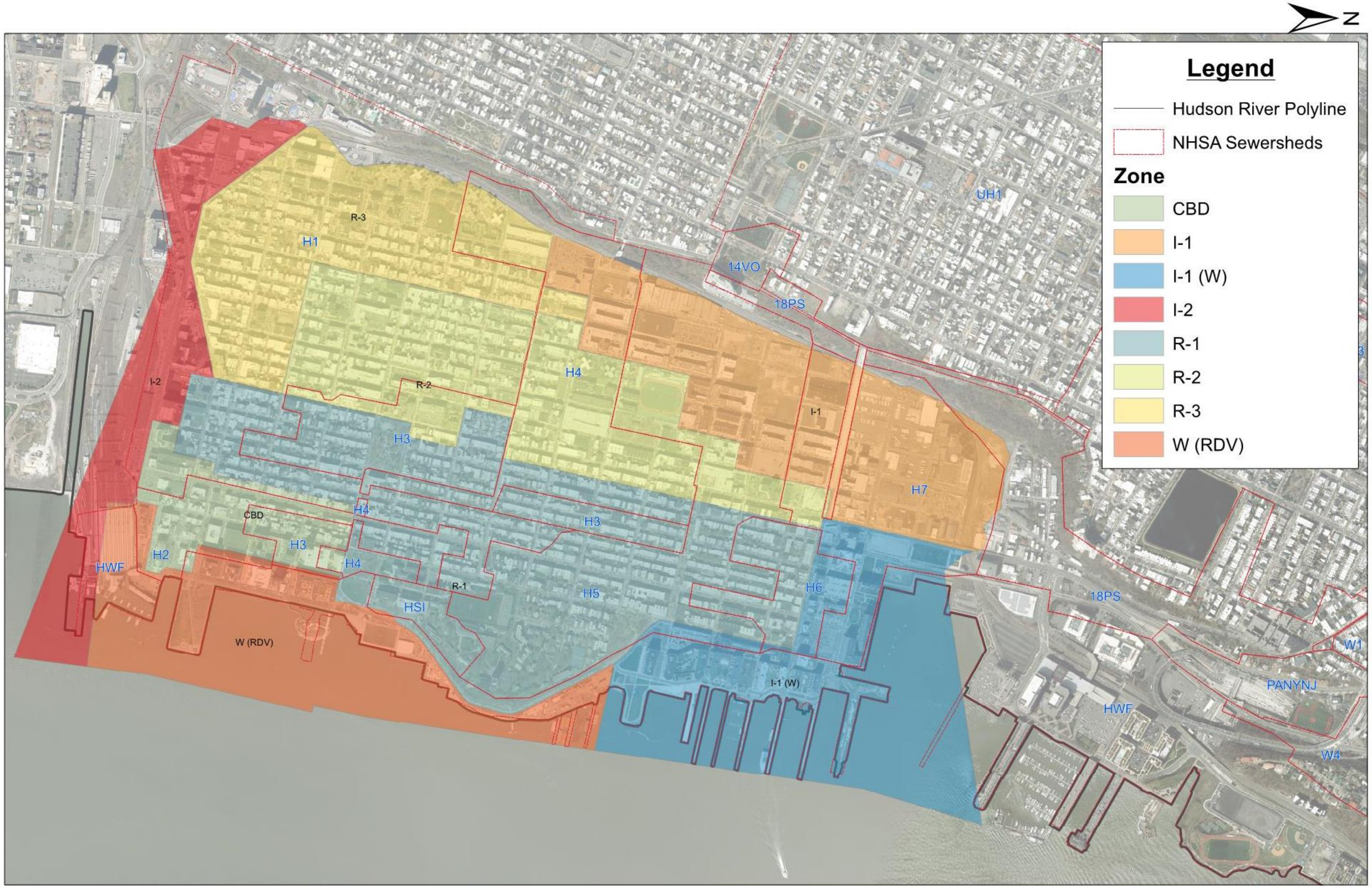


Figure 7-7. Map Overlaying Zoning Districts and Sewersheds

USDA's Natural Resources Conservation Service (NRCS) Technical Release 55 (TR-55) was utilized to develop curve numbers (CN) for various land use and soils combinations. Curve numbers in the existing conditions varied from 48 to 88 after extensive optimization of hydrologic parameters and sewershed runoff flows. Landuse and soils data was used to assign appropriate curve numbers for each subcatchment. Table 7-4 provides a summary of the land use characteristics within the study area and Figure 7-8 and Figure 7-9 show the spatial distribution of the land use and soils data. It should be noted that the soil data obtained from USDA's SSURGO database did not assign a hydrologic group the high urbanized City of Hoboken area.

Time of concentration was determined using CN lag method for each sewershed, with a minimum lag time of 5 minutes used wherever calculated lag times were less than 5 minutes. Due to the highly urbanized nature of the study area, runoff conditions would likely induce sheet flow therefore lag times in general vary from 5 minutes to 15 minutes. The sole exception is a lag time of 1.5 hours used to approximate the Jersey City network flows. Hydrologic parameters (area, CN, and times of concentration) for the individual subcatchments in each modeled scenario are included in Appendix G.

Table 7-4. Land Use Characteristics in the Study Area

No	Landuse Classification	Area (Hectares)	% Of Total Area
1	Artificial Lakes	0.29	0.06%
2	Athletic Fields (Schools)	4.56	0.96%
3	Commercial/Services	72.70	15.34%
4	Deciduous Brush/Shrubland	2.97	0.63%
5	Deciduous Forest (10-50% Crown Closure)	7.86	1.66%
6	Industrial	23.47	4.95%
7	Mixed Urban Or Built-Up Land	27.57	5.82%
8	Old Field (< 25% Brush Covered)	0.07	0.02%
9	Other Urban Or Built-Up Land	17.51	3.69%
10	Railroads	11.23	2.37%
11	Recreational Land	17.28	3.65%
12	Residential, High Density Or Multiple Dwelling	268.44	56.66%
13	Stormwater Basin	1.65	0.35%
14	Tidal Rivers, Inland Bays, And Other Tidal Waters	0.01	0.00%
15	Transitional Areas	1.74	0.37%
16	Transportation/Communication/Utilities	16.46	3.47%
	TOTAL AREA (HECTARES)	**473.82**	**100.00%**

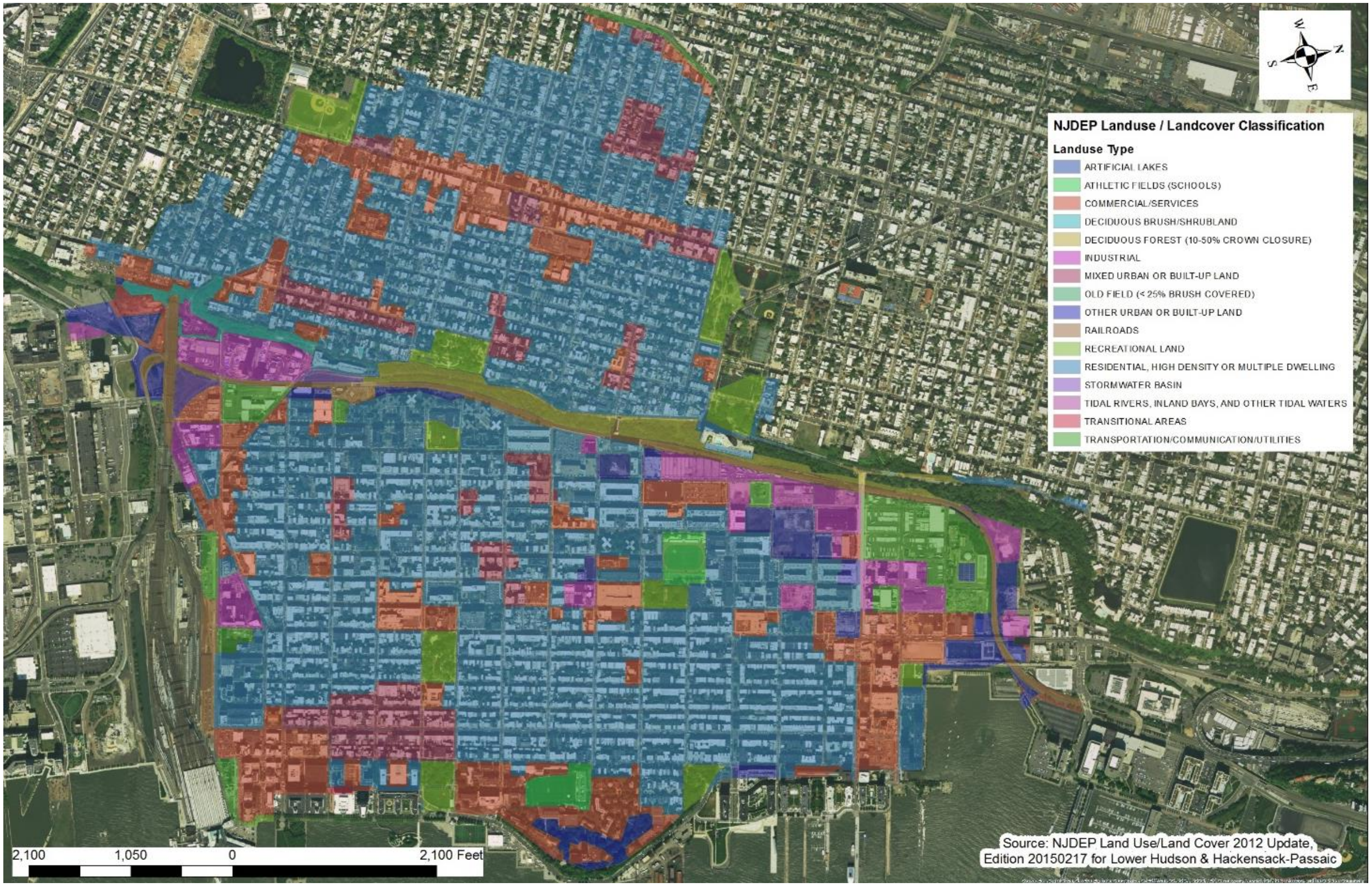


Figure 7-8. Land Use and Land Cover over the Model Area

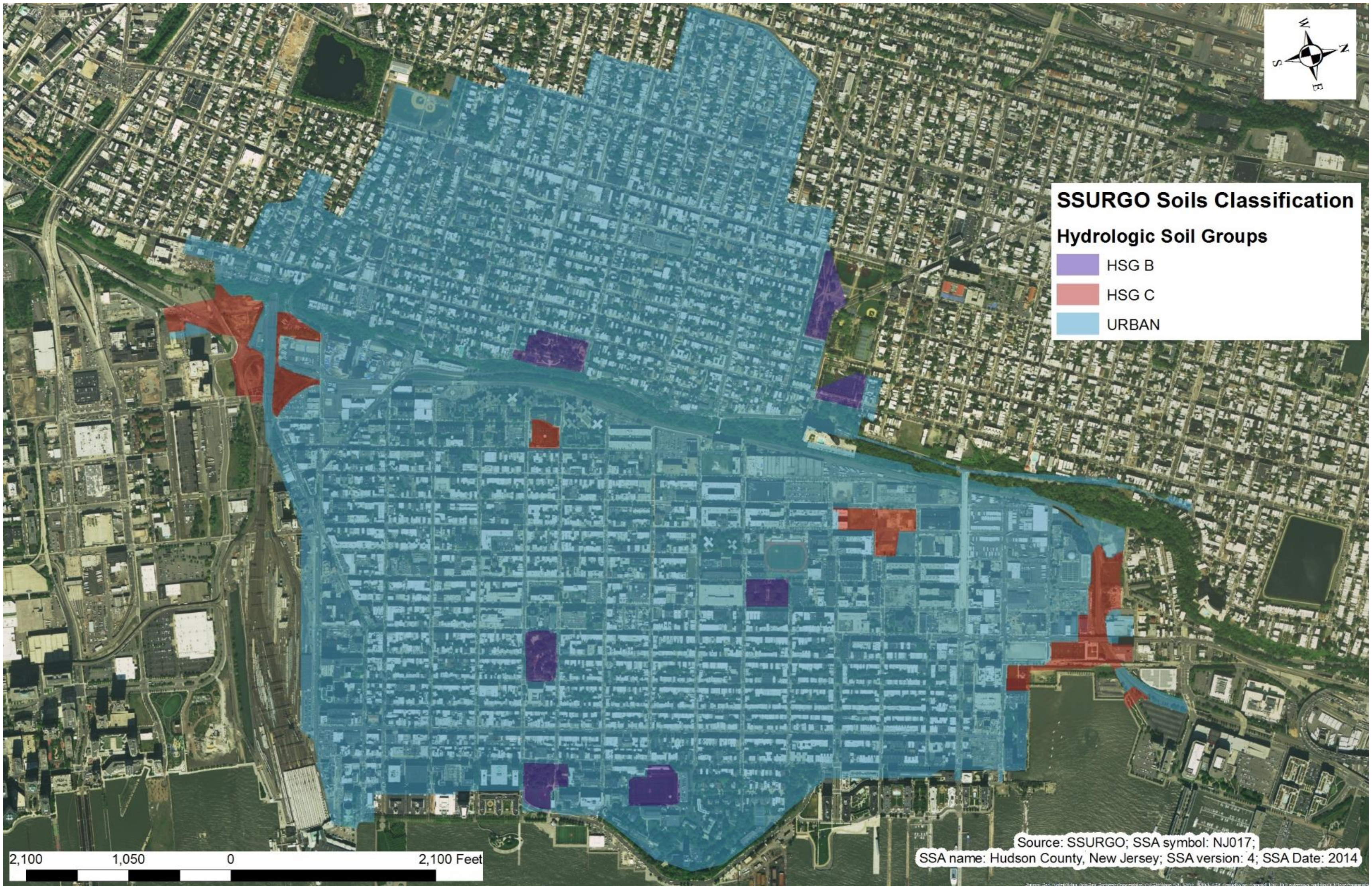


Figure 7-9. Soils Classification over the Model Area

Figure 7-10. Impervious Area over the Model Area (from USGS NLCD 2011 Landcover data)

The rainfall depths with return periods corresponding to the 5-, 10-, 25-, 50- and 100- year recurrence intervals were obtained from NOAA Atlas 14 as shown in Table 7-5. The SCS Type III rainfall distribution which is applicable for the State of New Jersey was used to develop rainfall depth distribution using the 24 hour rainfall depths from NOAA Atlas 14. Table 7-5 and Table 7-6 shows the 24 hour rainfall depth for various rainfall return period and rainfall distribution, respectively. Figure 7-11 shows the 24 hour rainfall distribution graph used to simulate hydrologic conditions for various rainfall return period events in the MIKE URBAN model.

Table 7-5. 24-hour Rainfall Depths from NOAA Atlas 14

Return Period	Rainfall Depth (mm.)	Rainfall Depth (inches)	Max. Intensity (mm/hr)
5 year	106.68	4.2	26.78
10 year	125.98	5.0	31.62
25 year	154.94	6.1	38.89
50 year	179.58	7.1	45.07
100 year	206.50	8.1	51.83

Table 7-6. SCS Type III Rainfall Distribution Table for various Rainfall Return Periods

Duration (hours)	Rainfall Intensity (mm/hr)				
	5 Year	10 Year	25 Year	50 Year	100 Year
0	0	0	0	0	0
1	1.07	1.26	1.55	1.80	2.07
2	1.07	1.26	1.55	1.80	2.07
3	1.28	1.51	1.86	2.15	2.48
4	1.17	1.39	1.70	1.98	2.27
5	1.60	1.89	2.32	2.69	3.10
6	1.49	1.76	2.17	2.51	2.89
7	1.81	2.14	2.63	3.05	3.51
8	2.77	3.28	4.03	4.67	5.37
9	3.52	4.16	5.11	5.93	6.81
10	4.37	5.17	6.35	7.36	8.47
11	6.51	7.69	9.45	10.95	12.60
12	26.67	31.50	38.74	44.89	51.63
13	26.78	31.62	38.89	45.07	51.83
14	6.40	7.56	9.30	10.77	12.39
15	4.05	4.79	5.89	6.82	7.85
16	3.95	4.66	5.73	6.64	7.64
17	1.92	2.27	2.79	3.23	3.72
18	1.92	2.27	2.79	3.23	3.72

Duration (hours)	Rainfall Intensity (mm/hr)				
	5 Year	10 Year	25 Year	50 Year	100 Year
19	1.81	2.14	2.63	3.05	3.51
20	1.92	2.27	2.79	3.23	3.72
21	1.28	1.51	1.86	2.15	2.48
22	1.07	1.26	1.55	1.80	2.07
23	1.07	1.26	1.55	1.80	2.07
24	1.17	1.39	1.70	1.98	2.27
Total Rainfall (mm)	**106.68**	**125.98**	**154.94**	**179.58**	**206.50**

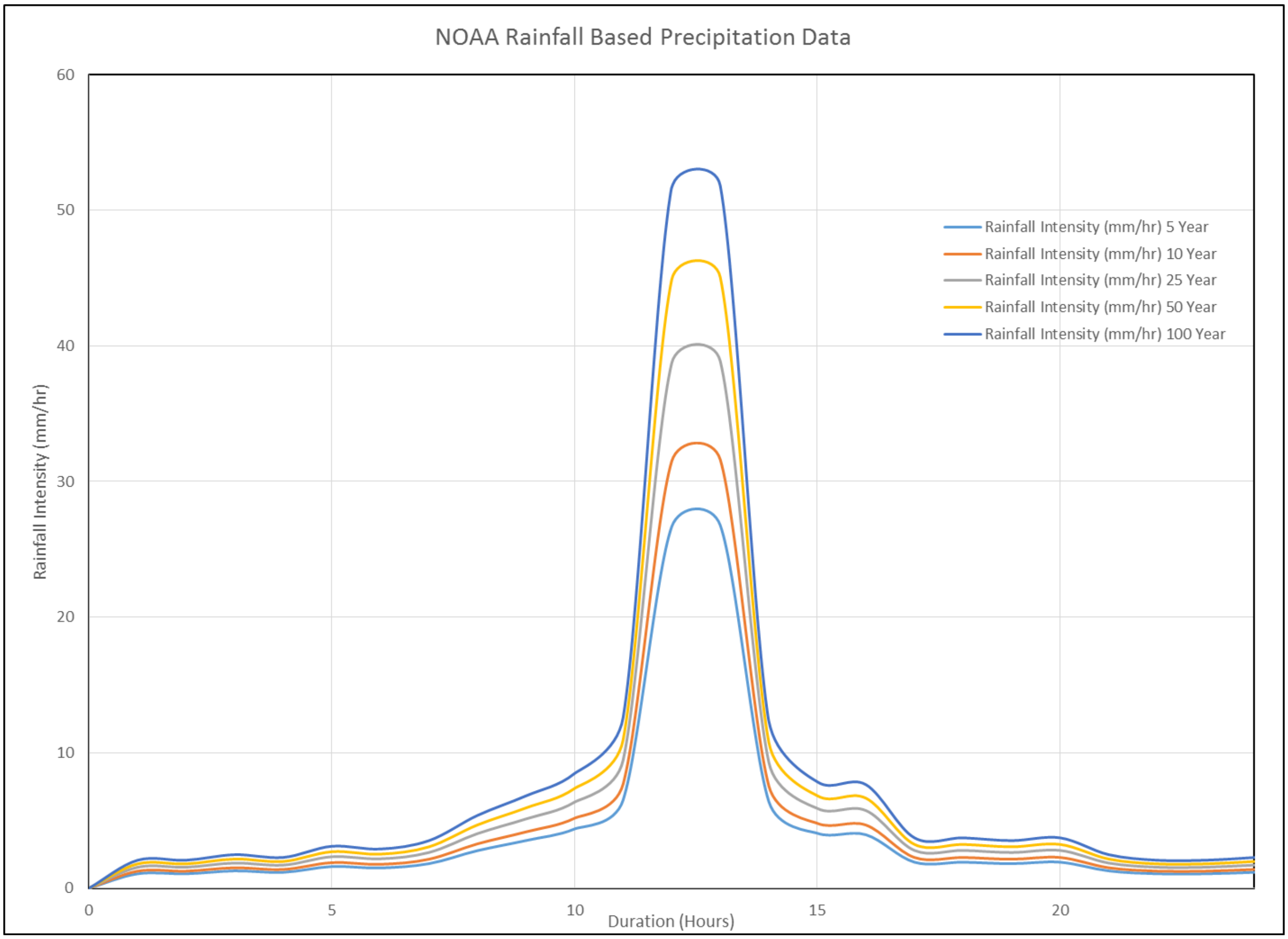


Figure 7-11. 24 Hour Rainfall Distribution Graph for the Modeled Storm Events

7.3.3 Hydraulic Model Setup

The MIKE URBAN model's MOUSE engine was utilized to develop the storm-sewer collection system network to simulate the conveyance of sewer and rainfall runoff flows within the City of Hoboken. NHSA provided their best-available data on their collection system either in the form of GIS datasets, reports and conceptual level hydraulic model for Adams Street WWTP. However, NHSA did not have any datasets such as water levels and flow measurements taken during various rainfall induced flooding events. Additionally, NJ Transit provided data on the drainage canal adjacent to the Hudson Bergen Light Rail (HBLR) system. The MIKE URBAN requires the following inputs to represent the collection system network –

- Location of manholes (X and Y coordinates), invert and overt elevations and their sizes
- Location of pipes (X and Y coordinates), size of pipes, material of pipe, connections to appropriate manholes, and invert elevations
- Cross-section of channels/canals that include the shape of channel/canal
- Location of regulators (X and Y coordinates) and configuration of regulators including inverts and weir elevations
- Location of pumps (X and Y coordinates), pump curves and trigger elevations
- Location of outfalls (X and Y coordinates) and invert elevations

The NHSA and NJ Transit's dataset consisting of pipes, manholes, channels, regulators, outfalls and pumps were imported into MIKE URBAN model to develop the conveyance network system within the City of Hoboken. The hydraulic model development steps included definition of network data, specification of tidal boundary conditions, adjustment of computation parameters through a validation process, and results analysis. Hydraulic elements incorporated into the model include nodes (manholes), structures (storage basins for large sized manholes, rain gardens, etc.), pipes, open channels, weirs, orifices, and pumps.

Wet weather stormwater flows and dry weather sewer flows were routed to the nearest manhole, and conveyed through gravity sewer flow pipes to the interceptor line through the system of regulators, forced main, and siphon that would discharge into Adams Street WWTP and the outfalls. During the data analysis process, several gaps and shortcomings in NHSA's datasets were identified. In addition to missing invert elevations for several manholes and pipes, at several locations, there were major inconsistencies between the sewer manhole and pipe invert elevations. There were also challenges where data was available; for instance, even when all inverts were known for a set a pipes, the slope was frequently adverse to the intended direction of flow. Dewberry brought these issues to NHSA's attention and they agreed that some of their sewers within the system are back pitched. After a thorough and detailed review of the data, the following assumptions were made to fill-in the data gaps in NHSA's storm-sewer data that would allow to evaluate the hydraulic conditions at a feasibility level:

- Runoff was routed directly to the manholes so that catch basins (inlets) were not imported into the model

- Use only current, active, and verified pipes and manholes data from NHSA dataset
- Where hydraulically defendable, remove redundant manholes retaining the pipe slope based on valid upstream and downstream manhole inverts
- Follow topography and vicinity drainage patterns to connect subcatchments to receiving manholes/pipes
- Manhole diameter size of 1 meter

NHSA's conceptual facility planning level Infoworks model for Adams Street WWTP was utilized to obtain inverts for the outfalls, pump station curves and regulator information. Weirs were modeled using weir type, crest level, crest width, orientation and water level based functional relations connecting two nodes. Orifices were modeled as devices connecting two nodes using orifice type, discharge coefficient and control rules. At the regulator locations, gates within a weir or an orifice were incorporated into the model. The gate starts closing from the top of the orifice downwards until the gate is completely closed once the trigger water level is achieved during the simulation. The weir moves upwards from the bottom of the orifice and closes completely when the weir crest reaches the top of the orifice opening. Figure 7-12 shows an example of how the regulators were set up in MIKE Urban.

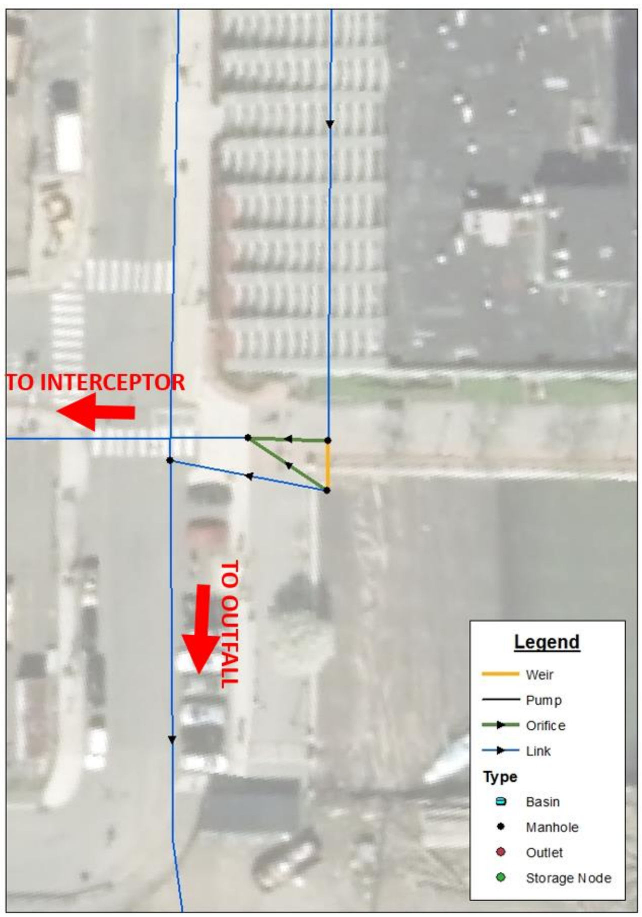


Figure 7-12. Example of a Regulator in MIKE Urban

Using the above stated assumptions and model development methodology, a collection system model was developed to simulate the conveyance of sewer and rainfall runoff within City of Hoboken as shown in Figure 7-13. Refer to Appendix H for large scale maps of the model hydraulic network. Table 7-7 shows the various types of pipes within the model domain and the associated Manning's "n" and "M" roughness coefficients. At all of the outfalls, a loss coefficient (Km) value of 0.25 was specified in the MIKE URBAN model.

Table 7-7. Pipe Material and Roughness Coefficients

Pipe Material	Manning's n	Manning's M
Concrete	0.0150	66.7
Brick	0.0160	62.5
Cast Iron	0.0130	76.9
Ductile Iron	0.0130	76.9
Reinforced Concrete	0.0150	66.7
Vitrified Clay	0.0130	76.9

A rainfall – tide correlation analysis was performed and is included in Appendix I. According to Section 3.2 in Hydrologic Analysis of Interior Areas, USACE EM 1110-2-1413 (15 January 1987), a joint probability type analysis is probably not applicable for areas served by CSO systems like in the City of Hoboken. Dewberry discussed the appropriate interior drainage analysis methodology with FEMA and concluded to simulate the storm-sewer system with two conditions – average low tide and average high conditions – in the Hudson River. The observed tidal data at Battery gage was evalutaed to obtain average low and high tide values of -1.05 meters and 0.95 meters (NAVD datum) to be used as boundary conditions at the outfalls for each rainfall recurrence storm event.

Figure 7-13. Hydraulic Model Network Key Plan (Hurricane Irene Conditions)

7.3.4 Integrated Stormwater and Coastal Model Setup

A two-dimensional MIKE 21's rectilinear model mesh that represent the overland topography over the collection system network was developed using MIKE URBAN flood model. The MIKE 21 model mesh simulates overland flow from surcharged manholes (nodes) in the MIKE URBAN model. A 3 meter resolution post Sandy LiDAR topography was used to create a rectilinear fixed mesh. The mesh cell size of 4 meter that was optimized through an iterative process to ensure accuracy and efficiency in the model simulations. Through an iterative process, approximately 200 manholes (nodes) that are typically surcharged for various rainfall return period events were connected to the two-dimensional model mesh via standard link option in the MIKE FLOOD module. A constant Manning's M of 40 (Manning's n of 0.025) was assigned to reflect the bed roughness for the street which would be subject to overland flooding. Additional parameters included drying and flooding depths of 0.002m and 0.003m, respectively.

Figure 7-14 and Figure 7-15 shows the two-dimensional MIKE 21 rectilinear model mesh and the resultant topographic mesh with all of the nodes that were coupled from the MIKE URBAN's hydraulic model to the two-dimensional overland topography mesh, respectively. Full-scale maps showing the coupled nodes with the MIKE Urban pipe network can be found in Appendix H. Table 7-8 summarizes the typical model simulation parameters used to simulate the integrated stormwater and coastal model within the MIKE FLOOD module.

Table 7-8. Model Setup Parameters

Parameter	Values
Simulation time step	0.75 seconds
Duration of simulation	24 hours

First, hydrologic conditions were simulated to generate a runoff output file with the flow volumes for each subcatchment. This runoff file is dynamically linked to the collection systems model in MIKE URBAN which takes the flows from the runoff from each subcatchment and routes it through the storm-sewer system. All the outfalls have a constant tide elevation to reflect the coastal conditions either as a low tide or high tide condition. During the entire model simulation duration, if a manhole is surcharged and is connected to the two-dimensional MIKE 21 overland flow mesh, then the runoff volume from this surcharged manhole flows overland onto an area that can temporarily store this surcharged runoff volume.

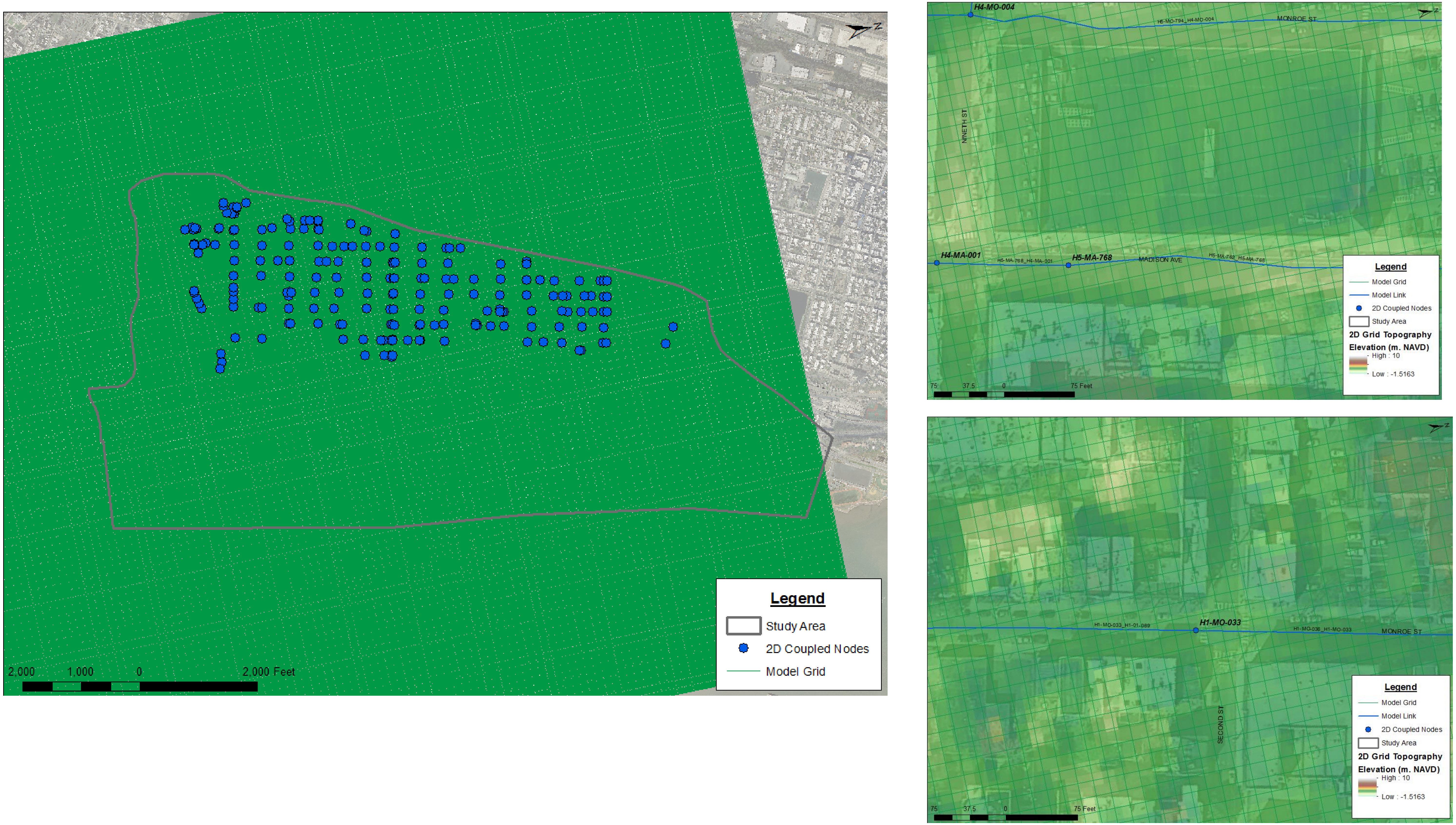


Figure 7-14. Map showing the Overall and Zoomed in MIKE 21's 2-D Overland Flow Model Mesh

Figure 7-15. MIKE URBAN 2D Topography and Coupled Nodes

7.3.5 Model Simulation Scenarios

The No-Action Alternative (NAA) scenario with the on-going or completed stormwater management projects were developed using data provided by City of Hoboken and NHSA. As part of Task 5-Feasibility Assessment, various components for the "Delay, Store, Discharge" (DSD) alternative were developed. A description of the NAA and DSD alternative is provided in Section 9 of this report. Prior to evaluating the NAA scenario, the integrated stormwater and coastal model was validated using the observed datasets from the 2011 Hurricane Irene storm. Details regarding the model validation scenario is provided in Section 8 of this report. As stated previously, the effectiveness of the storm-sewer system was evaluated for various rainfall events/tide combinations. Table 7-9 provides a list of twenty (20) integrated stormwater and coastal model scenarios that were simulated using the MIKE URBAN and MIKE FLOOD modules.

Table 7-9. Integrated Stormwater and Coastal Model Simulation Scenarios

Model Scenario No.	Scenario Conditions	Rainfall Event	Tide Conditions
1	Model Validation	Hurricane Irene Rainfall	Boundary at Battery during Hurricane Irene
2	No-Action Alternative (NAA)	5-year, 24-hour duration	Low Tide in Hudson River
3	No-Action Alternative (NAA)	5-year, 24-hour duration	High Tide in Hudson River
4	No-Action Alternative (NAA)	10-year, 24-hour duration	Low Tide in Hudson River
5	No-Action Alternative (NAA)	10-year, 24-hour duration	High Tide in Hudson River
6	No-Action Alternative (NAA)	25-year, 24-hour duration	Low Tide in Hudson River
7	No-Action Alternative (NAA)	25-year, 24-hour duration	High Tide in Hudson River
8	No-Action Alternative (NAA)	50-year, 24-hour duration	Low Tide in Hudson River
9	No-Action Alternative (NAA)	50-year, 24-hour duration	High Tide in Hudson River
10	No-Action Alternative (NAA)	100-year, 24-hour duration	Low Tide in Hudson River
11	No-Action Alternative (NAA)	100-year, 24-hour duration	High Tide in Hudson River

Model Scenario No.	Scenario Conditions	Rainfall Event	Tide Conditions
12	Delay, Store, Discharge Alternative (DSD)	5-year, 24-hour duration	Low Tide in Hudson River
13	Delay, Store, Discharge Alternative (DSD)	5-year, 24-hour duration	High Tide in Hudson River
14	Delay, Store, Discharge Alternative (DSD)	10-year, 24-hour duration	Low Tide in Hudson River
15	Delay, Store, Discharge Alternative (DSD)	10-year, 24-hour duration	High Tide in Hudson River
16	Delay, Store, Discharge Alternative (DSD)	25-year, 24-hour duration	Low Tide in Hudson River
17	Delay, Store, Discharge Alternative (DSD)	25-year, 24-hour duration	High Tide in Hudson River
18	Delay, Store, Discharge Alternative (DSD)	50-year, 24-hour duration	Low Tide in Hudson River
19	Delay, Store, Discharge Alternative (DSD)	50-year, 24-hour duration	High Tide in Hudson River
20	Delay, Store, Discharge Alternative (DSD)	100-year, 24-hour duration	Low Tide in Hudson River

The maximum flood inundation areas for each of the NAA and DSD alternative was extracted from each integrated model simulations. These flood inundation areas were analyzed using GIS techniques to evaluate the effectiveness of the proposed DSD alternative over the NAA scenarios. Section 9 of this report provides details on the NAA and DSD alternatives.

8 Stormwater Model Validation

Various datasets such as reports and anecdotal information provided by NHSA and others regarding flood extents during various rainfall events were obtained and evaluated. Based on this evaluation, limited information such as rainfall depths, tidal conditions, flood inundation photos and anecdotal information for Hurricane Irene (August 27 – 29, 2011) was then used to validate the integrated stormwater and coastal model. The model uses observed tide levels at NOAA Battery gage and observed rainfall data from Central Park for the entire 24-hour Hurricane Irene simulation duration from 9 am on August 27th, 2011 to 9 am on August 28th, 2011. Due to unavailability of observed and verified high water mark elevation during this storm, Dewberry utilized photos from social media to estimate the extent of flooding and flood depths at key locations such as Madison & 9th Street, and Harrison & 1st Street within City of Hoboken.

8.1 Hurricane Irene Observed Conditions

Figure 8-1 shows the time series data for rainfall depths observed at Central Park and the tidal conditions at Battery gage during Hurricane Irene.

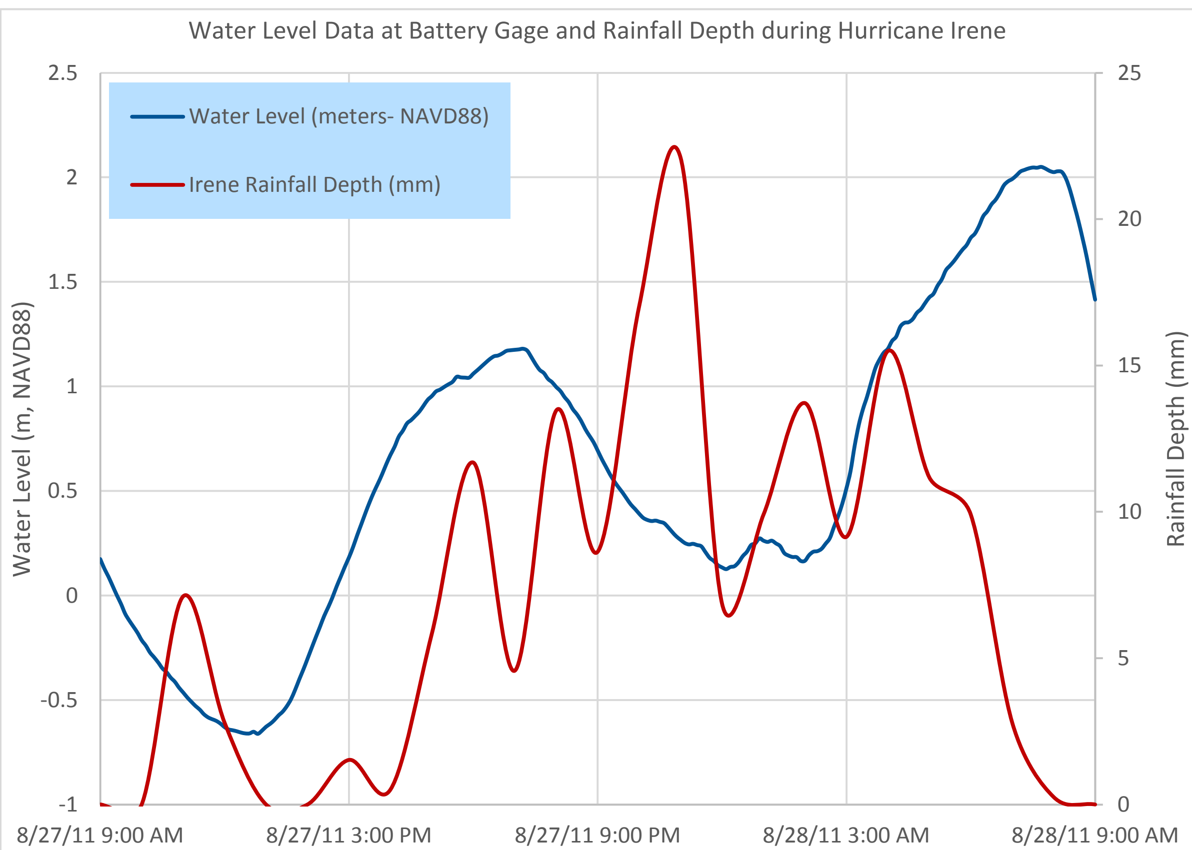


Figure 8-1. Rainfall and Tide Data at Central Park and Battery, respectively, during Hurricane Irene

Since rainfall gage data was unavailable in the City of Hoboken study area, a comparison with the observed rainfall depths from Central Park, NY with other available rainfall gage data was conducted. Table 8-1 below compares the rainfall depth recorded during Hurricane Irene at three nearby rainfall gage stations which can be seen spatially in Figure 8-2. The Emnet monitoring reports (Emnet 2011, 2013) indicates that the rainfall depths at Central Park, NY were similar to those observed in City of Hoboken during Hurricane Irene. Additionally, the Central Park gage is the closest gage to the City of Hoboken limits which indicates that the rainfall depths observed at Central Park have the potential to be in similar range to those observed during Hurricane Irene. Hence, the rainfall depths from Central Park, NY gage was utilized for the Hurricane Irene model simulation.

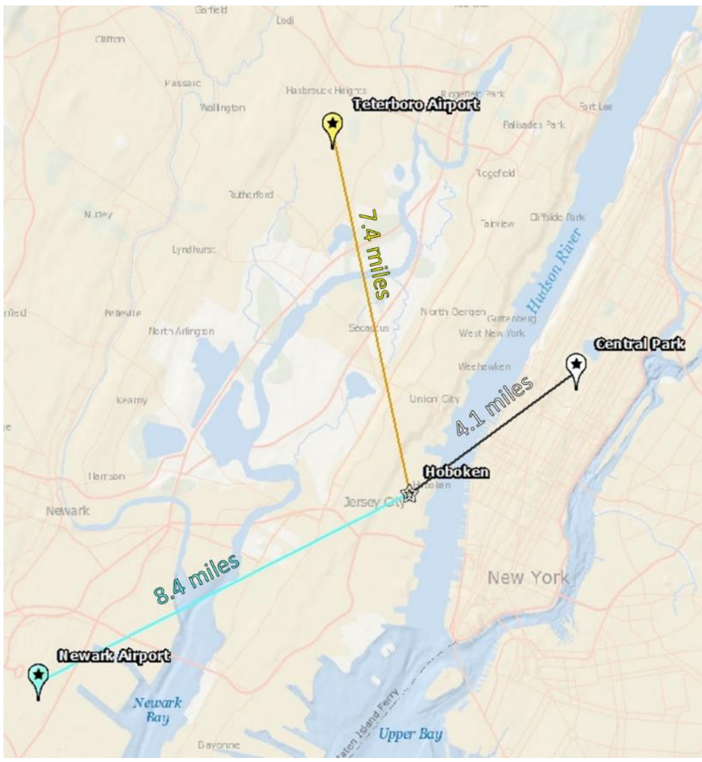


Figure 8-2. Map showing Spatial Location of Rain Gauge Locations from Study Area

Table 8-1. Rainfall Depths at various locations around City of Hoboken, NJ

Rain Gauge	Total Rainfall Depth during Irene (in.)	Distance to Hoboken (mi.)
Central Park, NY	6.87	4.1
Newark Airport, NJ	8.92	8.4
Teterboro Airport, NJ	7.62	7.4

The following observations during large storm events provided in Emnet report (Emnet, 2011) were used as part of the model validation:

- Flooding was detected in H1, H4, and H5 sewersheds. Flooding is likely to occur in H7 sewershed
- Northern regulators were able to overflow
- Flows from H3 sewershed into H1 aggravated H1 flooding issues without providing any benefit to H3
- Flows from H5 aggravated flooding in H7 and H4
- H5 was able to relieve excess flows into H4 and H7
- When a storm occurs during high tide, outfalls are not able to discharge excess water into the river
- Flooding was detected at Marshall at 5th Street, Jackson at 5th Street, Willow Avenue at Newark Avenue, and Madison at 9th Street

Figure 8-3 and Figure 8-4 shows the known flooding locations from the Emnet Report (Emnet, 2011) during Hurricane Irene and the general chronic flood prone areas identified by the City of Hoboken, respectively.

Figure 8-3. Observed Flood Locations during Hurricane Irene by Emnet LLC

Figure 8-4. Flood Prone Areas Identified by the City of Hoboken

8.2 Stormwater Model Parameter Adjustments

Several model iterations were performed by adjusting some hydrologic and hydraulic parameters to validate the integrated stormwater and coastal model. The primary parameter adjusted were curve numbers (CN) which allowed the model to generate adequate rainfall runoff volume which would allow the model to match the observed inundated areas within City of Hoboken. With the lack of high water mark type data, and qualitative observations, CN values were adjusted at a sewershed level to reduce the flows and validate the model against observed conditions. CN value reduction of 20% for H4 and H5, and 10% for all other sewersheds yielded water surface elevations that matched the ones observed during Irene at known areas. In general, the CN values of 98 that reflected urban areas were reduced to CN value of 88 which is on the lower end of the acceptable CN values for the urban areas. It should be noted that some of the newer residential and commercial development within the City of Hoboken especially in H4 and H5 sewersheds have on-site stormwater management system which would justify use of lower values for curve numbers. Table 8-2 provides a summary of the model parameters used for the Hurricane Irene validation simulation scenario.

Table 8-2. Model Parameters for Hurricane Irene Scenario

Parameters	Value
No. of subcatchments	1,560
No. of manholes	658
No. of pipe segments	669
No. of pumps	5
No. of weirs and orifices combined	30

8.3 Stormwater Model Validation Results

As stated in previous section, social media such as YouTube videos were used to estimate observed flood depths at identifiable locations to validate model simulated water depths. Appendix J shows a compilation of still shots from these videos and Table 8-3 compares the water depth observed from the photos and the water depths simulated by the model. Figure 8-5 provides the spatial locations of these photos. Figure 8-6 compares the flood inundation areas simulated by the model with the observed flood locations from the Emnet report (Emnet, 2011). As seen from these figures and tables, during Hurricane Irene, the southern and western portions of Hoboken were flooded by the rainfall event. It should be noted that NHSA did not have any wet weather pump stations at the time of Hurricane Irene to pump excess rainfall runoff from portions of Hoboken into the Hudson River. The flood prone areas identified by City of Hoboken (Figure 8-4) witnessed flooding during Hurricane Irene. The flood depths ranged between 0.5 – 2.5 feet at various locations within the City of Hoboken during Hurricane Irene. The model simulates that approximately 129 acres within City of Hoboken was inundated during Hurricane Irene. Dewberry confirmed the extent of flooding with NHSA's anecdotal knowledge of flood extents during Hurricane Irene. Appendix K provides the input and output results for Hurricane Irene from the MIKE URBAN and MIKE FLOOD model.

Table 8-3. Comparison of Observed and Model Simulated Flood Depths

ID	Location	Flood Depth from Photo (ft.)	Model Predicted Depth (ft.)
1	2nd St.- Walking East towards Jackson St.	1	0.04 - 1.71
2	Harrison St. & 2nd St.	2	1.71
3	Clinton St. & 2nd St.	2	1.61
4	Grand St. & 2nd St.	1	1.12
5	Jackson St. & 4th St.	2	1.48 - 1.7
6	Jackson St. between 3rd and 4th St.	2	1.4 - 1.7
7	Monroe St. & 3rd St.	0 - 0.5	0.13 - 0.44
8	Monroe St. & 9th St.	0.5 - 2	0.39 - 1.63
9	Jackson St. & 4th St.	1.5	1.57
10	Jackson St. & 2nd St.	1	0.74
11	Monroe St. & 10th St.	1	1.19
12	Madison St. & 10th St.	2	2.26
13	Jefferson St. & 4th St.	0.5	0.62

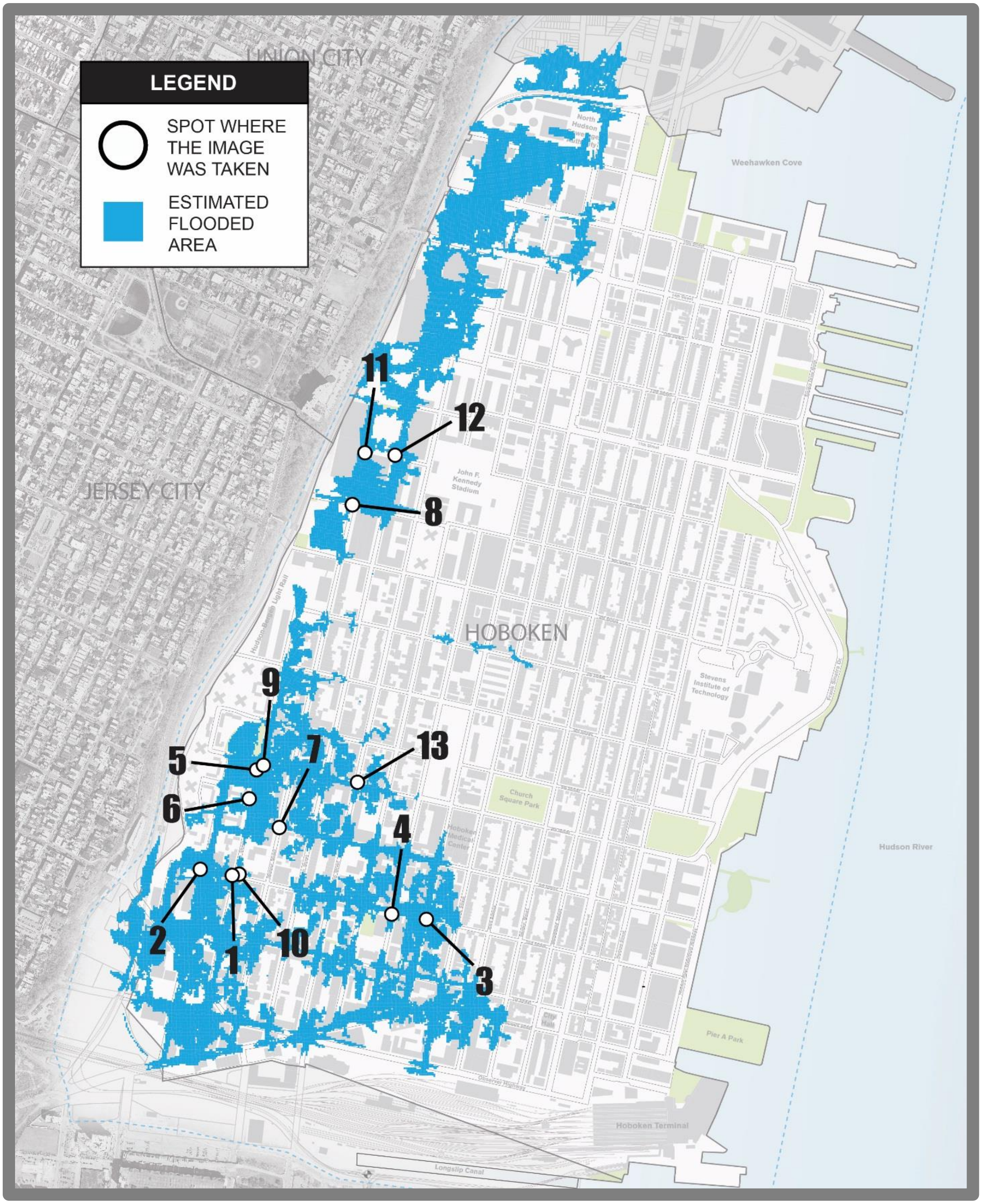


Figure 8-5. Locations of Photos Used for Model Validation

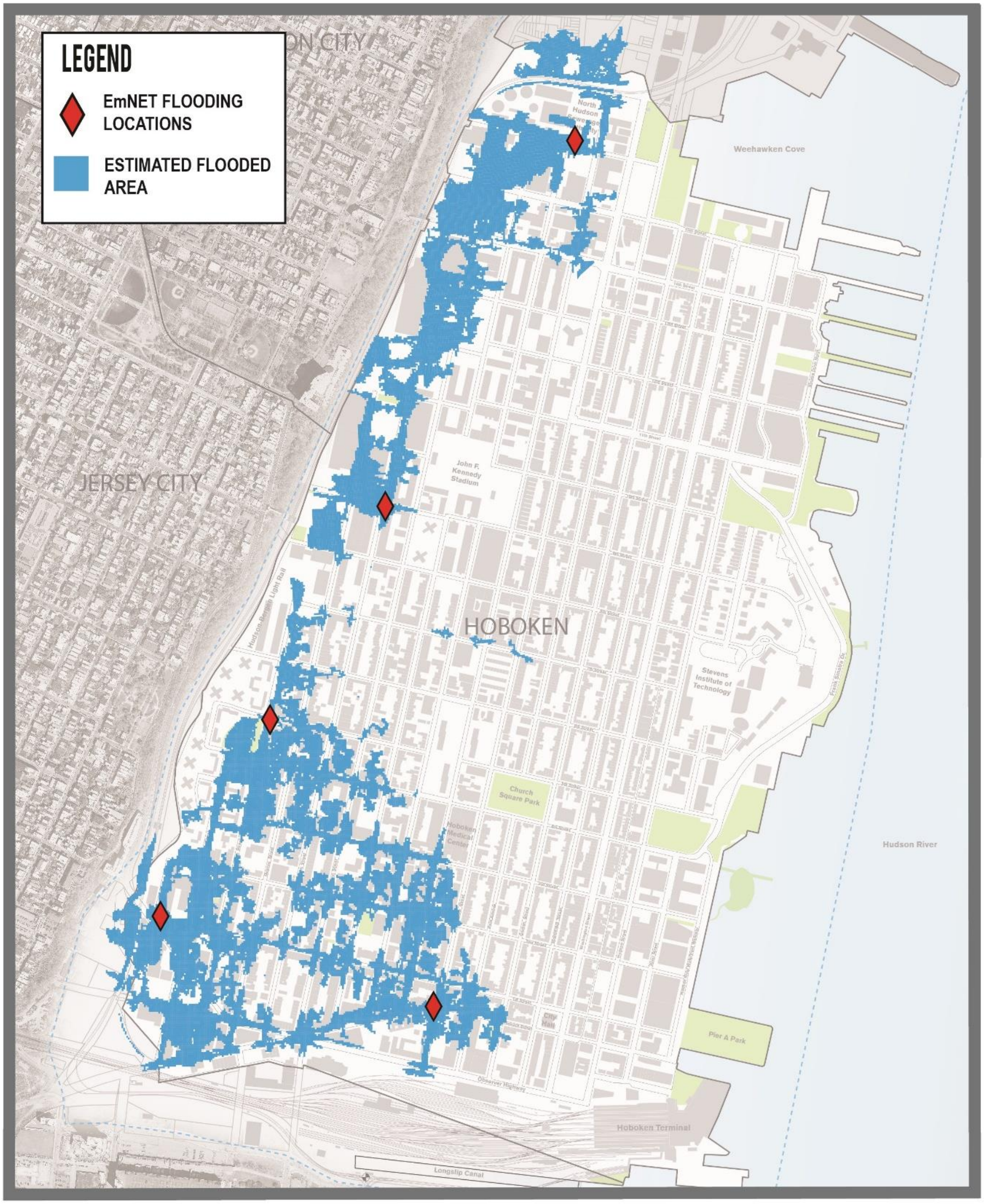


Figure 8-6. Comparison of Model Simulated Flood Inundation Areas with Observed Flooding Locations from Emnet, LLC

9 Stormwater Modeling Alternatives and Results

The validated integrated stormwater and coastal model was updated with stormwater management projects that are currently on-going along or completed after Hurricane Irene (year 2011) to develop the No-Action Alternative (NAA) model. The NAA model was then updated with all the proposed "Delay, Store, Discharge" DSD components to evaluate the effectiveness of the DSD components to reduce flooding from various rainfall events.

9.1 No-Action Alternative (NAA) Stormwater Model Results

Figure 9-1 shows the locations of the projects included as part of the No-Action Alternative (NAA). A description of these projects is provided below -

a. H1 (Wet Weather) Pump Station – 2 pumps with 50 MGD pump capacity that discharges excessive rainfall runoff primarily from H1 sewershed directly to the Hudson River.
b. H5 (Wet Weather) WW Pump Station – 2 pumps with 41 MGD pump capacity that discharges excessive rainfall runoff primarily from H5 sewershed directly to the Hudson River.
c. Southwest Resiliency Park (Block 12) – A multipurpose park located within H1 sewershed that has potential to store, delay and discharge up to 200,000 gallons of rainfall runoff.
d. City Hall Site Green Infrastructure Improvements – Consists of 4 cisterns and 2 rain gardens that together treat about 14,000 gallons of stormwater.
e. Washington Street Rain Gardens – 15 rain gardens with potential for each rain garden to store and delay at least 5,000 gallons of rainfall runoff along portions of Washington Street

NHSA and City of Hoboken reports provided the required input data such as pump curves, inflow hydrographs, outflow flow hydrographs, storage volume capacity and other parameters for the above listed projects. It should be noted that the stormwater management system proposed at Pino site located at 7th street and Jackson Street in City of Hoboken was not included as part of the NAA alternative due to uncertainty in the implementation of this proposed project at the time of this feasibility study.

The validated integrated stormwater and coastal model was updated by making adjustments to catchments and by adding additional hydrologic and hydraulic network data to reflect the NAA projects in the MIKE URBAN model. Table 9-1 summarizes a list of various model elements in the NAA scenario model. The MIKE URBAN model and MIKE FLOOD modules were utilized to simulate various combinations of rainfall return period and tidal combination events. The maximum flood extents were extracted from these model simulations to create maximum flood inundation maps. Figure 9-2. Flood Inundation Areas from 5-year Rainfall Event in No-Action Alternative through Figure 9-6 show the results of the integrated stormwater and coastal model simulations for the 5-year, 10-year, 25-year, 50-year, and 100-year rainfall events in both low and high tide events. As seen from the figures, the extent of flooded areas increases as the rainfall depth increases. Additionally, the flood inundation areas are higher during a high tide event in comparison with the low tide event for the same rainfall return period. Refer to Appendix L for the input and outputs results for all the NAA model simulation scenarios.

Table 9-1. Model Parameters for No-Action Alternative Scenario

Parameters	Value
No. of subcatchments	1,564
No. of manholes	676
No. of pipe segments	688
No. of pumps	5
No. of weirs and orifices combined	30

NO-ACTION ALTERNATIVE

Figure 9-1. No-Action Alternative (NAA) Projects

5-YEAR NO-ACTION ALTERNATIVE

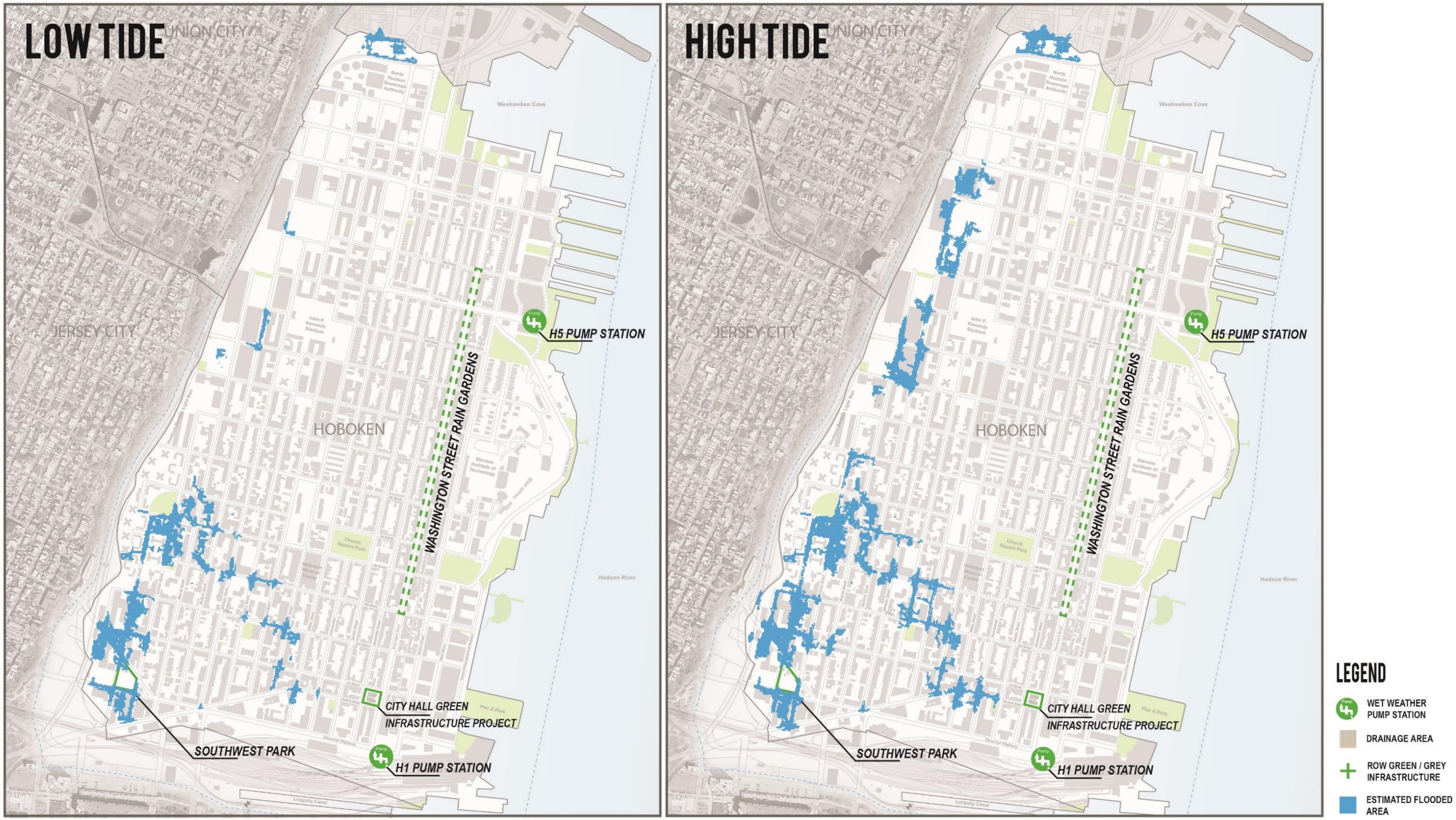


Figure 9-2. Flood Inundation Areas from 5-year Rainfall Event in No-Action Alternative

10-YEAR NO-ACTION ALTERNATIVE

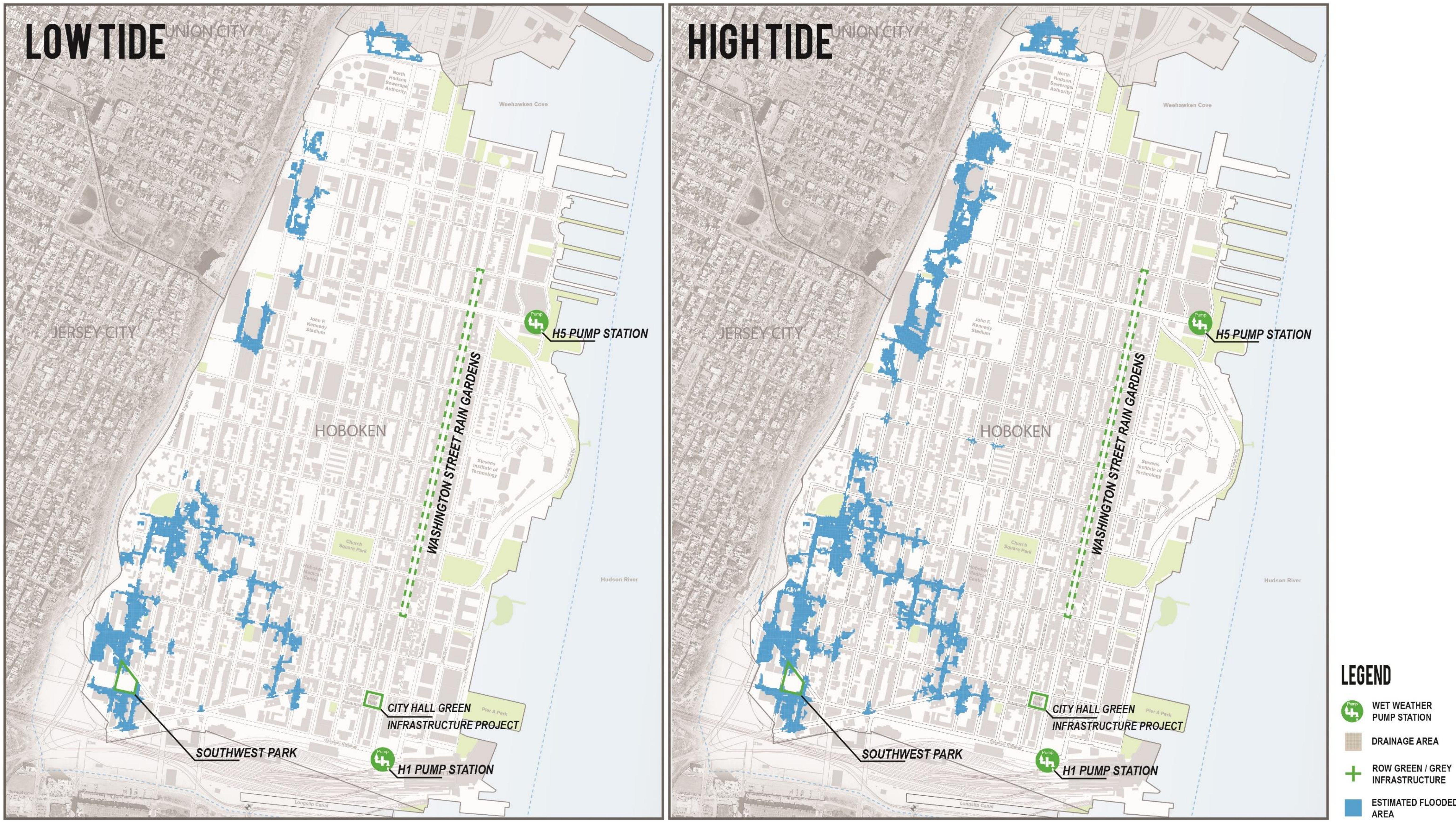


Figure 9-3. Flood Inundation Areas from 10-year Rainfall Event in No-Action Alternative

25-YEAR NO-ACTION ALTERNATIVE

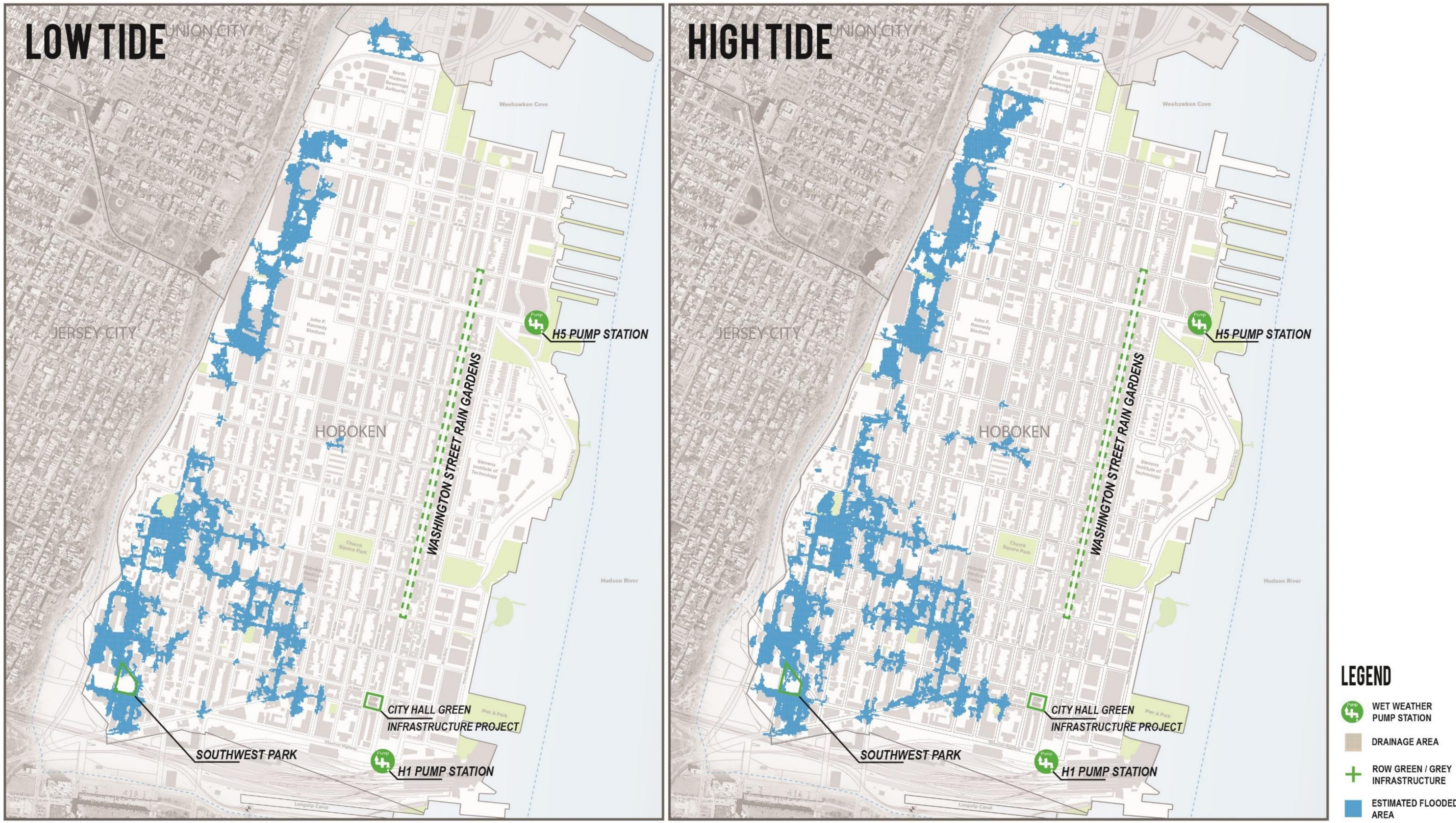


Figure 9-4. Flood Inundation Areas from 25-year Rainfall Event in No-Action Alternative

50-YEAR NO-ACTION ALTERNATIVE

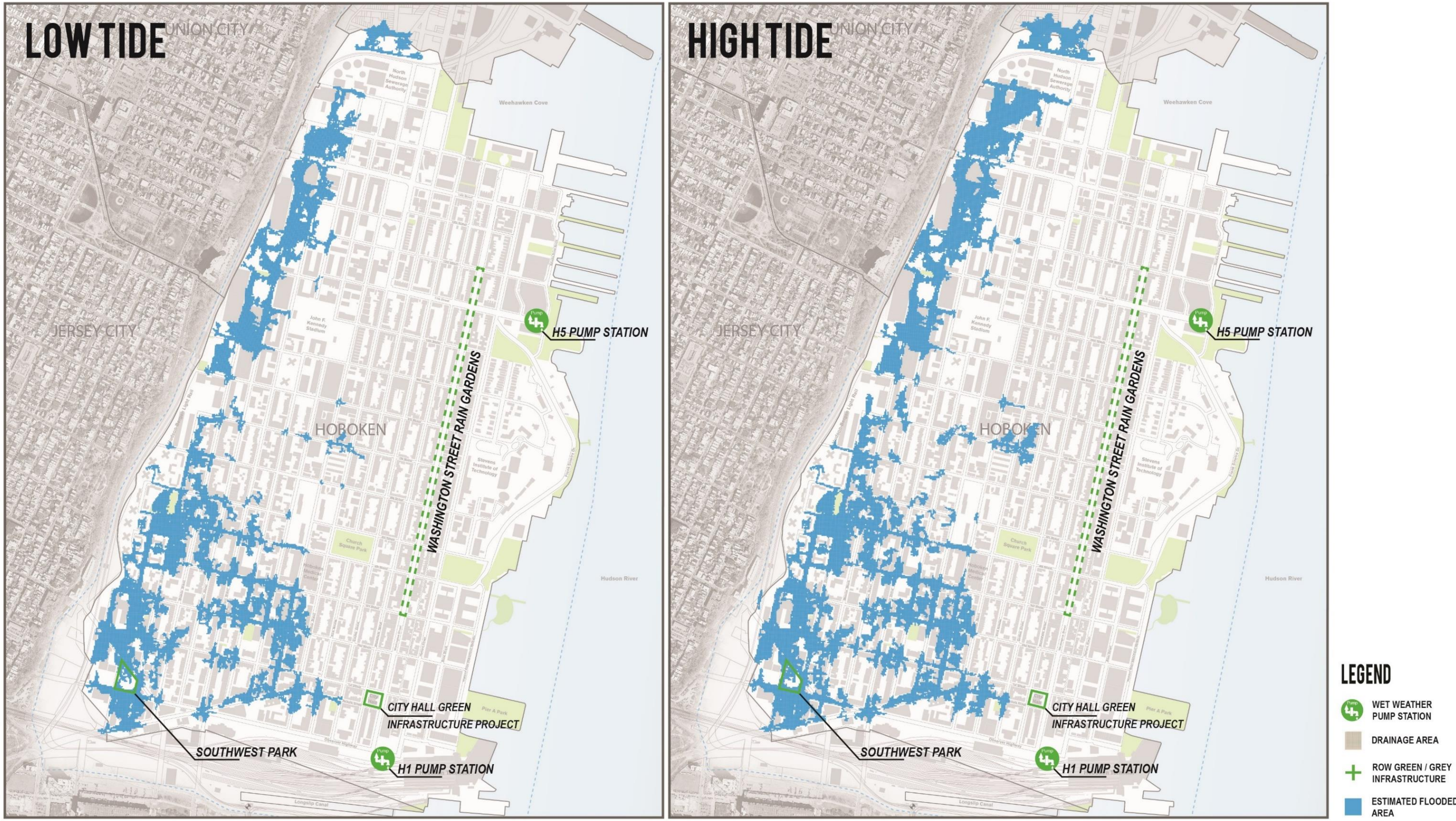


Figure 9-5. Flood Inundation Areas from 50-year Rainfall Event in No-Action Alternative

100-YEAR NO-ACTION ALTERNATIVE

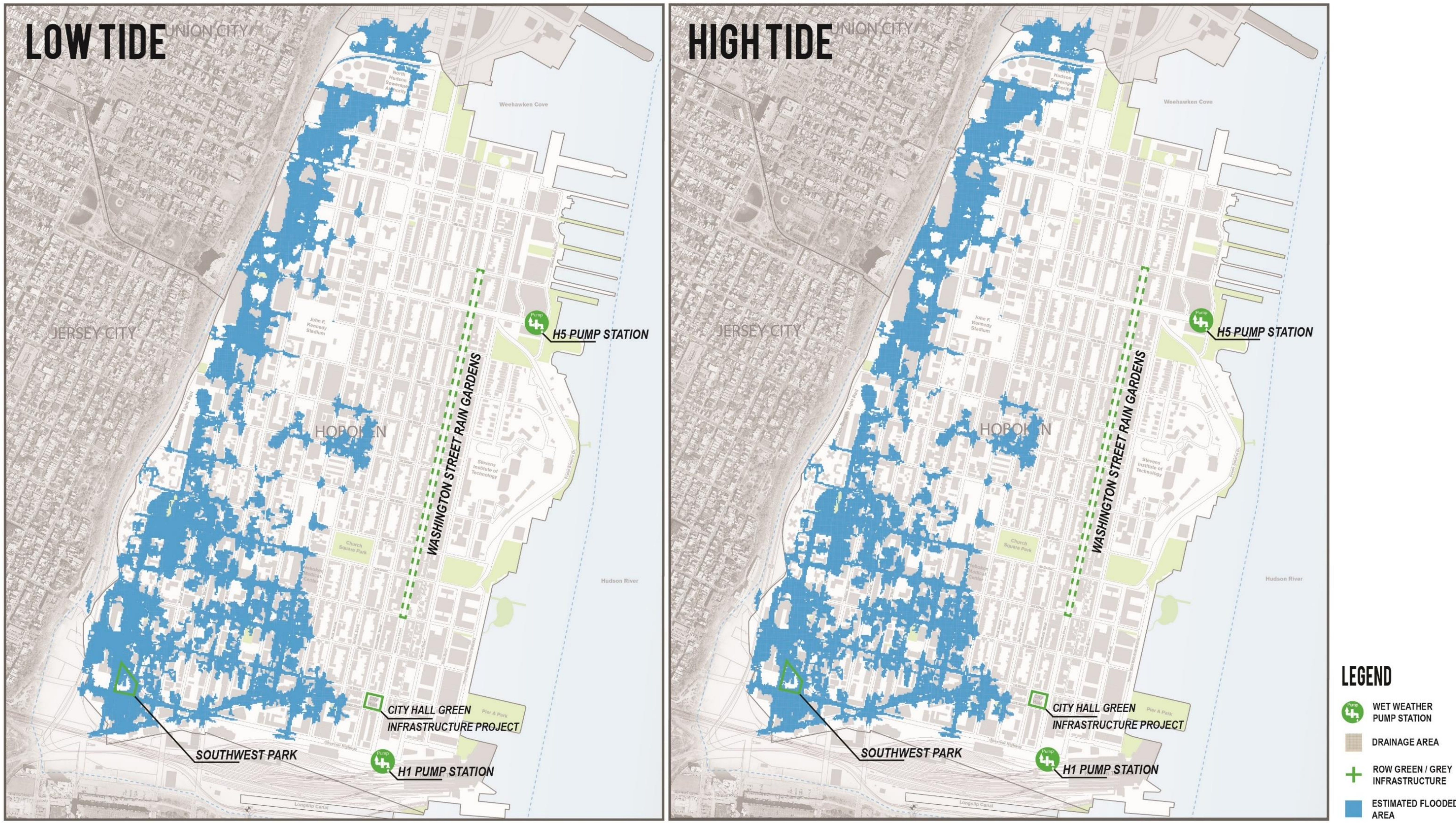


Figure 9-6. Flood Inundation Areas from 100-year Rainfall Event in No-Action Alternative

9.2 Delay, Store, Discharge (DSD) Alternative Stormwater Model Results

The No-Action Alternative integrated stormwater and coastal model was updated with all the proposed DSD components that were developed as part of this study as shown in Figure 9-7. It should be noted that all the proposed DSD components are common to all three Resist alternatives that were described in Section 5 of this report. A description of the various DSD components and the methodology to incorporate into the MIKE URBAN and MIKE FLOOD module is as follows -

a. BASF site – Proposed drainage improvements to delay, store and discharge runoff from approximate 55 acres of drainage area through a system of high level storm sewers, storage detention tanks and pumps. These improvements include separating the sewer system for the entire BASF site drainage area and discharging all storm runoff to a new outfall on the Hudson River via pumped force main.

   To incorporate these improvements into the model, 132 catchments that encompass the BASF site drainage area were combined into one large catchment that drains storm runoff to a storage basin located on the BASF site. Conceptual design drawings were used to determine the necessary geometry for the basin to achieve the design runoff volume of roughly 780,000 cubic feet. To mimic the sewer separation and maintain the sewer flow in the existing combined sewer links, the 132 catchments were given an effective area of zero so that runoff from these catchments would not be considered in the model engine's calculations but the dry weather flow would still be added to the appropriate receiving node. An orifice and overflow weir were connected to the outlet of the basin which then discharges to another basin serving as the wet well of the pump station. From this basin, flow is pumped to a new outfall node.

b. NJ Transit site – Proposed drainage improvements to delay, store and discharge runoff from approximately 15 acres of drainage area. These improvements include separating the sewer system for the entire Hoboken Housing Authority drainage area and discharging all storm runoff to the existing NJ Transit ditch along the Light Rail tracks via pump station.

   To incorporate these improvements into the model, 12 catchments that encompass the NJ Transit site drainage area were combined into one large catchment that drains to a storage basin. Conceptual design drawings were used to determine the necessary geometry for the basin in order to achieve the design runoff volume of roughly 183,000 cf. To mimic the sewer separation and maintain the sewer flow in the existing combined sewer links, the 12 catchments were given an effective area of zero so that runoff from these catchments would not be considered in the model engine's calculations but the dry weather flow would still be added to the appropriate receiving node. An orifice and overflow weir were connected to the outlet of the basin which then discharges to a wet well basin. From this basin, flow is pumped to a node located on the open channel link serving as the NJ Transit ditch.

c. Block 10 site – Proposed drainage improvements to delay and store runoff from approximately 8 acres of drainage area. This includes separating the sewer system for the entire Block 10 drainage area and storing runoff before discharging to the existing NHSA sewer system.

   To incorporate these improvements into the model, 14 catchments that encompass the Block 10 site drainage area were combined into one large catchment that drains to a storage basin. Conceptual design drawings were used to determine the necessary geometry for the basin in order to achieve the design runoff volume of roughly 83,000 cf. To mimic the sewer separation and maintain the sewer flow in the existing combined sewer links, the 14 catchments were given an effective area of zero so that runoff from these catchments would not be considered in the model engine's calculations but the dry weather flow would still be added to the appropriate receiving node. An orifice and overflow weir were connected to the outlet of the basin which then discharges to a wet well basin. From this basin, flow is pumped to a node located on the existing NHSA sewer network.

d. ROW Green / Grey Infrastructure Practices – 61 locations were identified to capture, delay and convey street drainage through green and grey infrastructure that utilized subsurface detention tanks. To incorporate these subsurface tanks into the model, each tank was added as a storage basin that would receive street runoff. An orifice and overflow weir was added to the outlet of each basin which then discharges to a node on the existing NHSA sewer network. Details of conceptual design and sizing calculations for the proposed tanks is included in Appendix M.

It should be noted that the conveyance system for these DSD components are not included in the stormwater model; however as part of the feasibility assessment, Dewberry developed conceptual conveyance system designs to illustrate the pipe sizes required to convey rainfall runoff to these proposed DSD sites. The validated integrated stormwater and coastal model was updated by making adjustments to catchments and by adding additional hydrologic and hydraulic network data to reflect the DSD projects in the MIKE URBAN model. Table 9-2 summarizes a list of various model elements in the DSD scenario model. The MIKE URBAN model and MIKE FLOOD modules were utilized to simulate various combinations of rainfall return period and tidal combination events. The maximum flood extents were extracted from these model simulations to create maximum flood inundation maps. Figure 9-8 through Figure 9-12 shows the results of the integrated stormwater and coastal model simulations for the 5-year, 10-year, 25-year, 50-year, and 100-year rainfall events in both low and high tide events. Refer to Appendix N for the input and outputs results for all the DSD model simulation scenarios.

Table 9-2. Model Parameters for DSD Alternative Scenario

Parameters	Value
No. of subcatchments	1,430
No. of manholes	951
No. of pipe segments	896
No. of pumps	8
No. of weirs and orifices combined	97

PROPOSED DSD* ALTERNATIVE

*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-7. Proposed DSD Alternatives Projects

5-YEAR PROPOSED DSD* ALTERNATIVE

*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-8. Proposed DSD Alternatives 5-Year Rainfall Results

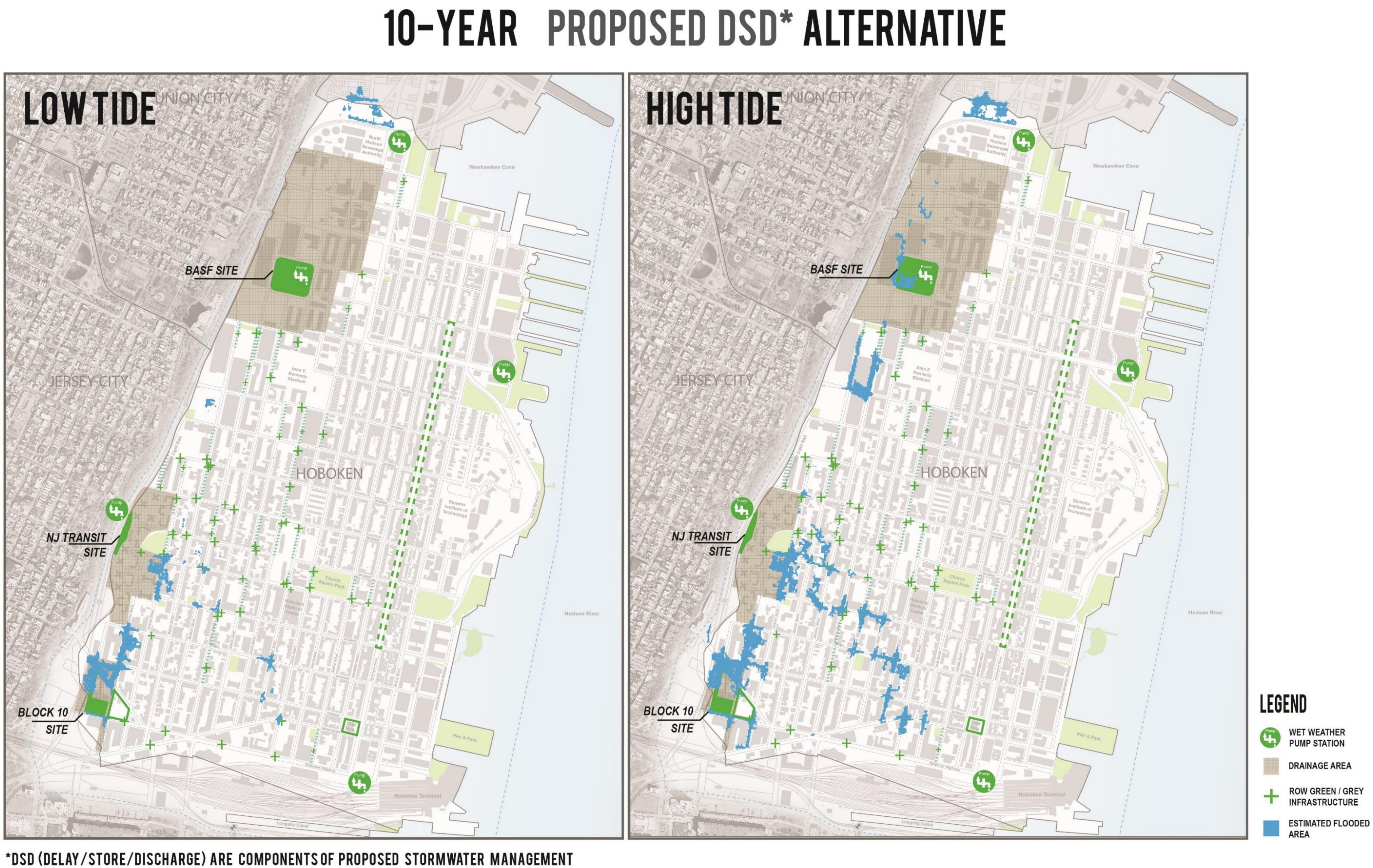
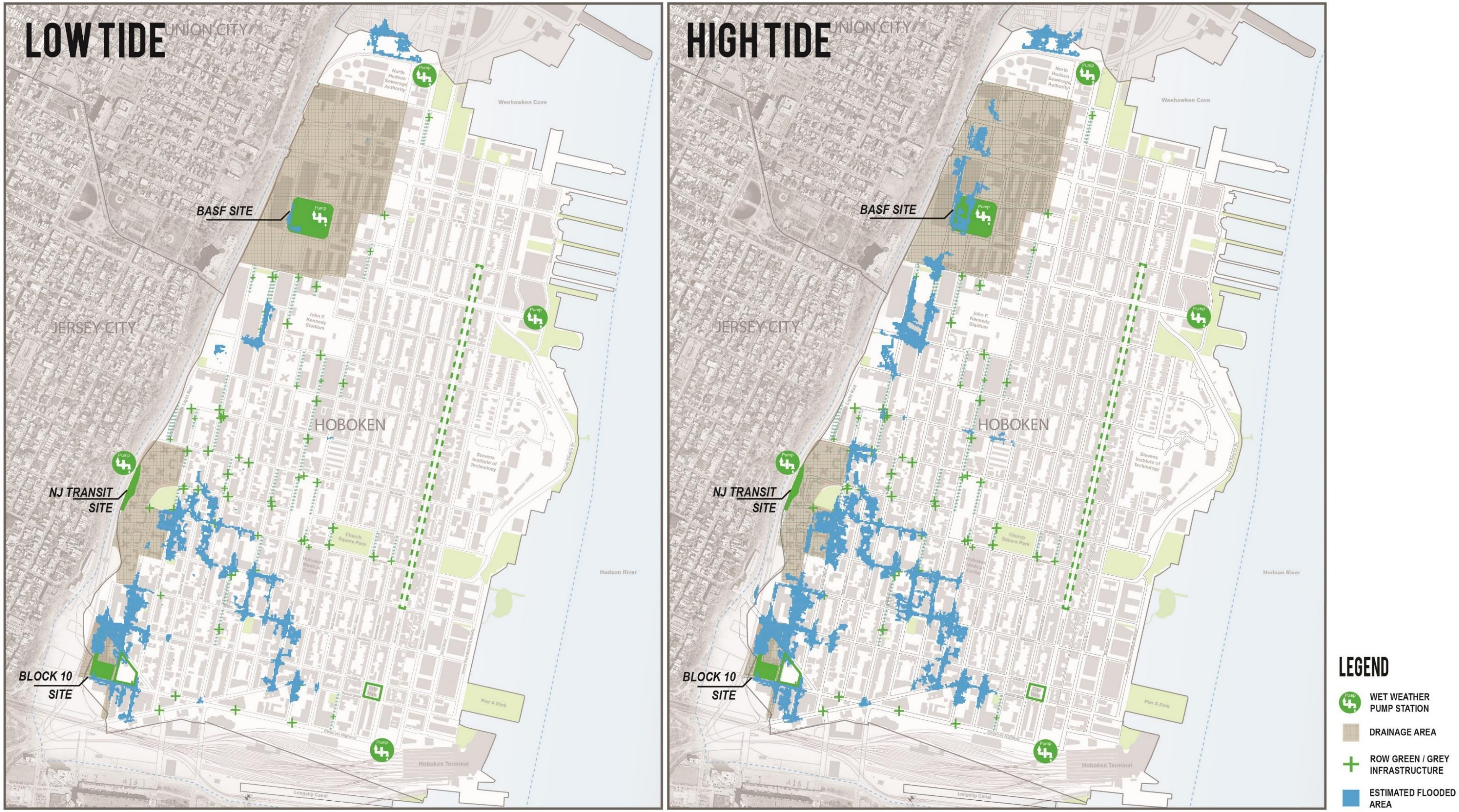


Figure 9-9. Proposed DSD Alternatives 10-Year Rainfall Results

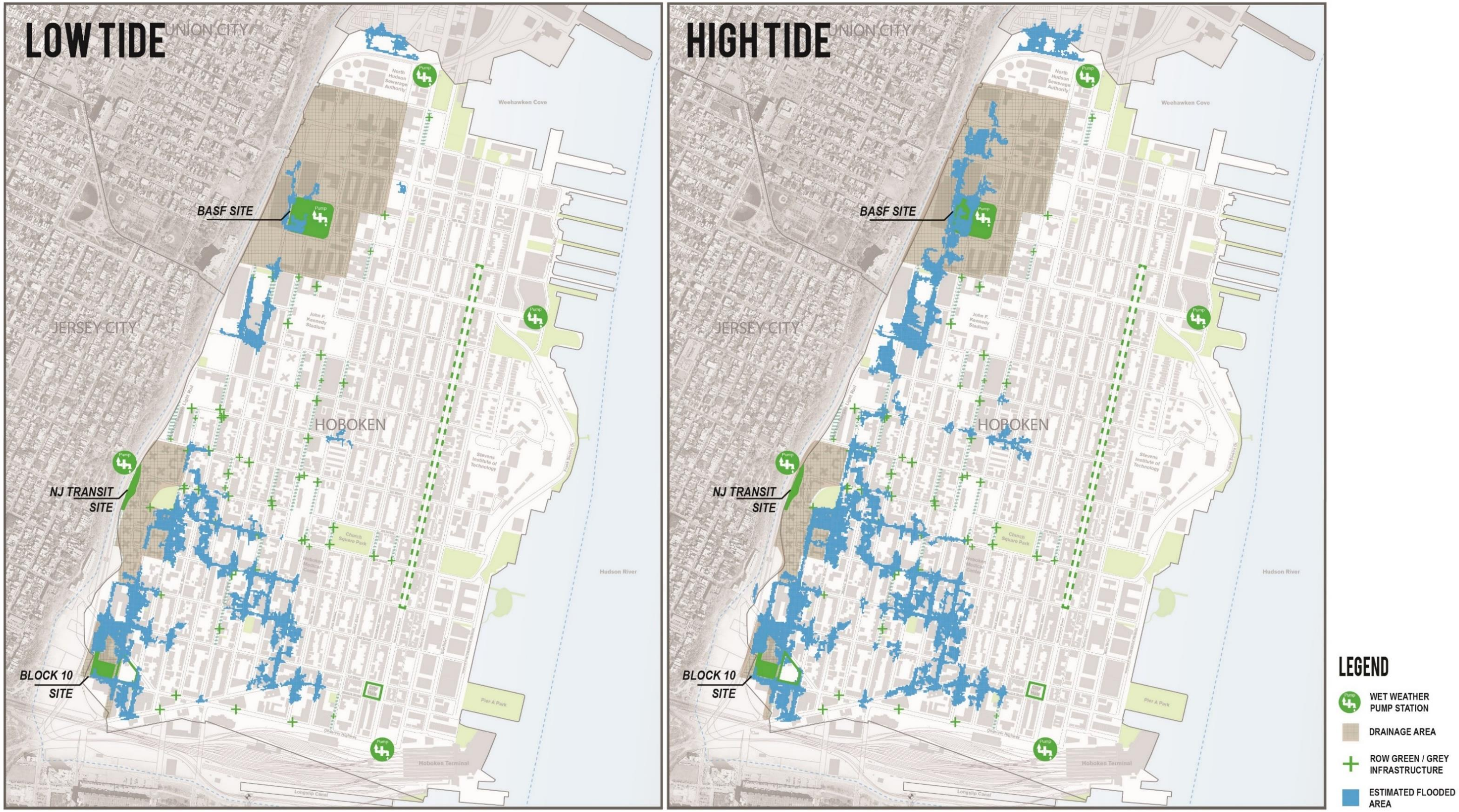
25-YEAR PROPOSED DSD* ALTERNATIVE



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-10. Proposed DSD Alternatives 25-Year Rainfall Results

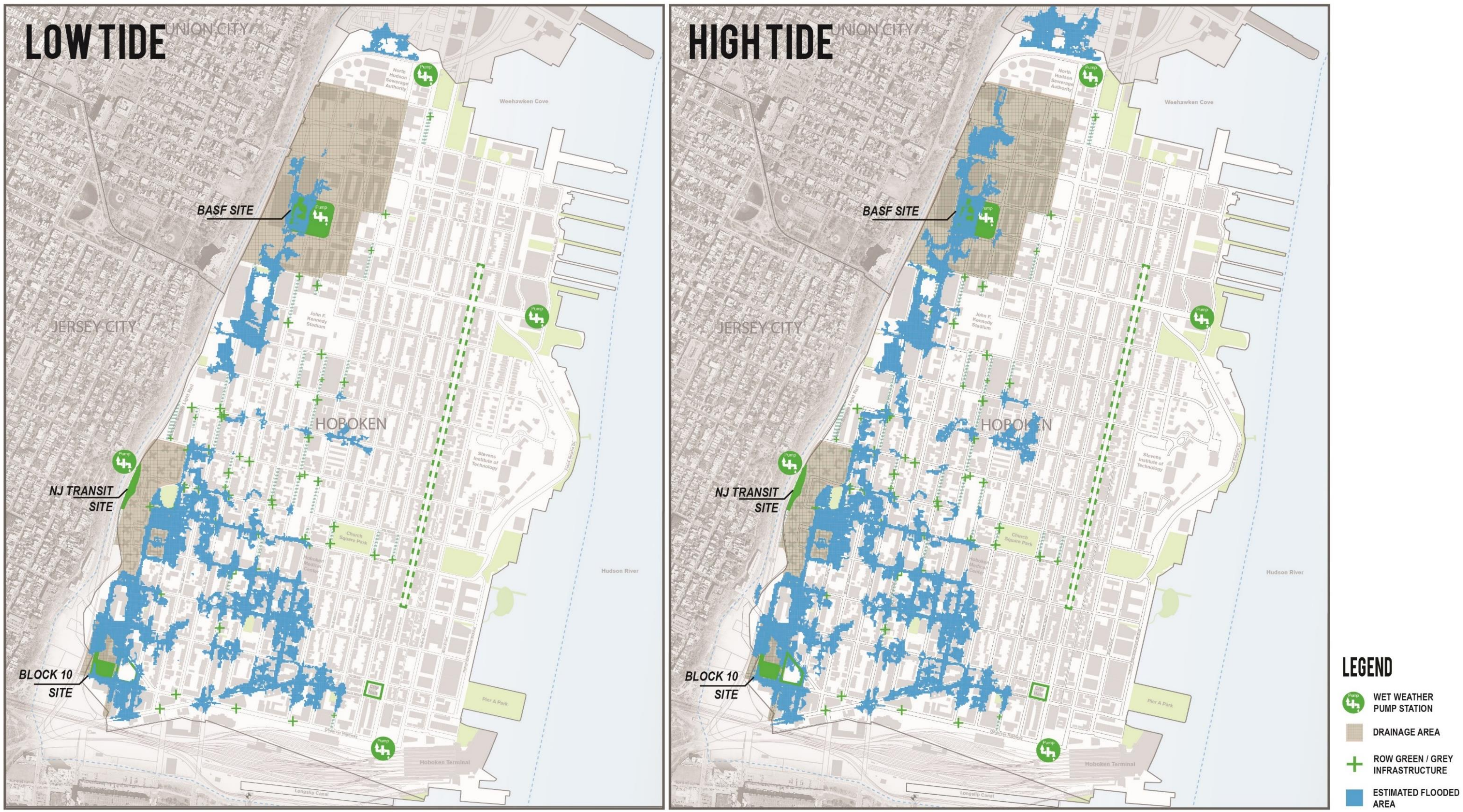
50-YEAR PROPOSED DSD* ALTERNATIVE



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-11. Proposed DSD Alternatives 50-Year Rainfall Results

100-YEAR PROPOSED DSD* ALTERNATIVE



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-12. Proposed DSD Alternatives 100-Year Rainfall Results

9.3 Comparison of NAA and DSD Alternatives

Figure 9-13 through Figure 9-22 compares the extent of potential rainfall flooding areas in the No-Action Alternative (NAA) and with the "DSD" alternative simulated by the MIKE URBAN and MIKE FLOOD models for various combinations of rainfall return period/tide combinations. Table 9-3 provides the acreages of the flooded areas in NAA and "DSD" alternative along with the potential reduction in flooded areas with all the components of the DSD alternatives in place.

Table 9-3. Flooded Area Reduction from NAA to Proposed DSD Alternatives

Rainfall Return Period	Tidal Condition	Flooded Areas (acres)		Percent Reduction in Flooded Areas
		NAA	DSD Alternative	
20% annual chance (5-year)	Low	25.5	4.8	81%
	High	48.4	13.0	73%
10% annual chance (10-year)	Low	35.5	10.2	71%
	High	59.7	26.0	56%
4% annual chance (25-year)	Low	64.5	26.8	58%
	High	95.9	49.1	49%
2% annual chance (50-year)	Low	95.1	42.0	56%
	High	122.1	69.9	43%
1% annual chance (100-year)	Low	147.5	91.7	38%
	High	148.6	93.4	37%

All the proposed components of "DSD" alternative provides significant flood risk reduction benefits during the 5-, 10-, 25-, 50- and 100-year rainfall recurrence interval events with low and high tides in Hudson River. In general, the percentage reduction in flooded areas are higher in the low tide event for the same rainfall recurrence interval event when compared with the high tide event. During a high tide event, all the outfalls are closed which prevents gravity flow of rainfall runoff from NHSA's surcharged storm sewer system into the Hudson River. The wet weather pumps are operational during the high tide event and thus the amount of flooded water that can be discharged into the Hudson River is restricted by the capacity of the pumps. In a low tide event, all the outfalls are open which would allow to discharge rainfall runoff directly to the Hudson River once NHSA's collection system reaches its capacity. Additionally, the pumps can be operational during the low tide event thus allowing to discharge additional volume of rainfall runoff into the Hudson River.

As seen from Figure 9-13, the proposed "DSD" alternative would reduce flooding in 81% of the areas in the southwest portion and central-western portions of the City of Hoboken that previously flooded in NAA during a 5-year rainfall event with low tide in the Hudson River. Similarly, Figure 9-14 to Figure 9-1422 show the extent of the flooded area reduction as a result of the DSD components in the Southwest of Hoboken and in the H4 and H5 sewersheds. In particular, the area from Monroe Street to Grand Street and 11th Street to 16th Street shows significant reduction from No-Action Alternative conditions to Proposed DSD conditions due in large part to the separation of sewers within the BASF site drainage area.

5-YEAR LOW-TIDE COMPARISON

*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-13. Comparison of NAA and Proposed DSD Alternatives 5-Year Low Tide Results

5-YEAR HIGH-TIDE COMPARISON

*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-14. Comparison of NAA and Proposed DSD Alternatives 5-Year High Tide Results

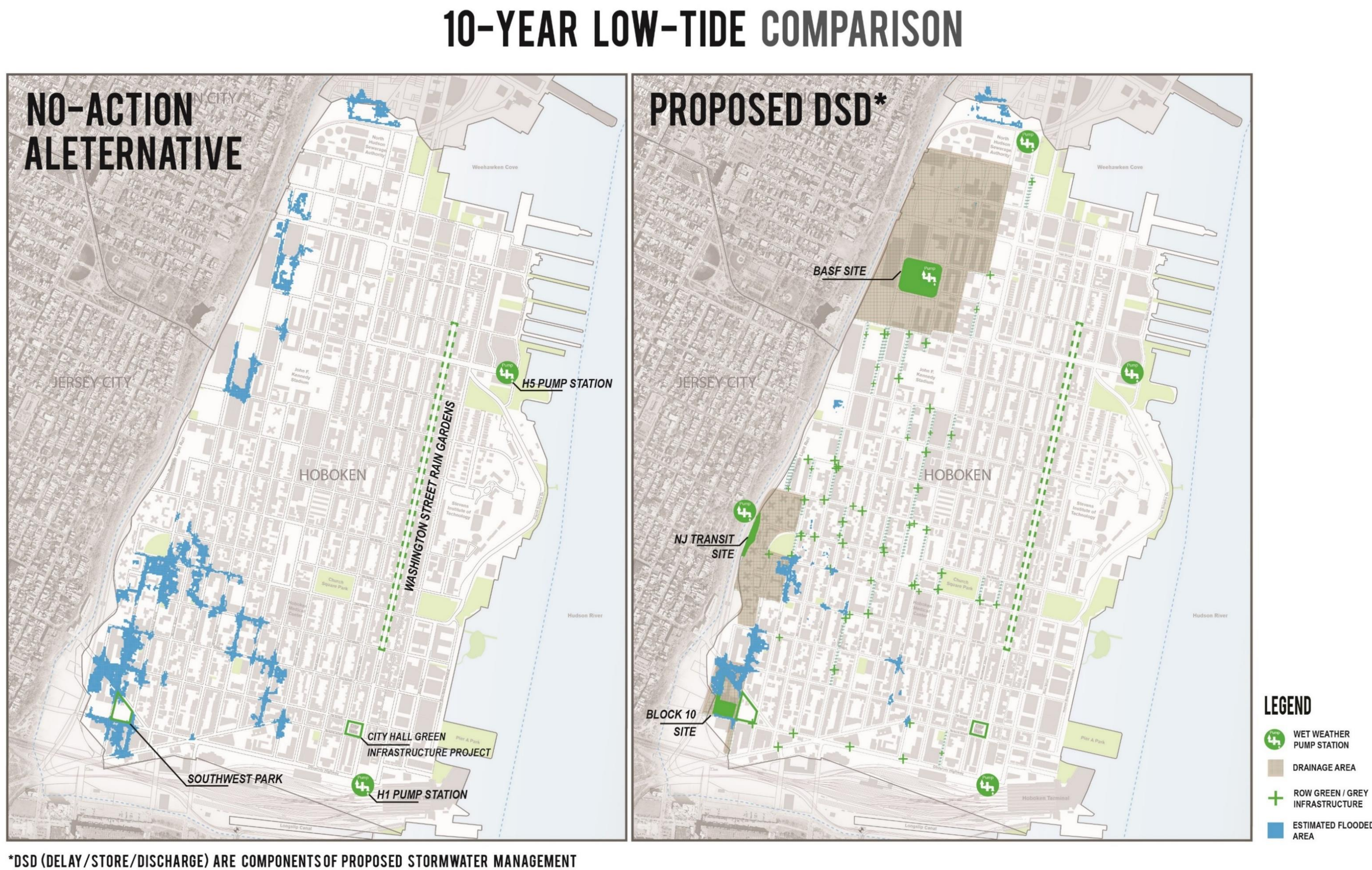
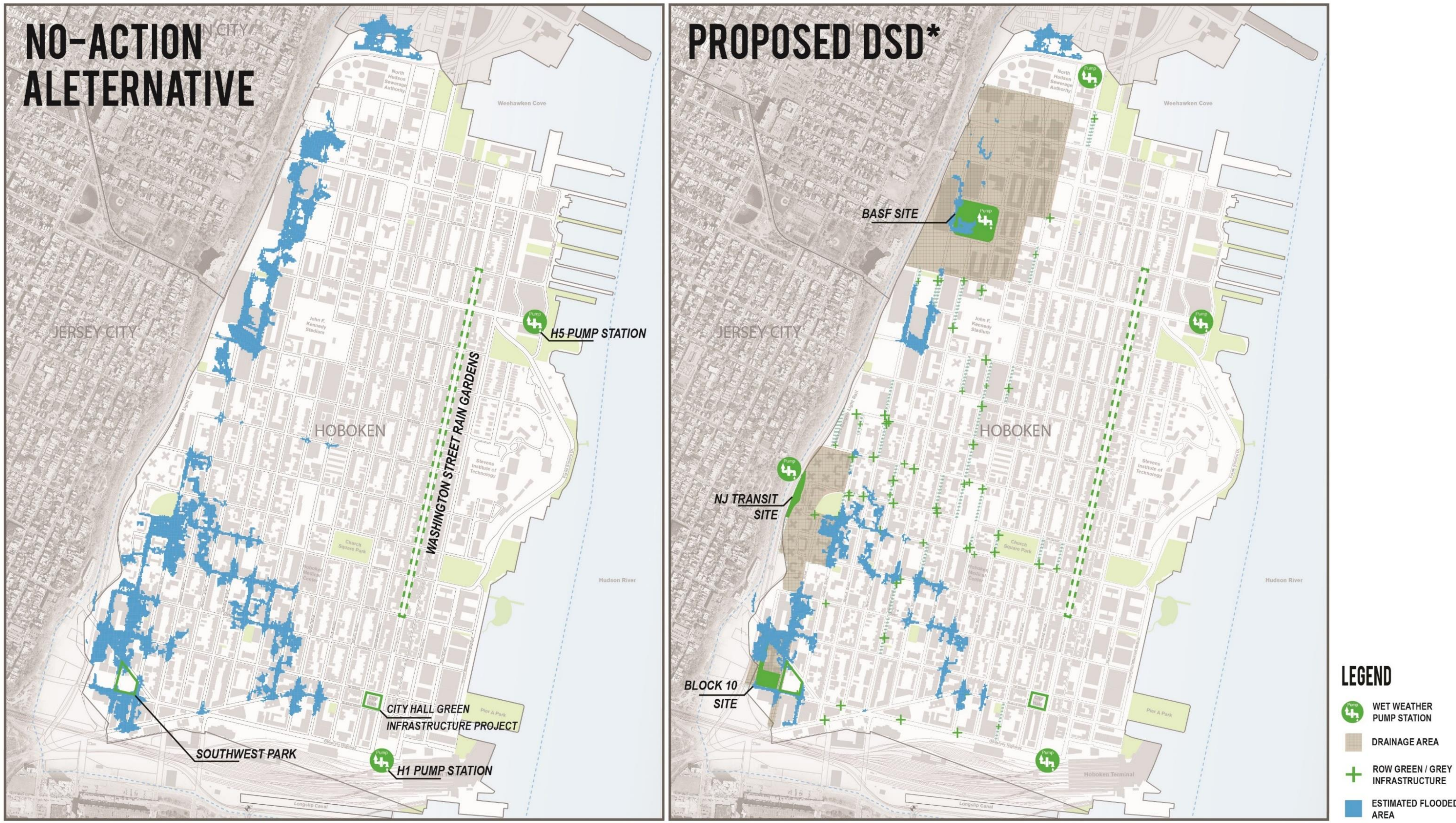


Figure 9-15. Comparison of NAA and Proposed DSD Alternatives 10-Year Low Tide Results

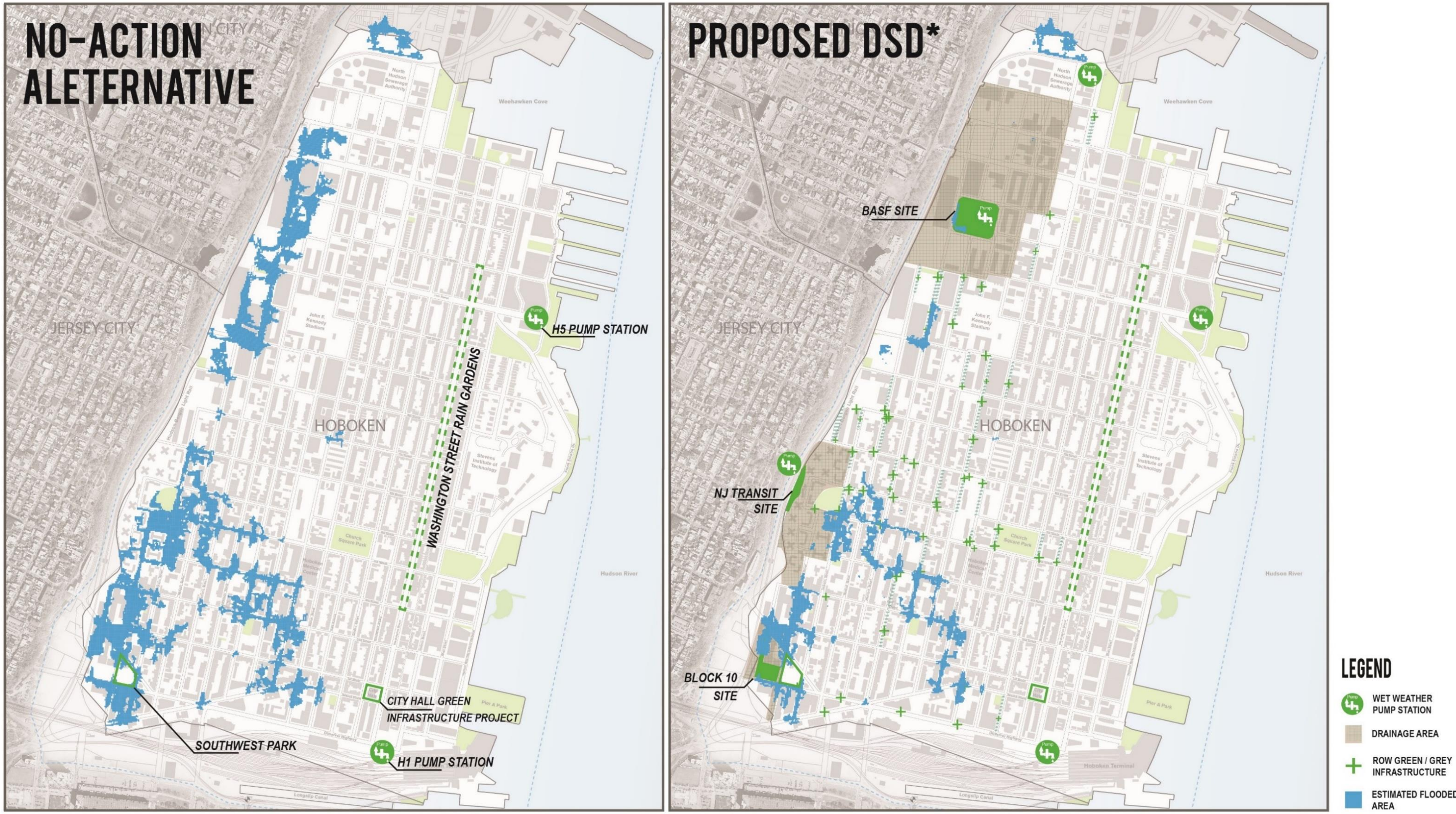
10-YEAR HIGH-TIDE COMPARISON



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-16. Comparison of NAA and Proposed DSD Alternatives 10-Year High Tide Results

25-YEAR LOW-TIDE COMPARISON



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

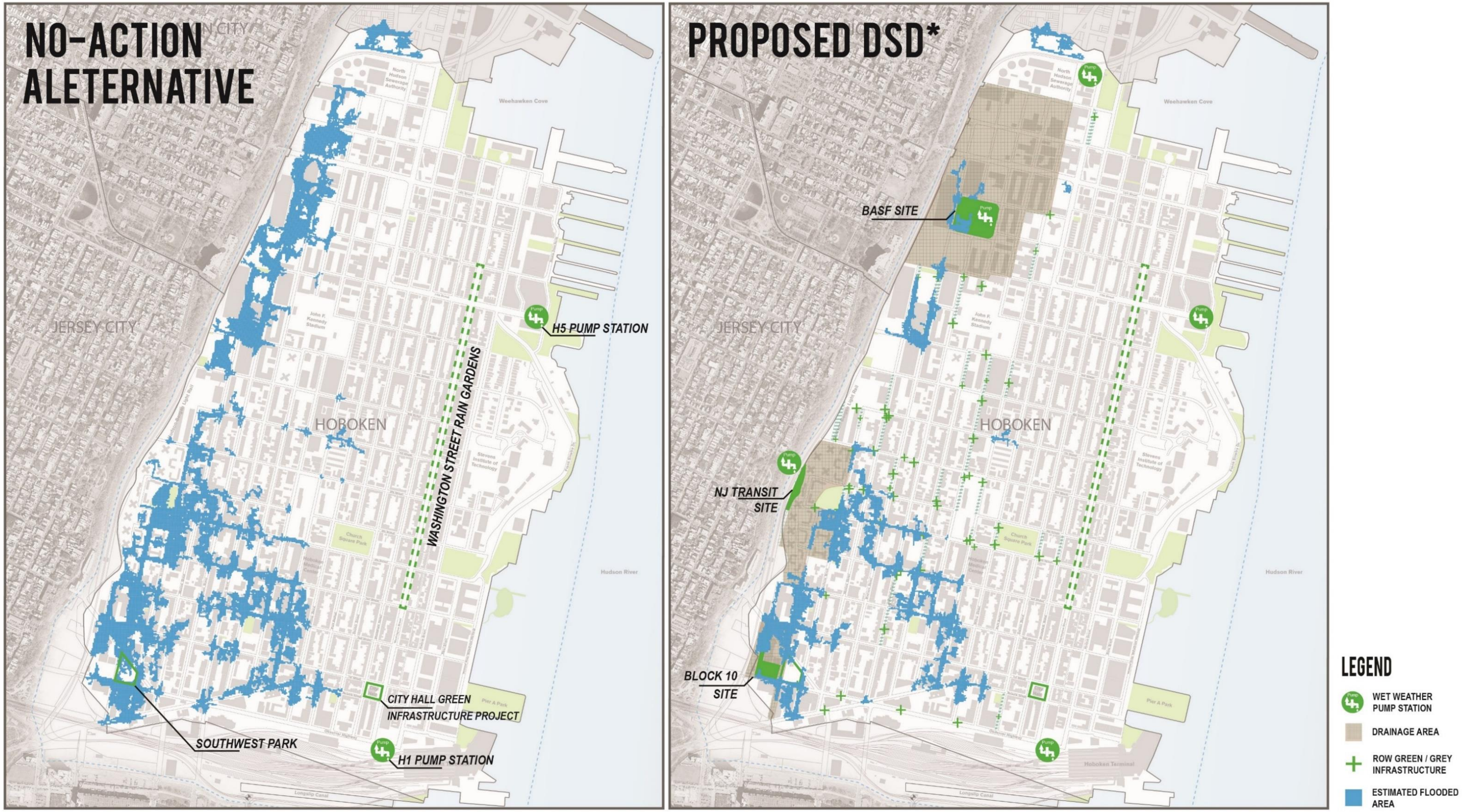
Figure 9-17. Comparison of NAA and Proposed DSD Alternatives 25-Year Low Tide Results

25-YEAR HIGH-TIDE COMPARISON

*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-18. Comparison of NAA and Proposed DSD Alternatives 25-Year High Tide Results

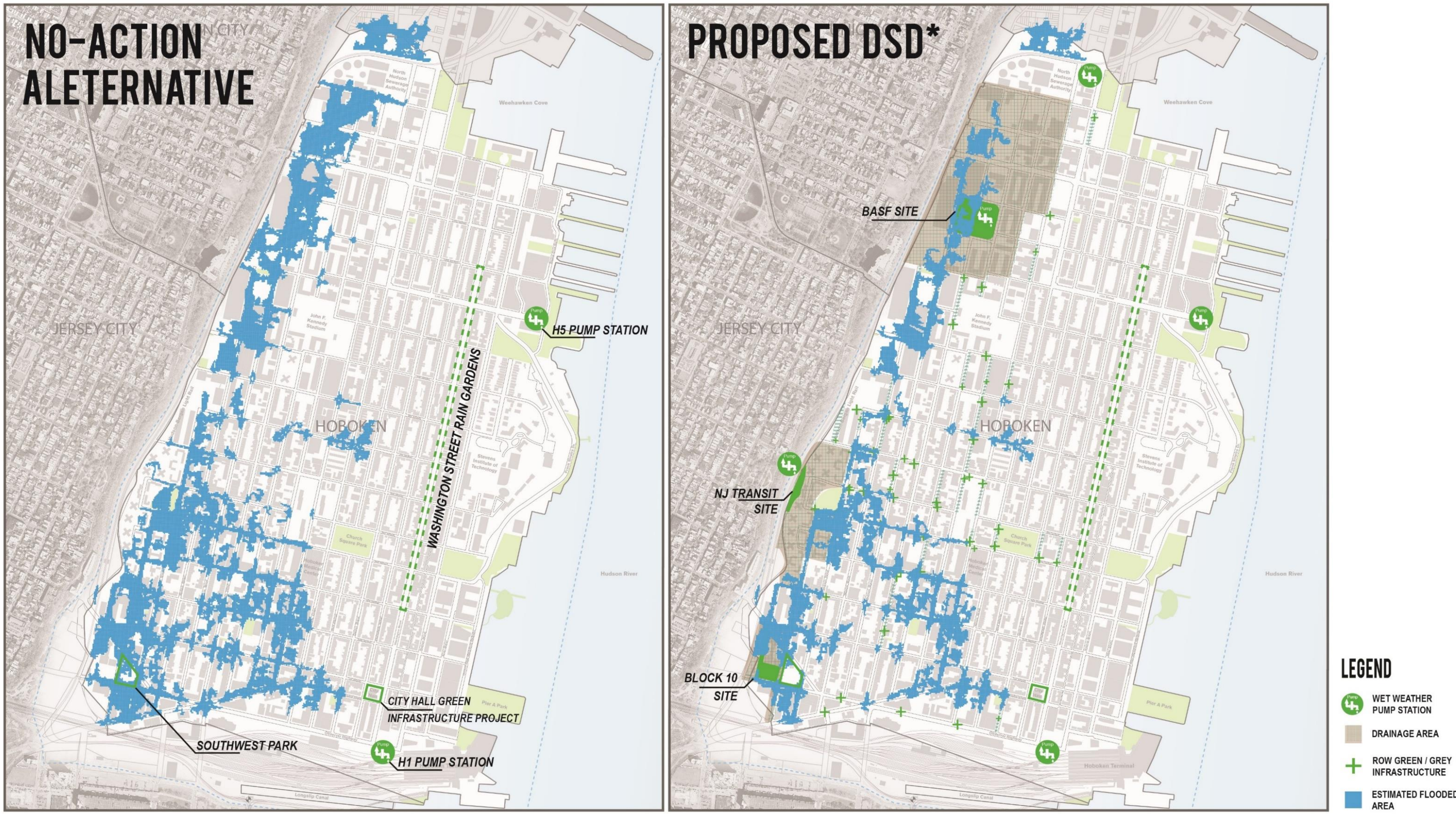
50-YEAR LOW-TIDE COMPARISON



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-19. Comparison of NAA and Proposed DSD Alternatives 50-Year Low Tide Results

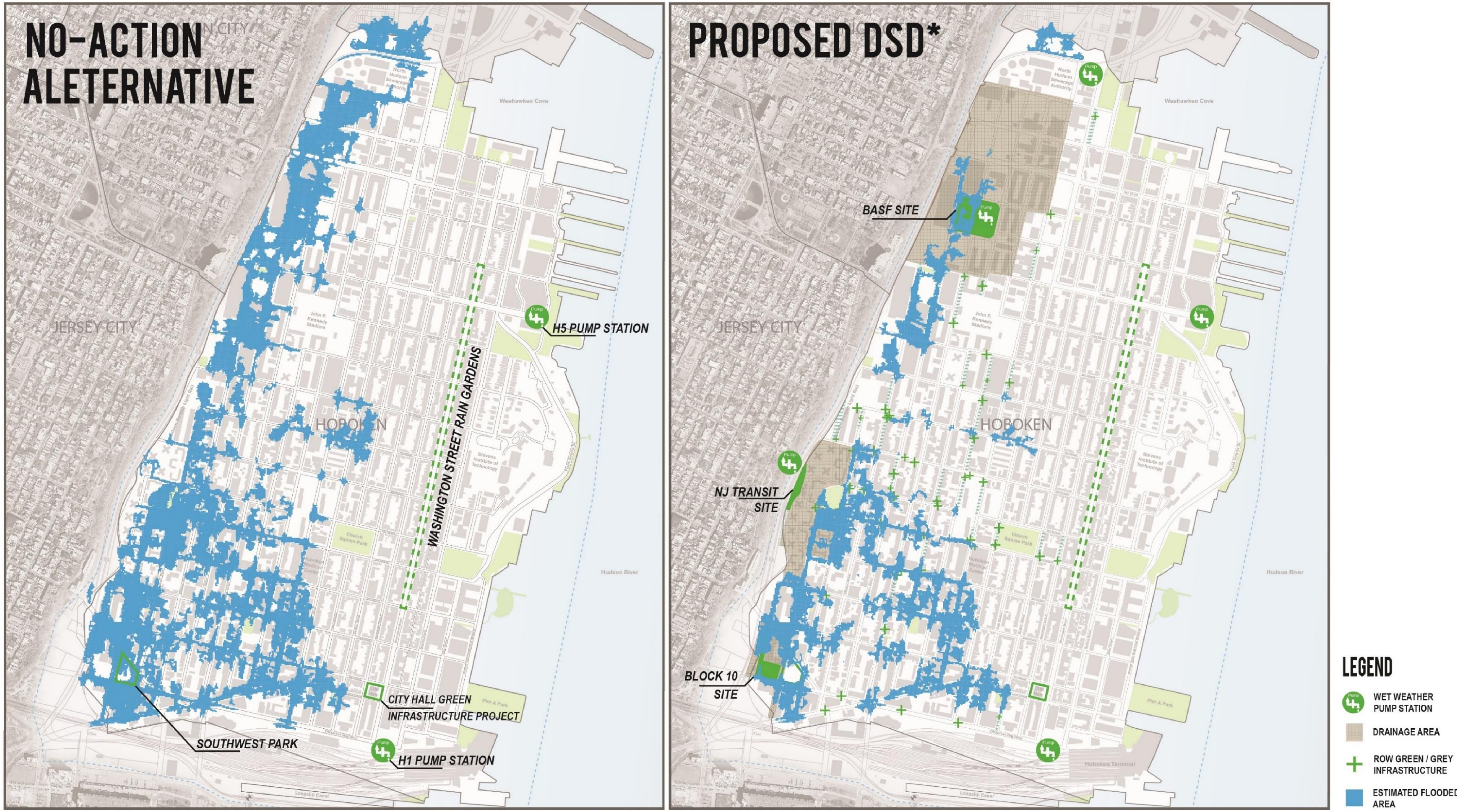
50-YEAR HIGH-TIDE COMPARISON



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-20. Comparison of NAA and Proposed DSD Alternatives 50-Year High Tide Results

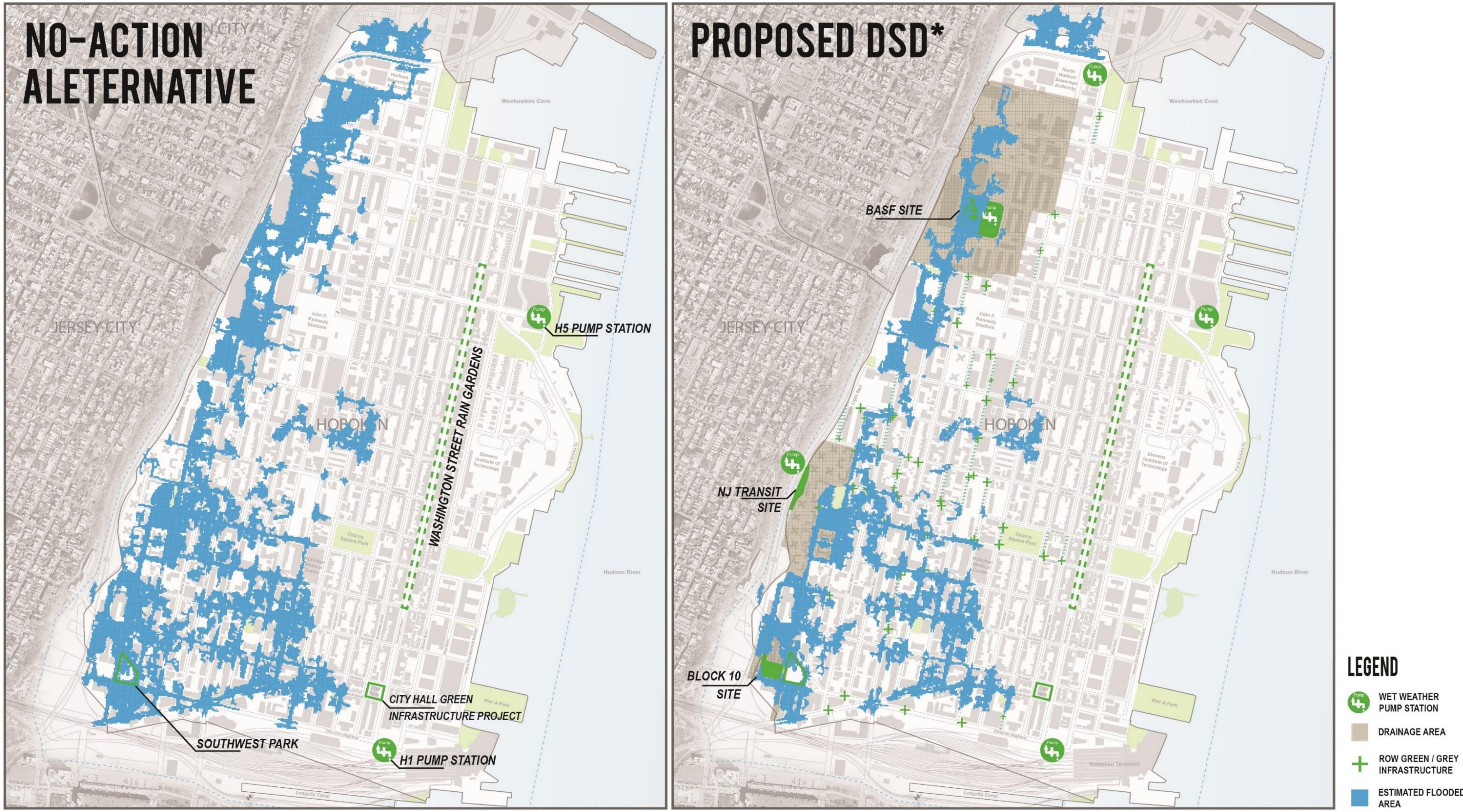
100-YEAR LOW-TIDE COMPARISON



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-21. Comparison of NAA and Proposed DSD Alternatives 100-Year Low Tide Result

100-YEAR HIGH-TIDE COMPARISON



*DSD (DELAY/STORE/DISCHARGE) ARE COMPONENTS OF PROPOSED STORMWATER MANAGEMENT

Figure 9-22. Comparison of NAA and Proposed DSD Alternatives 100-Year High Tide Results

10 Conclusions and Recommendations

The MIKE 21 coastal hydrodynamic model simulations for the 10% -, 2%- and 1%- annual chance coastal storm surge events for the three proposed “Resist” alternatives show that the “Resist” barrier will provide varying levels of flood risk reduction benefits by preventing the overland flow of coastal storm surge into the study area. The “Resist” Alternative 1 provides the maximum flood risk reduction benefits followed by the “Resist” Alternative 2 and 3 respectively. The potential residual flooding impacts to properties within the study area are the highest for Alternative 2 and 3 but the lowest for Alternative 1. Out of the total of 5 public and private properties that have potential residual flood impacts in Alternatives 2 and 3; 2 properties are located in the southern portion of the study area, one in Hoboken and the other being the New Jersey Transit yard and the remaining 3 properties are located in the northern portion of the study area in Hoboken and Weehawken. Model results show that each of these three “Resist” alternatives will prevent the overland flow of coastal storm surge from the project’s study area into portions of Jersey City that are located outside the study area (between 14th street and 18th street and west of Marin Boulevard) during the 10% and 2% annual chance storm events.

The MIKE URBAN and MIKE FLOOD model simulations for the various rainfall and tide combination events shows that the proposed “Delay, Store, Discharge” alternative will provide varying levels of flood risk reduction benefits for each rainfall/tide combination events. Model results show that the proposed “DSD” alternative provides the maximum flood risk reduction benefits during the 5-year and low tide combination event. The model results show that the level of flood risk reduction benefits gradually decreases as the rainfall intensity increases along with a high tide in the Hudson River.

Model results from the “Resist” and “DSD” alternatives will be used as part of the Task 5 feasibility assessment to inform the choice of the preferred alternative that can be advanced to the design phase upon acceptance from the stakeholders and the community. It is our understanding that NJDEP would advance further development of the coastal hydrodynamic model developed as part of this study in the design phase to evaluate and finalize the potential residual flooding impacts from the final “Resist” alignment. The stormwater model methodology used as part of this study should satisfy the interior drainage analysis requirements for the FEMA levee certification.

Dewberry proposes the following recommendations for the design phase of the project –

1. Utilize the latest Danish Hydraulic Institute’s MIKE model version 2016. Simulate the NAA and preferred alternative model scenarios using MIKE 2016 version instead of the currently used MIKE 2014 version. This model version update will ensure that the latest modeling package is utilized during the design phase to evaluate residual flooding impacts.
2. If possible, utilize the coastal model mesh to reflect the actual footprint and the Design Flood Elevation (DFE) of the proposed “Resist” alignment. In order to reflect the actual footprint and DFE, the coastal

model mesh from this feasibility study would require modification such as removal of building footprints immediately adjacent to the proposed “Resist” alignment. Additionally, we recommend to utilize the “dike” option in the MIKE 21 model program with the appropriate footprint and design flood elevation as well and model results from these two methods should be compared which can be included as part of the model sensitivity analysis.

3. If needed, perform uncertainty and sensitivity analysis to evaluate any potential changes to residual flooding impacted properties with the final detailed alternative alignment. It is quite possible that the number of properties impacted by residual flooding may increase or decrease depending on the model parameters that are tweaked during the sensitivity analysis.
4. In order to develop operational protocols for the proposed deployable “Resist” structures, it is recommended to simulate intrusion of coastal storm surge still water level at every 0.5 feet interval starting from an elevation of 5 feet-NAVD up to the minimum DFE of the proposed “Resist” barrier in NAA and with various gate closing scenarios as part of the final “Resist” alternative.
5. For the emergency action plan that needs to be developed as part of the maintenance and operations plan, it is important to understand the extent of flooding that may occur if the coastal storm surge water peak water level exceeds the design DFE of the “Resist” barrier. It is recommended to develop synthetic boundary condition with time-varying peak water levels above the DFE of the “Resist” barrier. These synthetic water level time series should be propagated from the boundary at Battery into the study area which will allow to simulate areas that will be flooded due to overtopping from the peak water level of the coastal storm surge that exceeds the DFE. The extent of flooding from this type of overtopping is dependent on the length of time that the water level overtops the “Resist” barrier. Floodplain maps should be developed for various scenarios that show flood extent for various overtopping depths and durations which then would be used to inform the emergency action plans.
6. It is our understanding that NDJEP intends to submit a Conditional Letter of Map Revision (CLOMR) to FEMA which would allow FEMA to review the proposed floodplain mapping changes and the levee certification documents. The CLOMR documentation would require updates to the Wave Height Analysis for Flood Insurance Study (WHAFIS) model developed by FEMA for the study area as part of the 2015 preliminary Flood Insurance Study for Hudson County. Updates to WHAFIS model would require utilizing the latest 1% annual chance stillwater elevation and wave height data published by FEMA at the time of the design study. The results from the WHAFIS model simulation would be utilized to re-map the 2015 preliminary FEMA floodplain maps with the final “Resist” alignment in place. It is quite possible that due to availability of newer topographic data, the remapped FEMA floodplain may be different than the 2015 preliminary FEMA floodplain map that currently exists on the unprotected side of the “Resist” alignment.
7. The levee accreditation would require an interior drainage analysis per 44 CFR65.10 requirements that would be used by FEMA to determine the 1% annual chance floodplain area from rainfall events on the protected side of the final “Resist” coastal barrier structure. It is assumed that the “Resist” coastal barrier

structure will be designed to the USACE and ASCE standards as required for FEMA levee accreditation standards. It is recommended to update the MIKE URBAN and MIKE FLOOD stormwater model developed as part of the feasibility study with any additional data provided by North Hudson Sewerage Authority (NHSA) to reflect the drainage conditions that would exist with the "Resist" coastal structure barrier in place. Another option would be to utilize NHSA's Long Term Control Plan (LTCP) hydrologic and hydraulic model that NHSA intends to develop in the near future. NHSA's model can be used to simulate the various rainfall and tide combination events to develop a range of potential flooding areas that can be used to determine the 1% annual chance floodplain behind the proposed "Resist" coastal structure.

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