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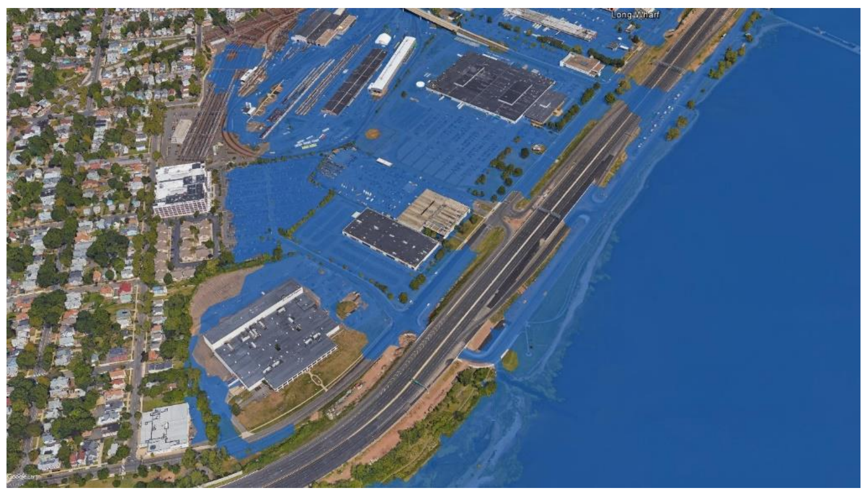
LONG WHARF FLOOD PROTECTION FINAL REPORT CITY OF NEW HAVEN New Haven, Connecticut

March 2017

01.0172596.00



100-year return period flood inundation model simulation by GZA

PREPARED FOR:
City of New Haven
New Haven, Connecticut

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March 30, 2017
File No. 01.0172596.00

Donna Hall
City of New Haven Plan Department
165 Church Street
5th Floor
New Haven, CT 06510

Re: Long Wharf Flood Protection Final Report
Long Wharf District
New Haven, Connecticut

Dear Ms. Hall,

We are pleased to provide you with the final "Long Wharf Flood Protection Study Report".

The report characterizes the coastal flood hazard within the Long Wharf District under tidal and extreme water level (storm surge and waves) flood conditions. The effects of sea level rise on both tides and extreme water levels are also evaluated. The report utilizes the results of the flood hazard characterization to evaluate the flood vulnerability and flood losses within the Long Wharf District assets, including buildings, infrastructure and shoreline features. Four flood protection alternatives are presented and a detailed discussion of one alternative (Alternative 4) is presented. Alternative 4 utilizes a combination of Living Shoreline, shoreline protection and flood protection features.

We appreciate the opportunity to work with you on this project and hope that this report will be a resource to the City of New Haven.

Very truly yours,

GZA GEOENVIRONMENTAL, INC.

Hande McCaw, P.E.
Senior Project Manager

Chad W. Cox, P.E.
Consultant/Reviewer

Daniel C. Stapleton, P.E.
Senior Principal

ACKNOWLEDGEMENTS

We would like to acknowledge and thank the following individuals for their contributions and guidance throughout the preparation of this study report:

CITY OF NEW HAVEN

Mayor Toni N. Harp

CITY PLAN DEPARTMENT

Karyn Gilvarg, Director
Donna Hall, Senior Planner

CITY ENGINEERING DEPARTMENT

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Rebecca Bombero, Director
Dave Moser, Landscape Architect

PLANNING, DESIGN, AND ENGINEERING TEAM

GZA GeoEnvironmental, Inc.

Utile, Inc.

Biohabitats, Inc.

Cambridge Systematics

We also would like to acknowledge and thank the Greater New Haven Water Pollution Control Authority; Connecticut Department of Energy and Environmental Protection; State of Connecticut Department of Transportation; Connecticut Institute for Resilience and Climate Adaptation; and Connecticut Department of Housing for their support and feedback on the project.

Lastly, we would like to extend our great appreciation to the residents, businesses, property owners, and advocacy organizations that provided their recommendations and input along the way.

Table of Contents

New Haven Long Wharf Flood Protection Study

Section 1.0 Introduction and Overview

Long Wharf Maritime Center during Hurricane Irene. Photograph provided by the City Plan Department.

1.0 PROJECT INTRODUCTION AND OVERVIEW

The New Haven Long Wharf Flood Protection Study supports Long Wharf District to be more resilient to coastal flooding and sea level rise.

Long Wharf, an approximately 350-acre district of New Haven, is a socio-economic center of Southern Connecticut. The Long Wharf is a commercial/industrial district of New Haven with several well-known companies (e.g., IKEA, Assa Abloy) as well as the Regional Water Authority, the New Haven Food Terminal, and the Long Wharf Maritime Center. The Long Wharf District also includes Union Station and the Connecticut Department of Transportation's (ConnDOT) largest railyard, recently transformed with over $1billion in capital investment. The Long Wharf shoreline, consisting of beach, waterfront walkways, tidal marsh, natural habitat, the new Canal Dock Boathouse, the Long Wharf Nature Preserve and the Veteran's Memorial Park, is a valuable cultural, recreational and ecological asset and provides the District with scenic views of New Haven Harbor. The Long Wharf shoreline provides a natural oasis in an otherwise urban environment. The shoreline is also an important historic marker for New Haven.

Located adjacent to New Haven Harbor, the Long Wharf District is vulnerable to coastal flooding. The area was significantly impacted during the Hurricane of 1938 and more recently during Hurricanes Irene and Sandy. Most of the District is located within Federal Emergency Management Agency (FEMA) special flood hazard zones. Sea level rise and other effects of climate change will increase the District's coastal flood risk and associated damages, loss, and disruption.

The State of Connecticut and the City of New Haven received resilience grants through the Community Development Block Grant Natural Disaster Recovery program (CDBG-NDRC). Part of New Haven's grant was dedicated to the protection of New Haven's Long Wharf area and the funding of the Long Wharf Flood Protection Study. The City of New Haven contracted with GZA GeoEnvironmental, Inc. (GZA) to perform the study. GZA's project team included the following consultants: Utile, Inc.; Biohabitats, Inc. and Cambridge Systematics.

The purposes of the Long Wharf Flood Protection Study are to:

1) characterize the coastal flood hazard;

2) evaluate the area's flood vulnerability; and

3) identify and evaluate alternatives that would mitigate the coastal flood risk.

Four flood mitigation alternatives, representing a range of cost, complexity and level of flood protection, were evaluated. One alternative employs a resilience strategy, relying upon compliance with flood regulations and the individual efforts of property owners. Two alternatives utilize deployable flood barriers and Interstate 95 to create a flood barrier system. The fourth alternative, a Living Shoreline and hybrid solution, involves improvement of the Long Wharf shoreline to provide significant flood and shoreline protection as well as enhance the recreational, economic and natural resource values of the Long Wharf District.

The results of the Study are presented in this report.

1.1 Study Approach

The New Haven Long Wharf Flood Protection Study combined rigorous science and engineering in order to characterize the coastal flood risk and presents a near-term focus on practical, cost- effective flood mitigation options and a long-term focus on flood protection measures that also restore and enhance Long Wharf's shoreline, natural systems, recreational use, and economic development.

The major elements of the Study approach include:

- Industry-accepted climate science;
- Statistical analysis of historical water level data from applicable tide gage stations, collected by the National Oceanic and Atmospheric Administration (NOAA);
- Use of high resolution terrain data (post-Hurricane Sandy);
- Hydrodynamic computer flood modeling to characterize coastal flooding and their effect on structures and natural features;
- Use of scenario-based flood maps to evaluate the vulnerability of the area to flooding from tides, storm surge and waves;
- Management of all information using ESRI ArcGIS geographic information system (GIS) software;
- A "risk-based" approach, defining coastal flood hazards in terms of probability, consistent with methods currently being used by state and federal agencies;
- Resilience strategies and alternatives that are consistent with the City of New Haven's current vision and plans for development; and
- Recognition of the existing natural shoreline features and the rich maritime history of Long Wharf.

1.2 Study Scope

The Study scope included:

1. Stakeholder Engagement;
2. Characterization of the existing site conditions (topography and bathymetry, visual condition survey);
3. Characterization of the coastal flood hazards (tides, storm surge and waves);
4. Flood vulnerability assessment (flood risk profiles, loss estimation);
5. Flood mitigation alternatives evaluation (design and evaluation criteria, feasibility, benefit-cost, visualization);
6. Concept Design (Alternative 4 only).

This study focuses on coastal flood hazards (tides, storm surge and waves). In addition to the coastal flood hazards, the Long Wharf District is also vulnerable to flooding from local intense precipitation (LIP). LIP and the Long Wharf stormwater infrastructure are being evaluated by others for the City (see below) and are not evaluated in this study.

1.3 Integration with On-Going Projects

The Long Wharf Flood Protection Study recognizes the other important resilience and economic development projects that are on-going or recently completed, including:

- A detailed study of the Downtown and Long Wharf District stormwater infrastructure, modeling and management, by Camp Dresser and McKee for the City.
- A concept design of the Long Wharf shoreline using Natural and Nature-Based Features by Milone & MacBroom for the State.

- The Long Wharf Erosion Protection and Revetment Design by Langan Engineering for the City.
- Long Wharf park restoration construction including recent revetment repair and plantings.
- The new Canal Dock Boathouse construction.
- Recent Long Wharf Drive and parking area paving and creation of the bikeway.
- Design of a Greenway and Vision Trail from Brewery Street to Long Wharf and the Canal Dock Road.
- Area Flood Hazard Characterization/Modeling (on-going) by Connecticut Institute for Resilience & Climate Adaptation (CIRCA) for ConnDOT.
- Connecticut Department of Housing Phase 2 NDRC Application (Bridgeport and New Haven projects).
- The proposed "Long Wharf Responsible Growth Plan".

Details from each of these informed the flood mitigation strategies, approach and alternatives that are presented in the Study. Further, the flood mitigation alternatives presented in the Study can be adapted and built upon, if concepts such as those presented in the NDRC Phase 2 Grant Application, or others that emerge from the "Long Wharf Responsible Growth Plan", are pursued in the future.

1.4 Summary of Relevant Reports and Information

GZA performed a literature search of relevant available reports and studies, including:

- New Haven Green Map, City of New Haven Plan Department (2004);
- New Haven Climate Action Plan, New Haven Community Clean Air Initiative (2004);
- New Haven Coastal Program Project Summary, Milone & MacBroom, (2006);
- City of New Haven Natural Hazard Mitigation Plan Update, New Haven City Plan Department (2011);
- Drainage Study for Route 34 and Union Avenue, Cardinal Engineering Associates (2012);
- Downtown Crossing Drainage Feasibility Study – Phase 2, Parsons Brinckerhoff (2014);
- New Haven Vision 2025 – A Plan for a Sustainable, Healthy and Vibrant City, City of New Haven Plan Department (2015);
- City of New Haven Zoning Ordinance, City of New Haven Plan Department (2015);
- Coastal Risk Reduction and Resilience: Using the Full Array of Measures, USACE (2013);
- Application of SLAMM to Coastal Connecticut, Warren Pinnacle Consulting, Inc. (2015);
- North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, USACE (2015);
- North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, Appendix D – State and District of Columbia Analyses, USACE (2015);
- Flood Insurance Study, New Haven County, Connecticut, Federal Emergency Management Agency (2013);
- Long Wharf Park Conceptual Shoreline Restoration and Park Enhancement Plan, LANGAN CT, Inc. (2014), including existing conditions analysis, geotechnical data and proposed construction plans.

1.5 Stakeholder Engagement

The project team reached out to project stakeholders from the State, regulatory agencies and the Connecticut Institute for Resilience and Climate Adaptation (CIRCA) as well as business owners and residents in the district, to inform them of the study goals, findings and progress and to solicit comments and concerns about coastal flooding. A total of ten stakeholder engagement meetings were held at different stages of the study. The agencies attended the meetings varied depending on the topic of discussion. Stakeholder engagement meetings were held with the attendance of the following parties:

- Connecticut Department of Energy and Environmental Protection (DEEP);
- State of Connecticut Department of Transportation (ConnDOT);
- State of Connecticut Department of Transportation Office of Rail;
- Connecticut Institute for Resilience and Climate Adaptation (CIRCA);
- Connecticut Department of Housing;
- Long Wharf District Business Owners.

In addition, the ConnDOT Hydraulics and Drainage office performed a review of a draft of the Study, and their comments have been addressed.

1.6 Study Report

The study report includes the following sections:

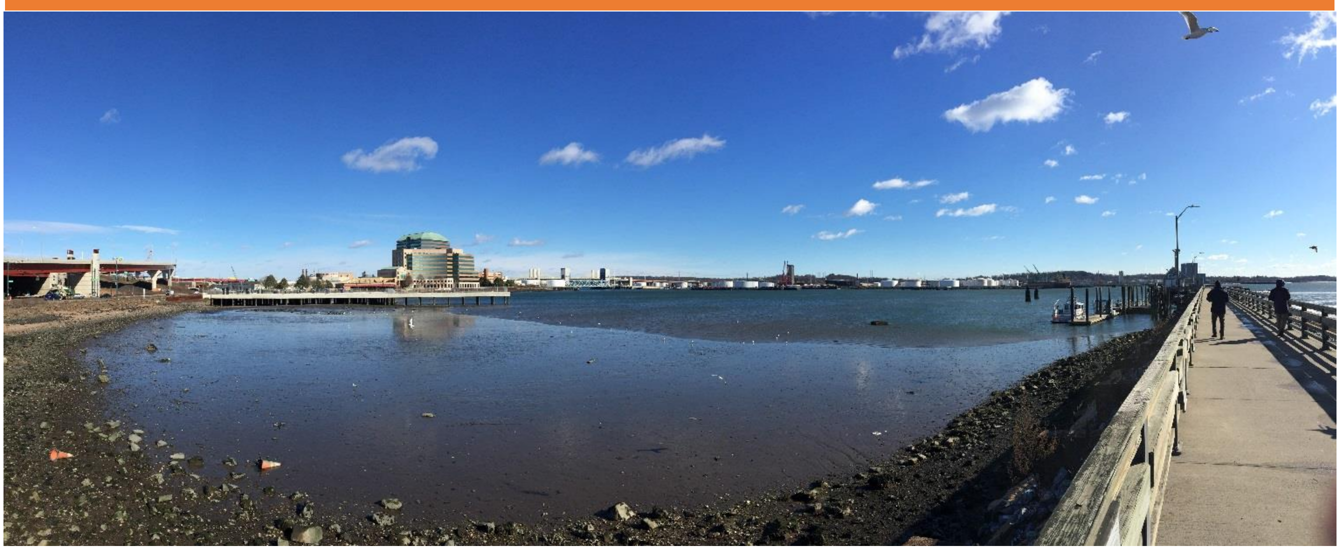
- Section 1.0 Introduction and Overview;
- Section 2.0 Existing Conditions;
- Section 3.0 Coastal Flood Hazards;
- Section 4.0 Coastal Flood Vulnerability;
- Section 5.0 Coastal Flood Mitigation Strategies and Alternatives;
- Section 6.0 Concept Design of Flood Protection Alternative 4.

1.7 Risk, Uncertainty and Sea Level Rise

The Study utilizes a risk-based approach which evaluates flood levels and sea level rise (and their consequences) in terms of probability of occurrence. Sea level rise presents a consequential risk to the property, critical infrastructure and coastal ecosystems within the Long Wharf District. While the long-term increase in sea level is an underlying and contributing factor, the Long Wharf District coastal flood risk is generally a result of extreme water levels (storm surge and waves). Increasing sea levels worsen the impacts of storm surge, high tides and wave action. Although the overall risks associated with coastal flooding are well understood, there is significant uncertainty around predictions of extreme water levels and sea level rise. Acknowledging and incorporating uncertainty is a central part of resilience and climate change planning.

Section 2.0 Existing Conditions

New Haven Long Wharf Flood Protection Study



View of Long Wharf Pier, New Haven and Looking North – Current Site Conditions

2.0 EXISTING CONDITIONS

This section presents an overview of the existing condition of the project study area. Key features presented include topography and bathymetry, utilities, shoreline features, ecology, transportation and land use. These features make up the existing baseline conditions that are relevant to characterizing coastal flood vulnerability.

2.1 Limits of the Study Area

Figure 2-1: Project Study Area

The limits of the Long Wharf Flood Protection Study area are indicated in Figure 2-1. The study area is comprised largely of industrial and commercial uses. The Metro-North and regional rail yard form the west and northwest boundaries of the study area. Interstate 95 (I-95), Long Wharf Drive and the shoreline frame the eastern boundary of the study area.

Figure 2-2: Project Study Sub-Areas

2.2 Study Subareas

For purposes of the Study, the project was divided into three sub-areas based on commonality of geomorphology and land use (Figure 2-2). Area 1 is a low-lying coastal zone and includes Long Wharf Drive, Long Wharf Park, the Veterans Memorial Park, the Long Wharf Nature Preserve, Long Wharf Pier and the Canal Dock Boat House (under construction). Area 1 is exposed to New Haven Harbor and Long Island Sound, beyond. Area 2 is also exposed to New Haven Harbor and Long Island Sound but is characterized by development and building improvements, including the Long Wharf Maritime Center. Area 2 also includes the City of New Haven Sanitary Pump Station, Sportech Venues and Long Wharf Drive properties. Area 3 includes: 1) the commercial and industrial properties located to west of I-95, 2) the rail yard, and 3) residential and City properties. Area 3 is not directly exposed to New Haven Harbor, but is still vulnerable to coastal flood inundation.

2.3 Zoning, Land Use and Property Ownership

Figure 2-3 shows current zoning. Area 1 consists of the areas zoned as Park (Long Wharf Park) and General Business. Area 2 consists of Planned Development District (Long Wharf Maritime Center) and Heavy Industrial. Area 3 consists of Light Industrial, Wholesale and Distribution (Rail Yard and U.S. Post Office) and Planned Development Districts (IKEA and New Haven Public Housing). Figure 2-4 shows land use. Figure 2-5 shows parcels by size within the study area. Figure 2-6 shows property ownership per the City Assessor's data.

The implications of the current zoning and land use relative to flood vulnerability is that the Long Wharf District is zoned principally as industrial and commercial with no residential zoning.

2.4 Topography

Topographic setting (i.e., ground surface elevation relative to water level) is one of the key factors affecting flood vulnerability. GZA created a high resolution Digital Elevation Model (DEM) for the Study based on available topographic (LiDAR) and bathymetric data. Attachment 2 identifies the data sources and metadata used to develop the DEM. An existing condition and topographic survey of the Long Wharf Park was also performed by Langan Engineering & Environmental Services, Inc. in 2010 and updated in 2014.

Figure 2-7 presents the site topography relative to the North American Vertical Datum of 1988 (NAVD88). Within the project study area, the ground elevations typically range between 5 to 10 feet NAVD88, with the exception of I-95. The ground surface elevations within Area 1 range from about 0 to 12 feet NAVD88 (typically 6 to 10 feet NAVD88). The ground surface elevations within Area 2 range from about 6 to 13 feet NAVD88 (typically 9 to 11 feet NAVD88). The ground surface elevations within Area 3 range from about 5 to 12 feet NAVD88 (typically 6 to 9 feet NAVD88).

Most of I-95 within the project study area is constructed on an earthen embankment. Elevations along I-95 range between 10 and 30 feet NAVD88 with lower ground elevations in the vicinity of the Church Street/Sargent Drive intersection and at the Hudson Street Bridge. Higher elevations exist closer to the northern and southern ends of the study area. Note that during the time of the study, I-95 was under re-construction. Differences in topography from that shown here associated with the construction should be anticipated.

Findings from review of the ground elevation data indicate that: 1) most of the Long Wharf District is low-lying, with ground surface elevations lower than predicted flood elevations; and 2) due to the elevated embankment, I-95 acts as a flood barrier (with openings) located parallel to the shoreline across much of Long Wharf District.

2.5 Pervious and Impervious Surfaces

The study area is approximately 19.7 million square feet (450 acres). As illustrated on Figure 2-8, 60 percent of the study area is impervious (mostly asphalt pavement) and includes parking areas, roadways and buildings. Surface parking represents about 1/3 of the study area.

About 40 percent of the study area is pervious. See Figure 2-9. With the exception of Long Wharf Park, the majority of pervious surface coverage is comprised of interstitial spaces: highway landscape buffers, trees, lawns.

Most pervious surface areas are currently used for active or recreational open space or for green infrastructure (such as stormwater treatment and infiltration).

The implication of the existing land surface relative to flood vulnerability is that most of the land area is paved providing little to no stormwater infiltration; however, interstitial space is available for creating stormwater infiltration in the future.

2.6 Utilities

Key utilities within the study area include storm and sanitary sewer infrastructure, electrical service and fiber optic conduit.

Figure 2-10 shows the existing sanitary sewer infrastructure. The sewer system includes several critical features located along the Long Wharf shoreline that are vulnerable to the effects of shoreline erosion. A sanitary force main runs parallel to Long Wharf Drive from the Boulevard Pump Station along the seaward side of the road (outside the east curb line, crossing into the street near the existing Visitor's Center) to the East Street Pump Station (Area 2). The force main consists of a 36-inch ductile iron pipe (DIP) and has limited soil cover; invert elevations range from 3.45 feet NAVD88 to 2.22 feet NAVD88 at the south and north ends of the force main, respectively. The force main carries over 30 million gallons of sewer per day. An approximately 10-foot by 10-foot, 7-foot tall aboveground concrete air release chamber is located just north of the southernmost parking lot on the east side of the road.

Figure 2-11 shows the existing stormwater infrastructure. Seven stormwater outfalls are located within the study area shoreline, including:

- Four 18-inch diameter reinforced concrete pipe (RCP) outfalls that service Long Wharf Drive and the parking areas.
- One 36-inch diameter concrete masonry pipe (CMP) outfall that serviced I-95 (note that the details of the reconstructed I-95 stormwater management system, under construction at the time of the Study, were not reviewed as part of this study).
- Twin 42-inch diameter RCP pipe outfalls with a concrete headwall that service I-95, Long Wharf Drive and Sargent Drive.
- One 36-inch diameter RCP pipe outfall that services I-95 and IKEA.
- Twin 48-inch by 72-inch box culvert outfall that services Sargent Drive and surrounding areas.
- The system of catch basins, manholes and 15-inch to 36-inch RCP drain pipes located within and adjacent to Long Wharf Drive.

The outfalls are fitted with tide gates. Currently, several or all of the existing outfalls are inundated during high tide. There are also several combined storm-sanitary sewer outfalls.

There are additional roadway stormwater catch basins and drainage pipes that were constructed as part of the recent I-95 improvements; the details were not available for this Study.

Additional utilities include water supply, electric, gas and fiber optic lines in the project area:

- Water supply is provided through a 12-inch DIP that runs along Long Wharf Drive, outside of the east curb line. The water line ends at the southernmost parking lot on the east side of Long Wharf Drive.
- Electric service is provided through underground cables that run under Long Wharf Drive. Electric boxes are located along Long Wharf Drive. There is no overhead service located along Long Wharf Drive.

- A 6-inch high pressure steel gas line is located on the north end of Long Wharf Drive that turns west onto Canal Dock Road. The existing gas main is rated at 60 psi with an operating pressure of 30 psi. There is also a gas main located within Sargent Drive just to the west of I-95.

- Fiber optic conduit runs under Sargent Drive and across Long Wharf Drive and the Park at Canal Dock Road, extending into the harbor.

The implications of the existing utilities relative to flood vulnerability include:

1. Several key utilities (in particular, the sanitary sewer main), are located within areas that are vulnerable to storm-induced erosion;

2. Several key utilities are located within, or immediately adjacent to, proposed flood mitigation improvements; and

3. Stormwater outfalls will be increasingly effected by sea level rise causing regular, tidal inundation.

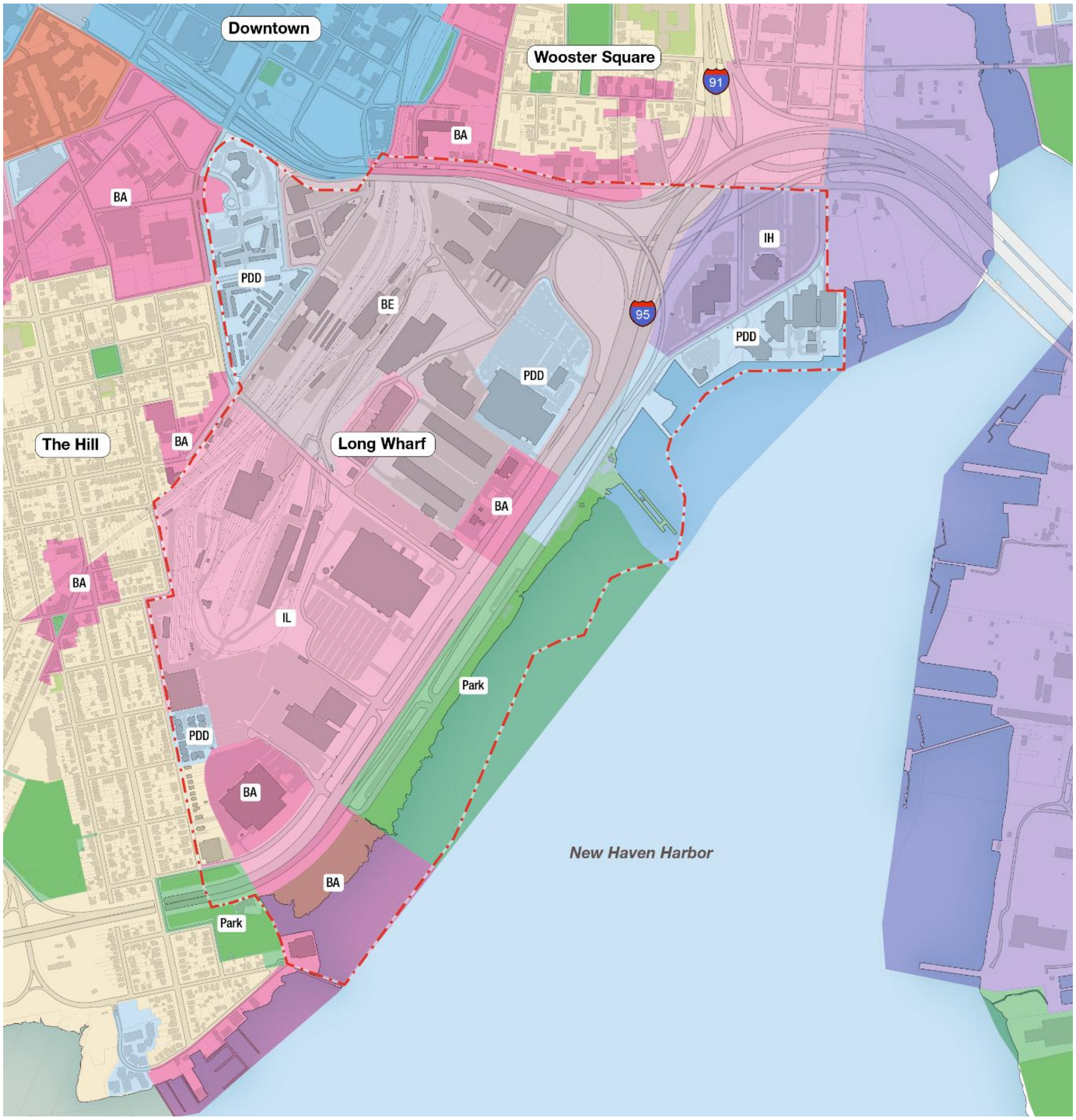
2.7 Geologic Materials

The Long Wharf area was originally an extensive tidal marsh and the land currently present was created with artificial fill, mostly in conjunction with the construction of the rail line (originally along the shore) and the construction of I-95. See Figure 2-12. The subsurface materials have been relatively well classified from previous studies, including logs of test boring performed along the Long Wharf shoreline and presented in the "Geotechnical Engineering Study, Long Wharf Park, New Haven, Connecticut", prepared by Langan Engineering & Environmental Services, Inc. during 2010.

In general, the Long Wharf area consists of layers of artificial fill, overlying natural deposits of highly compressible organic silt, overlying natural brown, medium to fine sand deposits over glacial till and bedrock (at depths greater than 400 feet below grade). The upper portion of the fill material is observed to be sand with organic clayey silt.

The implications of the subsurface materials relative to coastal resilience projects is the presence of the highly compressible organic silt and clay deposits. The presence of these deposits require the use of deep foundations for structures such as flood walls. They will also result in ground settlement in areas where the site grades are increased more than 1 to 2 feet.

Figure 2-3: Long Wharf Area Zoning



Zoning

- BA - General buisness
- BD/BD1/BD2 - CBD
- BE - Wholesale and Distribution
- IL - Light industrial
- IM - Marine Industrial

Figure 2-4: Property Land Use within Study Area

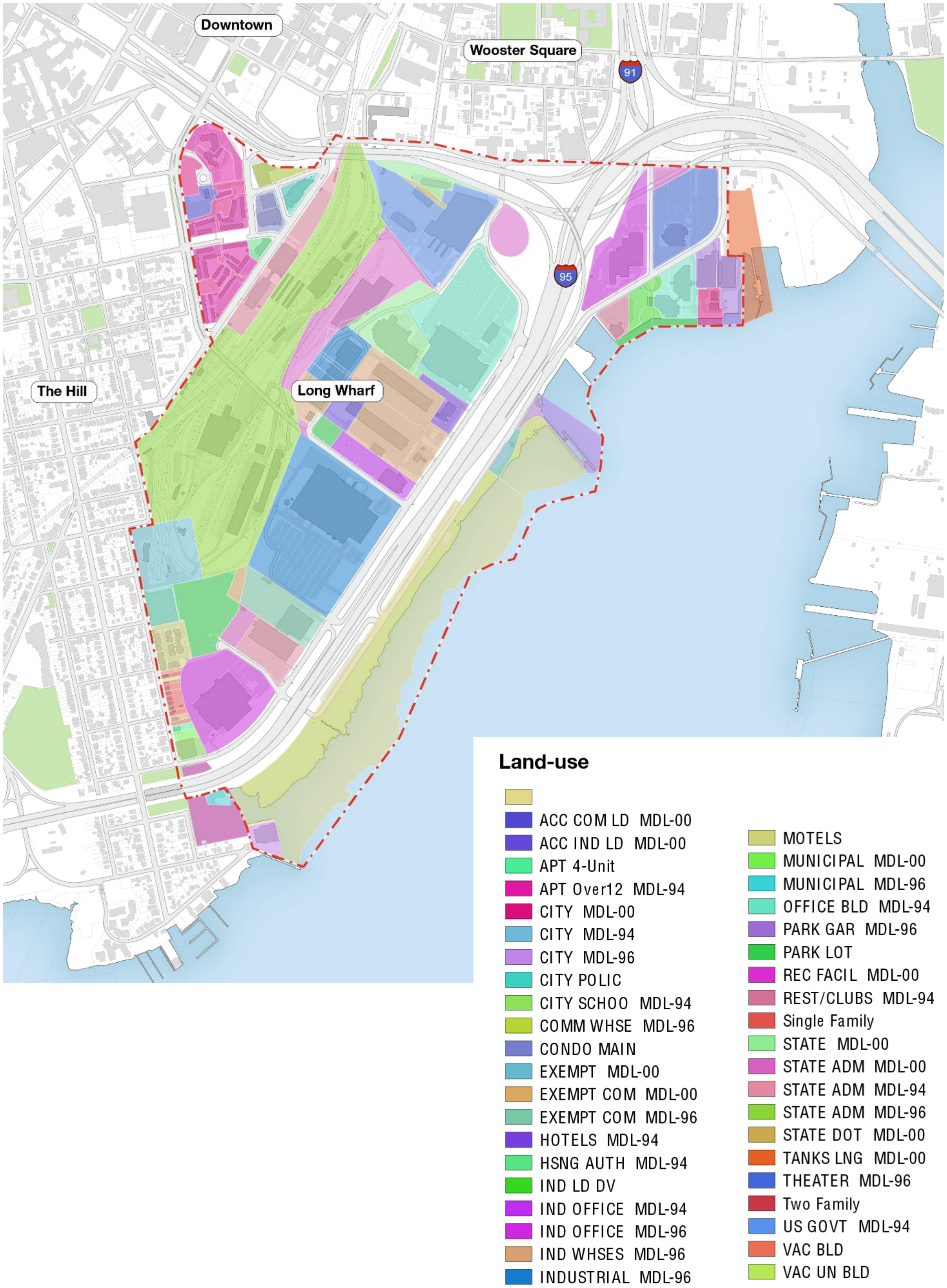


Figure 2-5: Parcels by Size within Study Area

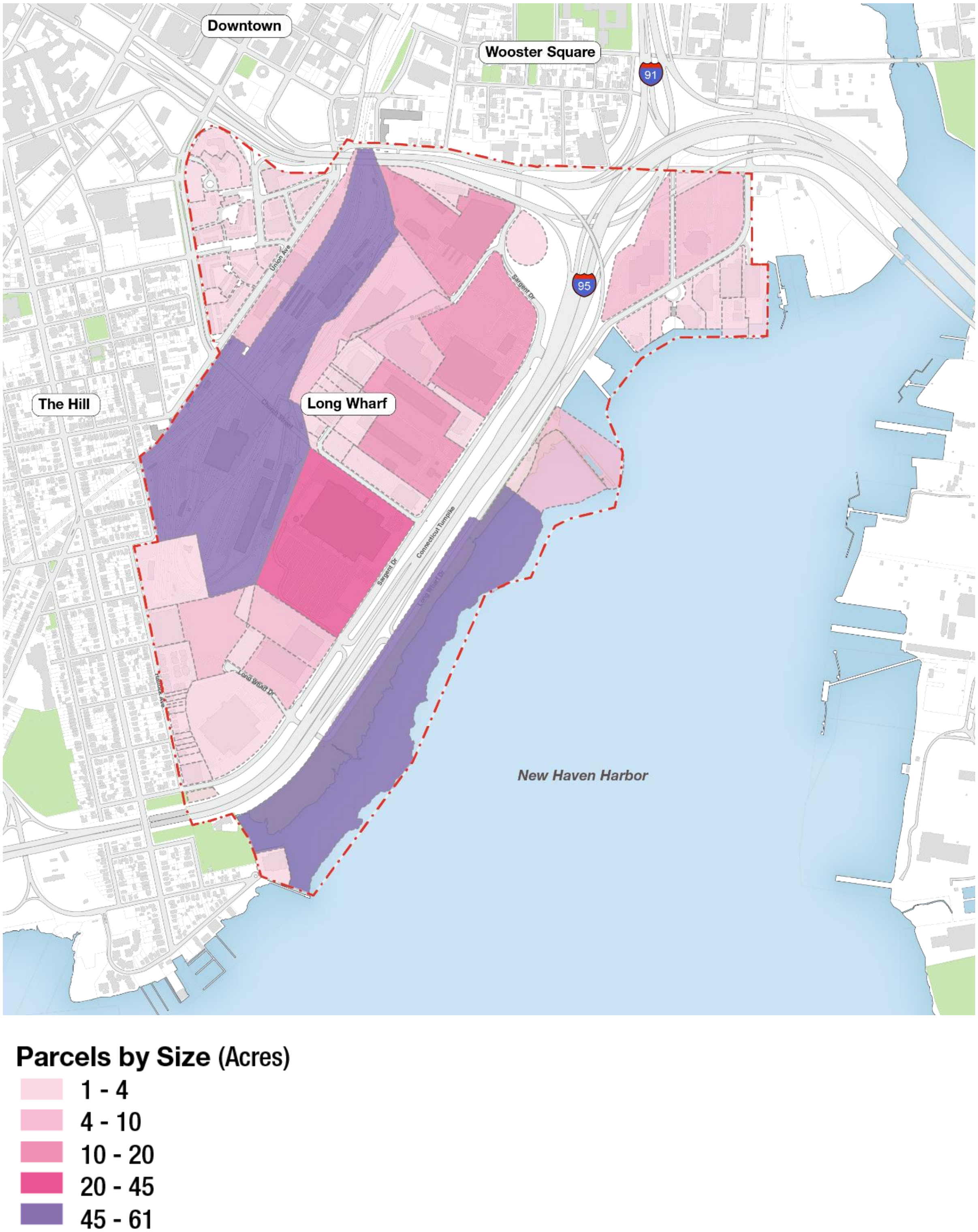
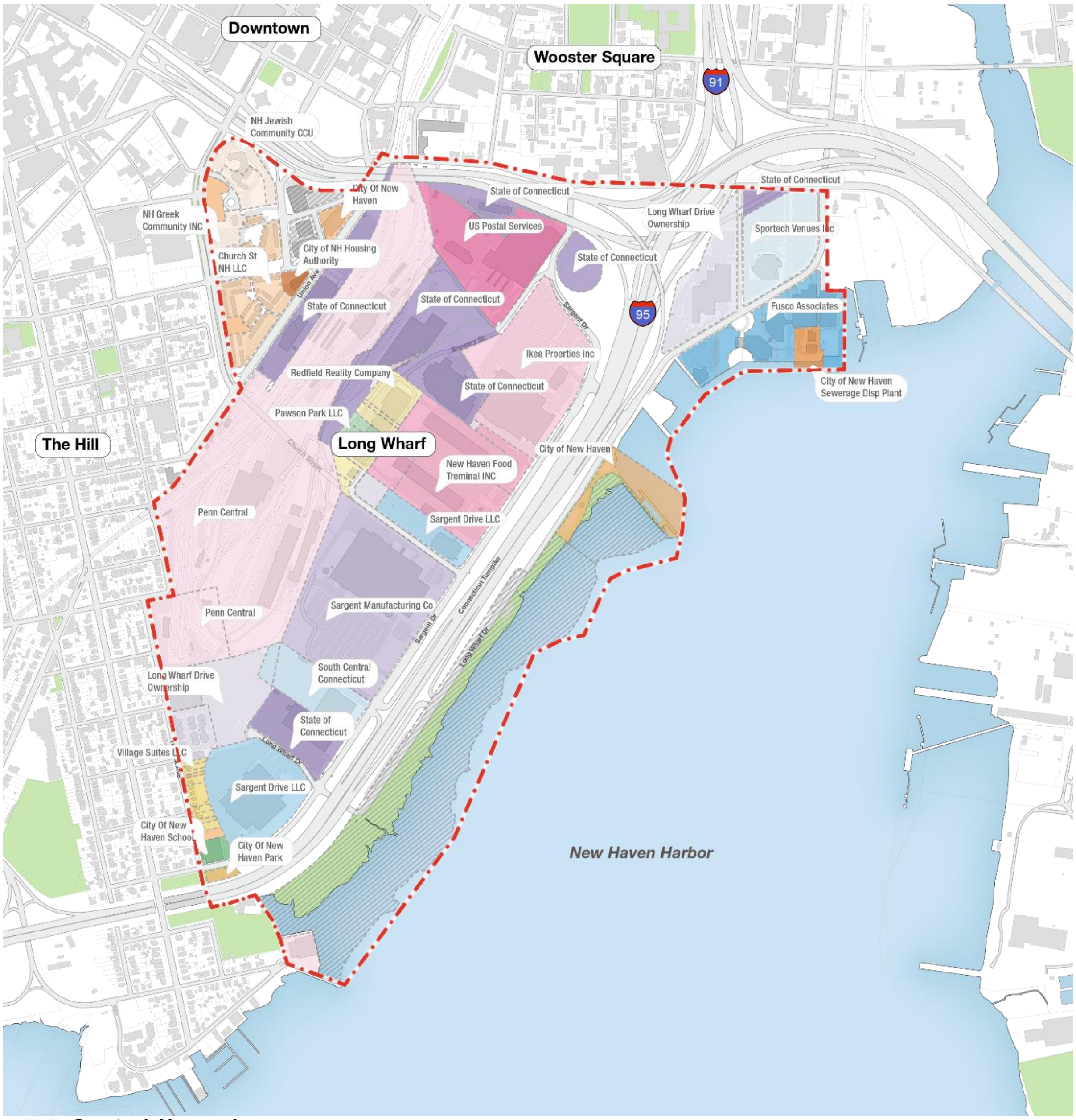


Figure 2-6: Property Ownership within Study Area



Sportech Venues Inc	
NH Jewish Community CCU	
Church St NH LLC	
City of New Haven	
City of New Haven Sewerage Disp. Plant	
City of New Haven Housing Authority	
City of New Haven School	
Pawson Park LLC	
Village Suites LLC	
Other	
No data	

Ownership

- Penn Central
- Ikea Property Inc
- New Haven Food Treminal INC
- US Postal Services
- State of Connecticut
- Sargent Manufacturing Co
- Long Wharf Drive Ownership
- Fusco Associates
- Sargent Drive LLC
- South Central Connecticut

Figure 2-7: Long Wharf Area Topography Relative to NAVD88 Datum.

Figure 2-8: Percentage and Location of Impervious Surfaces within Study Area

Study Area

Study Area Total - 19,645,200 SF

- Surface Parking Area - 5,621,990 SF
- Road Area - 2,898,854 SF
- Building Footprints - 3,029,384 SF
- Pervious Surface - 8,094,972

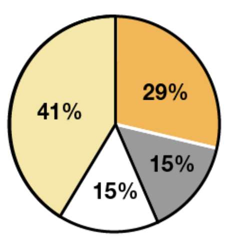


Figure 2-9: Tree Cover and Pervious Surface within Study Area

Figure 2-10: Sanitary Sewer System

Sewer System

- Sewer Volume
- Leachate and Wastewater Discharge Source
- CSO Tanks
- Sewer Feature Point
- Outfalls

Figure 2-11: Stormwater System

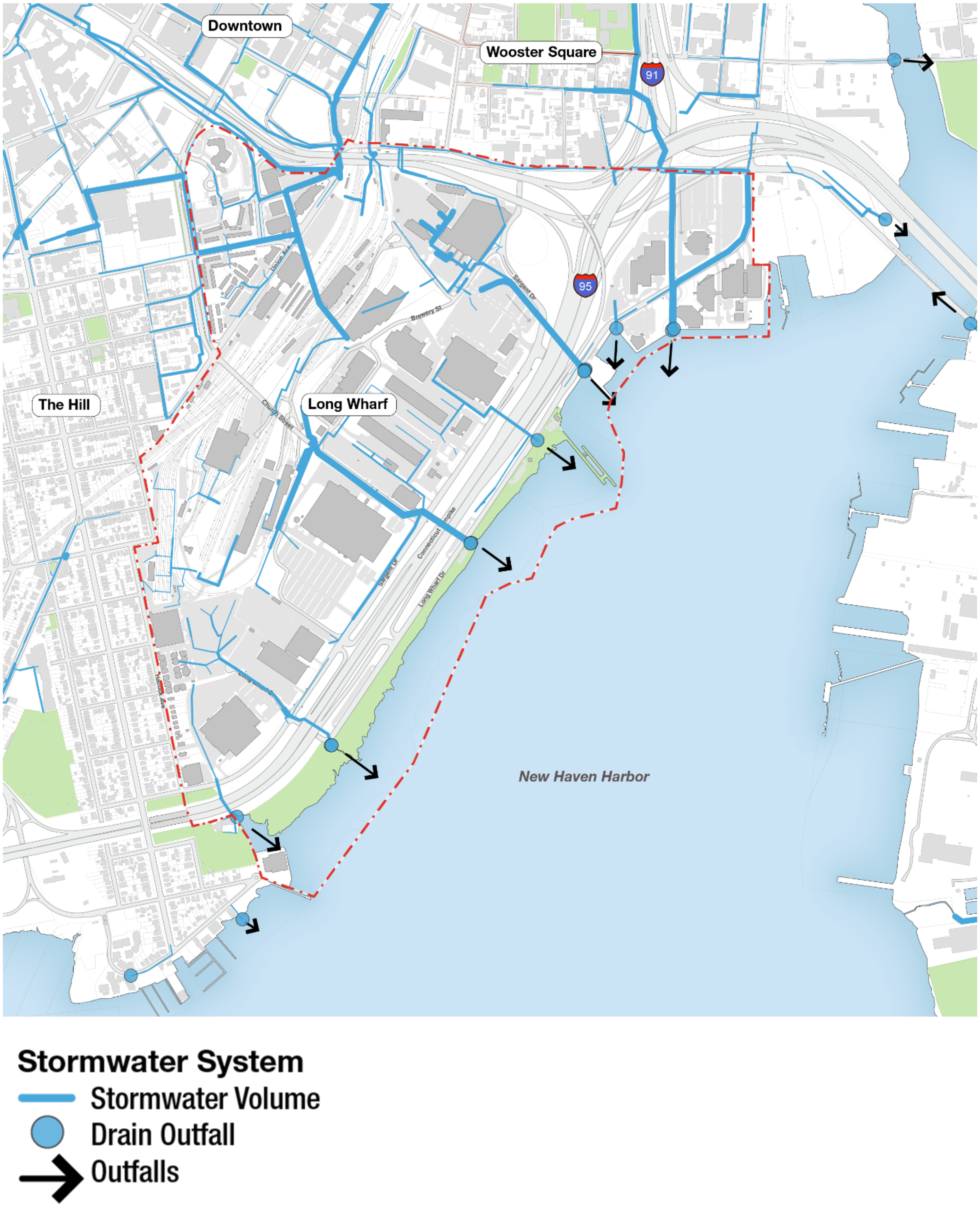
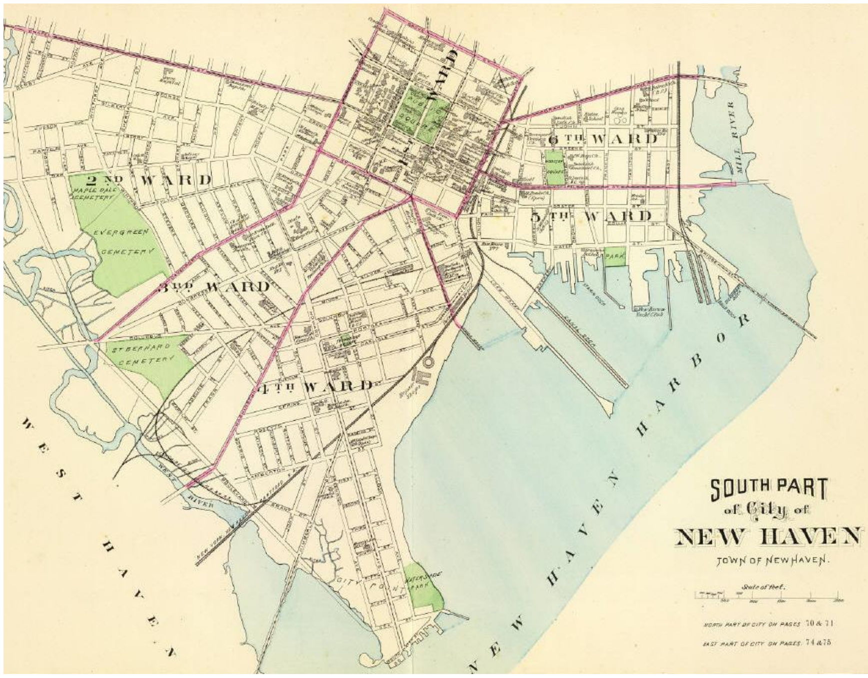


Figure 2-12: Historical New Haven Shoreline and I-95 Construction



2.8 Shoreline Features

The Long Wharf shoreline is subdivided into sub-areas based on the observed shoreline features and land use, including:

- Developed Commercial (Long Wharf Maritime Center);
- Long Wharf Pier and Canal Dock Boat House;
- Long Wharf Park;
- Vietnam Veteran's Memorial Park; and
- Long Wharf Nature Preserve.

The land in the study area is an artificial feature, created from dredge and fill material placed along the west shore of the New Haven Harbor during the mid-twentieth century. The primary purpose of the artificial feature was to create new land for transportation and development. Full development of the waterfront was never completed, resulting in patches of open space throughout the study area dominated by natural resources and passive recreation. Natural habitat, including tidal wetlands, grew in areas where the fill was placed to elevations conducive to marsh growth.

Figure 2-13 presents the shoreline features. Much of the Long Wharf shoreline is developed with structures including a quarry stone revetment, steel sheetpile bulkheads, piers and jetties, and sea walls. Other areas include an estuarine beach and tidal flat, sheltered wetlands and regularly-flooded (low) marsh.

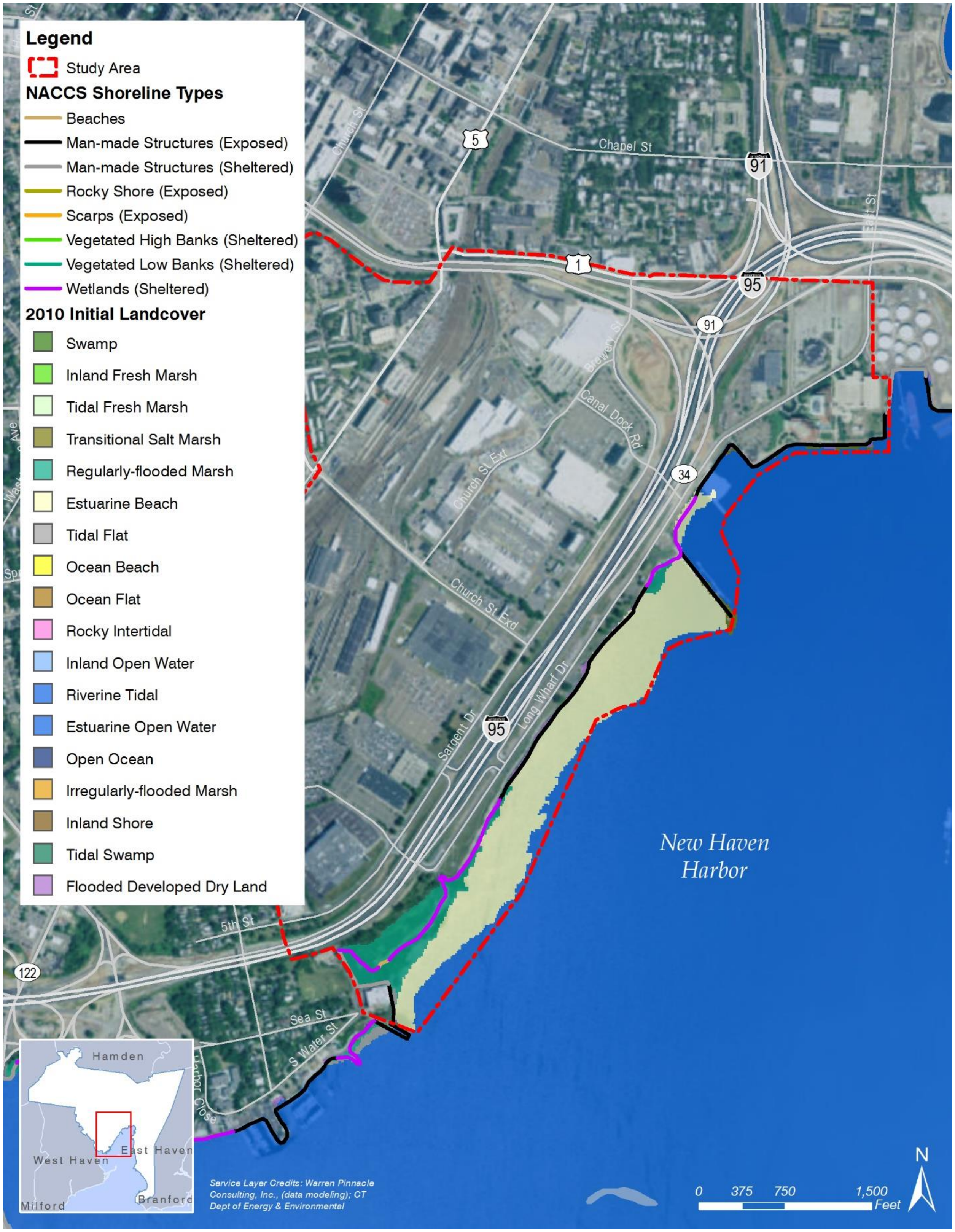
Maritime and Water Dependent Use

The Long Wharf shoreline includes several maritime and water dependent uses including:

- The new Canal Dock Boat House;
- Long Wharf Pier;
- A small vessel anchorage and mooring field (see Figure 2-14);
- Beaches and waterfront parks;
- Navigation channel for the Port of New Haven.

Long Wharf also has a rich maritime history. New Haven was historically the home of some of the richest oyster grounds in New England including oyster beds along the mud flats directly east of Long Wharf. See Figures 2-15 and 2-16.

Figure 2-13 Shoreline Features



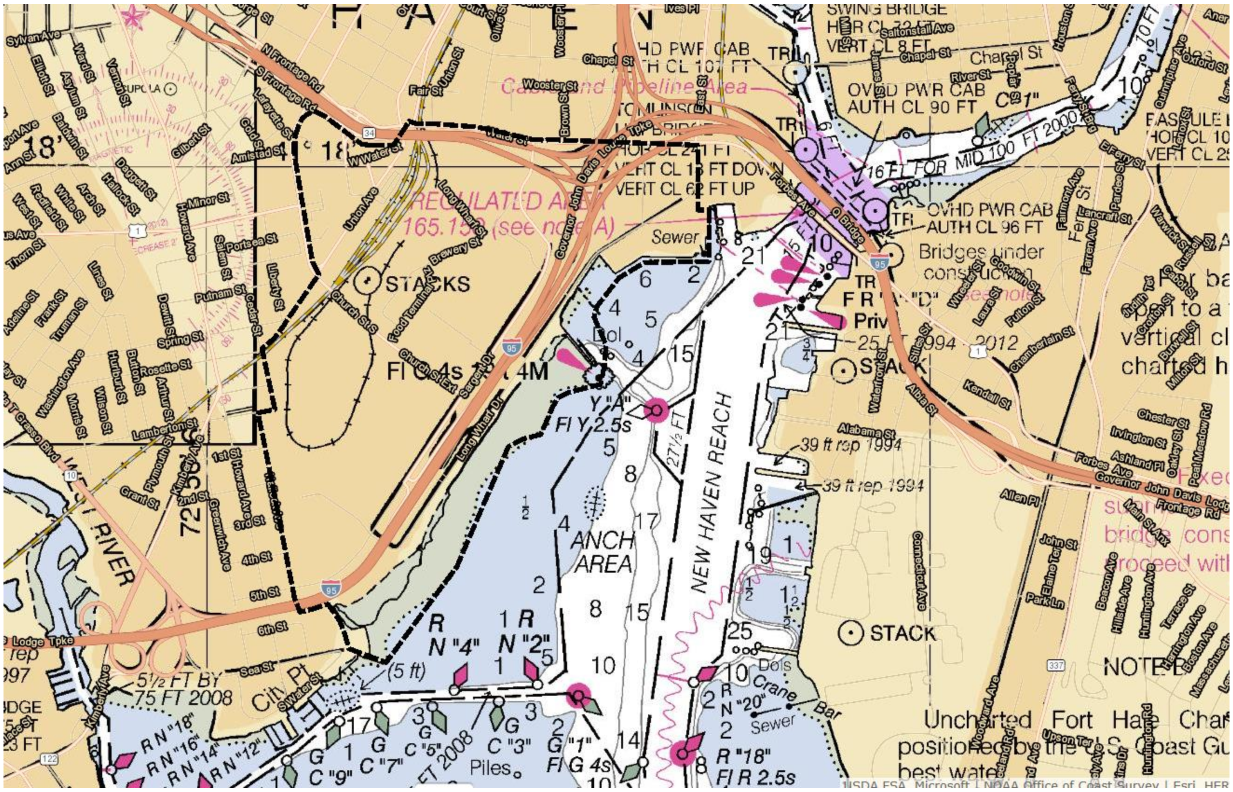


Figure 2-14 NOAA Navigation Chart for Long Wharf

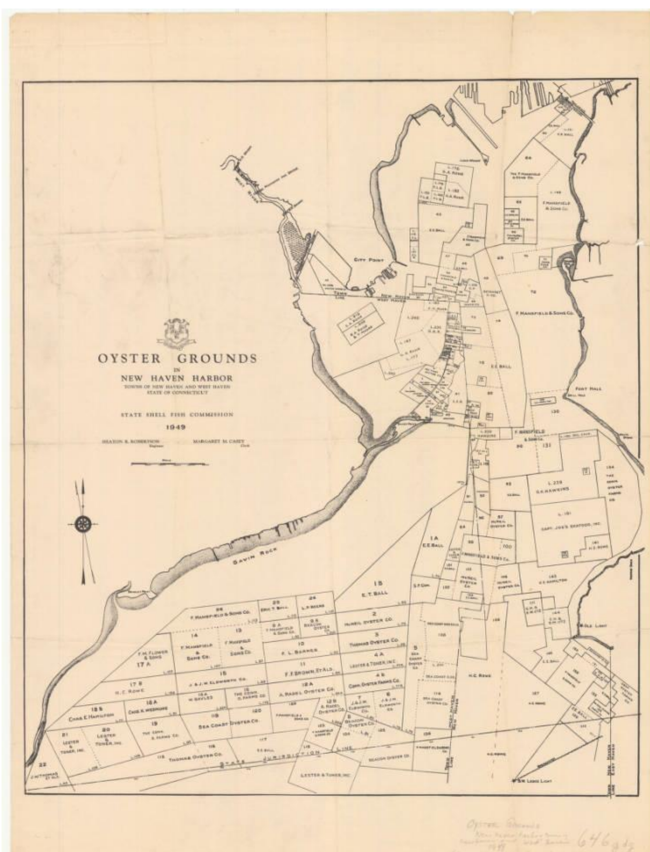


Figure 2-16 Historic Photograph of New Haven Shell Fishing operations

Figure 2-15 State Shell Fishing Oyster Ground Map 1949

2.9 Ecological and Natural Resource Setting

New Haven Harbor, located along the eastern edge of the study area, is an estuary, receiving freshwater inputs from the West, Mill and Quinnipiac Rivers and twice-daily tidal salt water inputs from the Long Island Sound. The harbor tidal range is approximately 5 to 7 feet. The harbor is generally shallow and at low tides there are large expanses of mud flat (see Figure 2-17). The harbor entrance is protected by three large stone breakwaters, the main harbor navigation channel entering through a gap between the easternmost and central breakwaters.

Figure 2-17 Long Wharf Pier and Surrounding Mud Flat

Based on information provided by the Connecticut Department of Energy and Environmental Protection (DEEP) Total Maximum Daily Loads data, this portion of the estuary is impaired due to elevated bacterial concentrations. The water quality designation is SB, with designated uses including commercial shellfish harvesting, recreation, habitat for marine fish and other aquatic life and wildlife, industrial water supply, and navigation.

Figure 2-18 Long Wharf Pier and Rocky Beach

The mud flats in New Haven Harbor are regionally significant staging areas for large concentrations of migrating sandpipers, terns, plovers, turnstones and other shorebirds and waterfowl that feed on these flats. Shorebird species of special note include semi-palmated sandpiper, dunlin, ruddy turnstone, least sandpiper and sanderling. The New Haven tidal flats are reported by State biologists to be the most important wintering area for American black duck in Connecticut.

The shoreline to the north of Long Wharf Park is developed. North of Long Wharf Pier, the water area has been dredged to support vessel navigation and berthing (see Figure 2-14). The shoreline north of Long Wharf Park is dominated by sheetpile and stone bulkheads and revetments. The shoreline to the south of Long Wharf Pier, along Long Wharf Park, is becoming wider, less steep, more vegetated and more natural than shoreline areas to the north.

Long Wharf Park

Long Wharf Park extends approximately 0.3 mile from south of the pier to the Veterans Memorial Park, forming the southern boundary. The shoreline along the park includes several different waterfront edge conditions, ranging from sandy beach, tidal wetlands and quarrystone revetment. The upland areas range in width from about

40 feet to 150 feet. There are two paved parking areas within this sub-area, one directly across from the Visitor Center and the second about halfway through this section, where another small kiosk sits.

This area is generally flat, and is characterized by small changes in elevation. At the lowest elevations, to the east, are the mud flats which are exposed at low tide. Slightly higher in elevation are sandy beaches and salt marsh areas, which are occasionally submerged by the tides. The salt marsh areas are dominated by the grasses, *Spartina alterniflora* (salt marsh cordgrass) and *Phragmites australis* (common reed) (see Figure 2-19). North of the small kiosk, the salt marsh area transitions gradually up towards the walkway.

South of the kiosk, there is little to no salt marsh, and the shoreline is steeper and has been hardened with a quarrystone revetment. The upland areas are characterized by mowed grass with some mature trees, a walkway and Long Wharf Drive, which are all roughly located at the same elevation. To the west is I-95, which is elevated approximately 10-20 feet higher than surrounding areas.

At the southern end of the site are two drainage pipes with tide gates, which allow discharge to flow towards the harbor but close to keep the tides from entering the pipes (see Figure 2-20). The shoreline in this area includes a concrete box culvert and steel sheetpile bulkhead.

Veteran's Memorial Park

The Vietnam Veteran's Memorial Park area is located to the south of Long Wharf Park and consists of approximately 17 acres of dedicated parkland.

The area stretches approximately 0.4 mile southward to the Long Wharf Nature Preserve. The beach, shoreline and adjacent upland in the northern section of the park are narrow, all becoming gradually wider near the south end of the park. The beach, shoreline and upland areas are similar to those present in the Long Wharf Park, with the mud flat at the lowest elevations, little to no salt marsh, rock-hardened shoreline (see Figure 2-21), mowed parkland with trees and walkway, and Long Wharf Drive. This area of Long Wharf Drive contains a small paved parking area adjacent to the shoreline in the north part of the park, and a much larger parking area located west of Long Wharf Drive. The parking area is used by large trucks and others, many of whom are attracted to the area for the food trucks.

Figure 2-19 Long Wharf Park Salt Marsh

Figure 2-20 Long Wharf Park Stormwater Outfalls at South End of Park

Figure 2-21 Mud Flat-Revetment Transition

The shoreline transitions from a revetment-hardened steep shoreline to a more gradually sloped shoreline that contains the remnants of an old walkway, and then transitions again to a more natural shoreline.

South of the intersection of Long Wharf Drive and the I-95 on- and off-ramps, the beaches, shoreline and parkland become much wider (Figure 2-22). The salt marsh areas become much more dominant and vegetated primarily by the native *Spartina* grass rather than the invasive *Phragmites*.

The park's memorials, which are located within the southern section of the park, consist of two monuments: one a small granite slab dedicated to the members of the nearby communities that served in the Vietnam War, and the other an 11-foot high V-shaped monument inscribed with the names of the residents who were killed or reported missing during the war. The park is separated from the nature preserve by a culvert and pipe that discharge to the harbor (Figure 2-23).

Figure 2-22 Wider Natural Features to the South of Long Wharf Drive and I-95 Intersection

Figure 2-23 Stormwater Outfall at South End

Long Wharf Nature Preserve:

The Long Wharf Nature Preserve is located at the southern end of the Long Wharf study area.
The preserve was created in 1994 by the New Haven Land Trust and the Garden Club of New Haven with land donated by the City of New Haven. The area includes approximately 24 acres of restored coastal habitat including mud flats, dunes, salt marshes and wooded upland habitat.

The shoreline in this area is natural and much wider. Long Wharf Drive veers westward at the northern extent of the park, no longer paralleling the study area, and I-95 is located at a much higher elevation and is less present due to the trees located between the shoreline and the highway.

The site includes a trail system and educational signs throughout (Figure 2-24). The trail cuts through the preserve in two areas, allowing passage through the salt marsh from the uplands to the beaches.

Figure 2-24 Long Wharf Nature Preserve Trail

The marshes gradually slope to the wooded upland area. Tree species within this area include *Ailanthus altissima* (Tree-of-Heaven), *Juniperus virginiana* (red cedar), and *Populus deltoides* (cottonwood). The trail cuts through this area, paralleling the shoreline.
The preserve extends to the south, ending at another stormwater discharge outfall and drainage channel.

The implication of the natural shoreline features relative to flood vulnerability include:

1. The tidal flats significantly attenuate wave heights during normal tide conditions.
2. Portions of the shoreline consist of sand beach and dune, which provide some shoreline protection and flood mitigation during normal tide conditions and high probability storms. However, these will erode (chronically) due to sea level rise and (acutely) during extreme storm surge and waves.
3. The tidal marsh is regularly flooded low marsh which provides some wave attenuation. Sea level rise could, if high enough, create open water conditions over portions of the marsh.

Figure 2-25 Beach and Low Marsh Transition

Figure 2-26 Tidal Pool

2.10 Shoreline Structures

The following series of photographs document the shoreline features from the Long Wharf Maritime Center to the north to the Long Wharf Nature Preserve to the south. The photos were taken by the project team during the visual condition survey held on January 19, 2016. Figures 2-27A and B show the locations of the photographs. Elevations presented in this section are estimated based on LiDAR topographic data; an elevation survey of specific structures was not performed and elevations discussed here should be considered approximate.

Figure 2-27A


Legend
Photo Locations
Study Area
Brewery St
Canal Dock Rd
Sargent Dr
Long Wharf Dr
East St
1
91
91
95
34
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 112.5 225 450
Feet
N

Figure 2-27B

Legend
Photo Locations
Study Area
34
Church St S
Church St Exd
Long Wharf Dr
Sargent Dr
95
26
28
29
30
27
31
34
32
33
35
36
37
38
39
40
42
41
43
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 112.5 225 450
Feet
N

Figure 2-28 (Photo 1)

Figure 2-28 presents a view looking north from the shoreline at the northeast end of the project study area. The brick building on the left side is the Long Wharf Garage. The enclosed waterway is the fueling terminal dock for the adjacent bulk storage terminal. The shoreline is hardened with a quarry stone revetment, approximately 350 feet long, on the northern side near Long Wharf Garage building. The revetment transitions into a concrete bulkhead at the southern side with a parapet wall bordering the lawn. The parapet wall is set back approximately 6 feet from the shoreline and is approximately 3 feet high. The crest elevation of the revetment appears to be about 6 feet NAVD88. The crest elevation of the parapet wall is approximately 11 feet NAVD88.

Figure 2-29 (Photo 2)

Figure 2-29 presents a view looking west from the shoreline at the eastern end of the project study area. The building behind the tree coverage is the Maritime Center building. The concrete bulkhead with the parapet wall wraps around the lawn and continues west for about 135 feet until the end of the parcel lot for the garage. The parapet wall is set back approximately 20 feet. The wall height and crest elevation are consistent with the eastern shoreline, approximately 3 feet high and at about 10 feet NAVD88.

Figure 2-30 (Photo 3)

The neighboring parcel, owned by the City of New Haven (East Street Pump Station), has a stone revetment at the shoreline that is approximately 225 feet in length. The crest elevation of the revetment is at about 13 feet NAVD88. Figure 2-30 presents a view looking east from the crest of the revetment in front of the City building.

Figure 2-31 (Photo 4)

Figure 2-31 presents a view looking north - northeast from the shoreline in front of Lenny and Joe's Fish Tale restaurant. The shoreline in front of the Maritime Center is hardened with a combination of a sheet pile bulkhead and quarry stone revetment. A quarry stone revetment and a concrete bulkhead combination is present to the west/southwest of the sheetpile bulkhead. Along the revetment on the western end of the Maritime Center, where topography is lower, a parapet wall that is approximately 2 feet high tops the revetment.

Figure 2-32 (Photo 5)

A view of the parapet wall in front of the Maritime Center building. Photo is taken looking east. The parapet wall is constructed on top of the steel sheetpile bulkhead. The pavement grade behind the parapet wall is about Elevation 10 feet NAVD88 indicating that the top of wall is at about Elevation 12 to 13 feet NAVD88.

Figure 2-33 (Photo 6)

A view of the bulkhead/revetment between the Maritime Center building and the Lenny and Joe's Fish Tale restaurant. Photo is taken looking west. This portion of the shoreline has the highest elevation within the Maritime Center, with revetment crest elevations reaching 12 to13 feet NAVD88.

Figure 2-34 (Photo 7)

The bulkhead/revetment continues westward to Lenny and Joe's Fish Tale restaurant. A view of the revetment/bulkhead combination taken from the top of the structure. Photo is taken looking west. The pavement grade at the top of the revetment is about Elevation 10 feet NAVD88.

Figure 2-35 (Photo 8)

The space between the bulkhead and the upper revetment widens and consists of concrete pavement in front of the Lenny and Joe's Fish Tale restaurant. The pavement elevation is about 6 feet NAVD88. Photo is taken looking west. Slab sitting over piles in the foreground is the Canal Dock Boat House construction area. The restaurant floor elevation is about 10 feet NAVD88. The quarry stone revetment continues to the northwest, toward Long Wharf Drive, with the revetment crest elevation at about 6 to 8 feet NAVD88.

Figure 2-36 (Photo 9)

A view of the Maritime Center taken from the southern shoulder of Long Wharf Drive, looking east. This section of Long Wharf Shoreline consists of a steel sheetpile bulkhead with a concrete cap/wall. The ground elevation behind the concrete cap/wall is about 8 feet NAVD88.

Figure 2-37 (Photo 10)

A view of the steel sheetpile bulkhead between the Canal Dock Boat House pier and the Maritime Center. Bulkhead is approximately 230 feet long with a crest elevation of 8 feet NAVD88. I-95 fly-over to Route 34 is visible in the background. Photo taken from the western shoreline of the Maritime Center.

Figure 2-38 (Photo 11)

Another view of the steel sheetpile bulkhead between the Canal Dock Boat House pier and the Maritime Center taken closer to Long Wharf Drive. Sand has accreted in front of the wall, making a small beach at low tide. An area of stone from a former revetment is present.

Figure 2-39 (Photo 12)

Sidewalk between Long Wharf Drive and the bulkhead. A portion of the sidewalk is cracked and displaced due to settlement (foreground).

Figure 2-40 (Photo 13)

Tidal flat to the west of the Canal Dock Boat House pier. Photo is taken from the shore looking southeast approximately around low tide. The concrete pier is supported on steel piles. The deck elevation of the pier was not determined but appears to match grade at about Elevation 8 feet NAVD88.

Figure 2-41 (Photo 14)

Three stormwater outfalls and the steel sheetpile bulkhead to the south of the Canal Dock Boat House pier.
The bulkhead is about 135 feet long.
I-95 fly-over connecting to Route 34 is in the background. Photo is taken around low tide and the color change on the bulkhead shows the high tide water elevation mark. Stormwater outfalls include: 1) concrete box culvert (with new concrete cap) with two 72-inch pipes; and 2) 42-inch CIP. Duck valves were observed in the box culver outlets.
The 42-inch outlet opening is grated.
The inverts of the three outlets were submerged during low tide and the duck valves appeared closed with some discharge.

Figure 2-42 (Photo 15)

Another view of the steel sheetpile bulkhead to the west of the Boat House. The sheeting of the bulkhead is in poor condition with holes at multiple locations. There is another stormwater outfall along the bulkhead across from Canal Dock Road. The bulkhead ties into a rock revetment on the southwest end. Concrete pieces in the foreground are pieces broke off from the revetment and the sidewalk during extreme storm events. Sand has accreted to the west of the outfall creating a sand beach at low tide.

Figure 2-43 (Photo 16)

Southern end of the bulkhead where it ties into the rock revetment. Revetment is in poor condition with displaced stone, asphalt and concrete pieces and uneven crest elevation. The condition of the revetment here is poor.

Figure 2-44 (Photo 17)

A view of the southern side of the revetment and the rocky sand beach leading up to the Long Wharf Pier. The revetment is approximately 300 feet long. Long Wharf Pier and the Information Center are in the foreground.

Figure 2-45 (Photo 18)

A view of the Information Center at Long Wharf Pier. Photo taken from Long Wharf Pier parking lot looking north - northeast.

Figure 2-46 (Photo 19)

A view of the Long Wharf Pier looking southeast. Timber piles and floating docks on north side of Long Wharf Pier for vessel berthing.

Figure 2-47 (Photo 20)

Long Wharf Pier jetty. Jetty is approximately 600 feet long.
Beach fronted with regularly flooded tidal marsh on south side of jetty.
The jetty/pier crest elevation is about 8 feet NAVD88.

Figure 2-48 (Photo 21)

A view of the Long Wharf Park shoreline taken from Long Wharf Pier looking southwest. Beach and marsh are visible. Tidal flats are visible beyond.
The 36-inch RCP stormwater outfall is located here.

Figure 2-49 (Photo 22)

A view of the Long Wharf Park tidal marsh and beach, north of Information Center.

Figure 2-50 (Photo 23)

A view of the Long Wharf Park Information Center. The ground surface around the Information Center ranges from about 8 feet to 10 feet NAVD88.

Figure 2-51 (Photo 24)

A view of Long Wharf Park looking southwest near Church Street where ground elevation is the lowest along I-95.

Figure 2-52 (Photo 25)

Revetment in front of the northern parking lot at Long Wharf Park.
The revetment is approximately 975 feet long bounded by the Long Wharf Park Information Center to the north and the stormwater outlet near Church Street to the south. Sediment accretion formed a gravelly sand beach in front of the revetment along the first 200 feet stretch of the revetment on the north side.
The revetment crest is at about Elevation 8 feet NAVD88.

Figure 2-53 (Photo 26)

A view of the Long Wharf Park parking lot. Photo is taken from the parking lot looking southeast. The asphalt-paved walkway is at about Elevation 8 to 9 feet NAVD88. Long Wharf Drive pavement is at about Elevation 10 feet NAVD88.

Figure 2-54 (Photo 27)

Another view of the revetment to the northeast of the stormwater outfall east of Church Street. Photo is taken looking north. The revetment is in fair condition with some displaced rock. Even though site visit was completed in the winter, vegetation stalks were observed on and within the revetment. Some scour damage was observed along the crest of the structure. Crest elevation is about 8 feet NAVD88. The observable toe of revetment is at about Elevation 2 feet NAVD88.

Figures 2-55 (Photo 28)

A view of the stormwater outfall east of Church Street.

Figures 2-56 (Photo 29)

Stormwater outfall east of Church Street. Outfall consists of twin 72-inch RCP pipe with tide gates. Pipe inverts are submerged at low tide and pile submerged at high tide. Sedimentation from discharge has created a large sand delta. Flood gates are present and were observed to be closed.

Figures 2-57 (Photo 30)

A view of the revetment to the south of the stormwater outfall east of Church Street. The revetment is approximately 650 feet in length. The revetment is in good condition near the stormwater outlet. At this location the revetment appeared to have been repaired as the stone differs in color than the rest of the structure. The length of the repaired section is about 500 feet.

Figures 2-58 (Photo 31)

A view of the revetment at the southern end of the structure. The southern end of the revetment is in poor condition. Revetment boulders are displaced and scattered around the shoreline and the structure, with slumping and scour observed behind the revetment crest.

Figures 2-59 (Photo 32)

Damaged sidewalk along Long Wharf Park due to loss of sediment behind the revetment. Pavement damage located in area where revetment is in poor condition or destroyed. Pavement damage is due to loss of substrate soil by erosion.

Figures 2-60 (Photo 33)

Damaged revetment with significant stone displacement and scour. Rocky beach in front of revetment.

Figure 2-61 (Photo 34)

Another view of the damaged sidewalk along Long Wharf Park.

Figure 2-62 (Photo 35)

A view of the shoreline to the south of the I-95 on- and off-ramp, near the Veterans Memorial Park. The shoreline has a narrow strip of sandy berm transitioning into shrubbery and green lawn space. Tidal wetlands seaward of beach.

Figure 2-63 (Photo 36)

A view of the shoreline in front of Veterans Park. Upland area is also shown. Grass lawn and asphalt walkway. The ground surface elevation of the upland area is about 9 feet NAVD88.

Figure 2-64 (Photo 37)

Revetment, beach and tidal wetlands located east of Veterans Memorial Park. Revetment in poor to moderate condition. Revetment crest varies between Elevation 6 feet and 8 feet NAVD88.

Figure 2-65 (Photo 38)

42-inch RCP stormwater outfall to the south of the Veterans Park. I-95 and Long Wharf Drive underpass is in the background. Photo is taken looking northwest.

Figure 2-66 (Photo 39)

Stormwater outfall drainage channel at the south end of the Veterans Memorial Park. Photo is taken looking southeast.

Figure 2-67 (Photo 40)

A view of the shoreline at the Long Wharf Nature Preserve to the south of Veterans Memorial Park. The beach is wider in the southern area.
Tidal wetlands shown.

Figure 2-68 (Photo 41)

A view from the Long Wharf Nature Preserve. Footbridge on the left side of the figure provides pedestrian access over a tidal wetland drainage channel.

Figure 2-69 (Photo 42)

A view of the Long Wharf Nature Preserve regularly flooded tidal marsh, looking landward.

Figure 2-70 (Photo 43)

A view of the Pump Station located south of the Long Wharf Nature Preserve. Drainage channel from 36-inch stormwater outfall is present between the marsh and the Pump Station. The ground elevation around the Pump Station is about 10 feet NAVD88.

The Long Wharf shoreline consists of a combination of structures and natural features. Natural coastal processes have resulted in accretion of sandy beach and regularly flooded marsh. The hardened shoreline consists of steel sheetpile bulkhead and quarry stone revetment. The revetment has been repaired and is in good condition in some areas. In other areas, it is severely damaged. Areas upland of the poor condition (or absent) revetment have experienced storm-related scour and erosion. The findings from observation of the shoreline features are that shoreline protection is inconsistent, damage has occurred during recent storm events and future damage of the shoreline due to storm surge and waves is likely.

2.11 Built Environment and Urban Setting

The study area is bisected in a north/south direction by I-95, essentially separating the area between the natural shoreline and large commercial and institutional complex on the northern end. The waterfront is lined with recreational paths, and on its southern end there is a nature preserve, offering a natural environment. The westernmost boundary of the study area is comprised of the rail yard and Union Station along Union Ave. The northern boundary is Route 34 which provides access to downtown New Haven. The southern edge of the study area is less defined by heavy infrastructure or natural shoreline, but rather by a residential neighborhood of The Hill.

The waterfront shoreline is recreational in nature, providing linear paths, picnic areas, an ecological restoration project and a future boathouse. The primary access road is Long Wharf Drive. The industrial district to the west of the highway has its own character and identity. These areas have different planning agendas and issues to be addressed, but should complement each other to form a holistic plan for Long Wharf.

The following discusses design considerations that are relevant to flood mitigation alternatives.

Few cities have waterfronts with such broad striking views as New Haven does, especially considering that most of the view within the study area is unobstructed once you are at the waterfront itself. This presents a significant opportunity to invest resources into the waterfront path systems and to place concerted emphasis on making the approach from downtown more appealing to pedestrians and bicyclists. Design considerations include:

1. Creating a dedicated and well-marked path from downtown, Wooster Square, Mill River and The Hill, that is separated from the roadway, will indicated the significance of the waterfront, as well as move people to it.
2. Tying pedestrian access and improvements into new flood protection systems along the shoreline.
3. Mixing commercial uses into the pre-existing industrial district, considering mixed-use structures that have ground floor industrial uses and commercial above.
4. The current pedestrian network to the west of the highway is also in poor condition and presents an uninviting environment. Efforts could be made toward streetscape improvements where possible.
5. Due to the presence of the highway, view corridors from the west to the east are difficult; however, views are unobstructed along the shoreline.
6. An improved bike network at a local level could have regional connection implications and act as an economic driver.
7. The Long Wharf shoreline recreational paths are in poor condition, often broken and unusable in sections. The erosion of the shoreline due to storm surge and waves have damaged these assets.
8. Long Wharf Drive appears oversized. This creates an undesirable condition for pedestrians trying to cross the street and access the parking on the western edge of Long Wharf Drive. The general scale of the road is unpleasant for people enjoying the more passive nature of the linear path. Major intersections at the northern-most underpass to Canal Dock Drive are another barrier for pedestrians. The intersection is likely scaled to serve large trucks accessing the industrial areas to the north of the study area.
9. Poor connections between Downtown New Haven and the waterfront are a concern. See Figure 2-72. There are currently only two access points to the waterfront from Downtown and the highway. The southernmost access point at Church Street and the northern most point at Canal Dock Drive are in difficult places for pedestrians to access. As a pedestrian, it is necessary to walk either along the length of Church Street from Union Ave and the Hill neighborhood or else through the industrial area north of IKEA to access the riverfront. This lack of pedestrian accommodations makes the waterfront incredibly difficult to access and does not incentivize using bicycles or walking to the waterfront. The preexisting vision trail is

poorly marked and incremental, not providing continuous access under the underpasses. The Long Wharf Industrial District to the west of I-95 is a barrier to accessing the waterfront, as well.

10. Area 3 internal circulation largely serves the large parcels and does not function as a traditional street network. See Figure 2-73.
11. Transit loops are largely relegated to the periphery of the project study area, with the exception of Church Street and Sargent Drive. See Figure 2-74.
12. The Vision Trail provides the primary multi-use path/access to the waterfront, but it is unappealing and disjointed.
13. Bike paths along Howard Avenue and Church Street go near the waterfront but do not connect to it.
14. The Long Wharf District is accessible via the regional bike path routes. See Figure 2-75.

Figure 2-71 Long Wharf Drive with Minimal Traffic

Figure 2-72 Long Wharf Area Access Points

Figure 2-73 Area 3 Internal Circulation

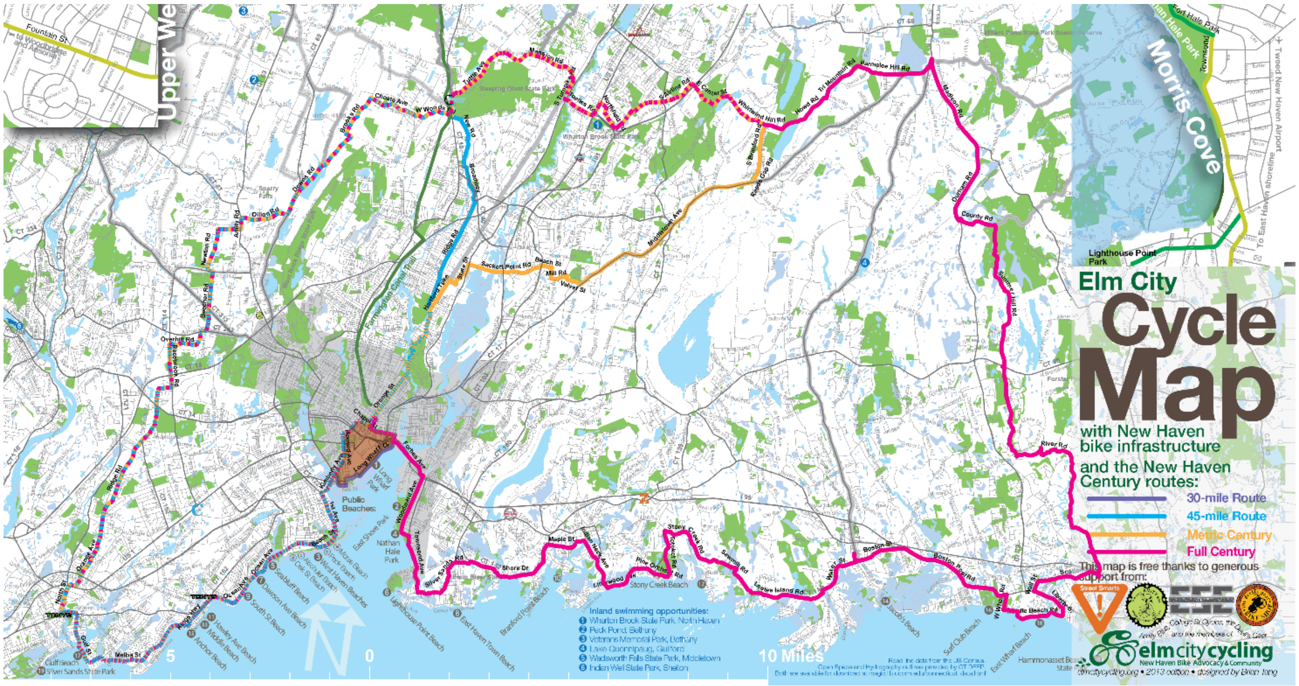
Figure 2-74 Transit and Bike Map

Transit

Bus routes

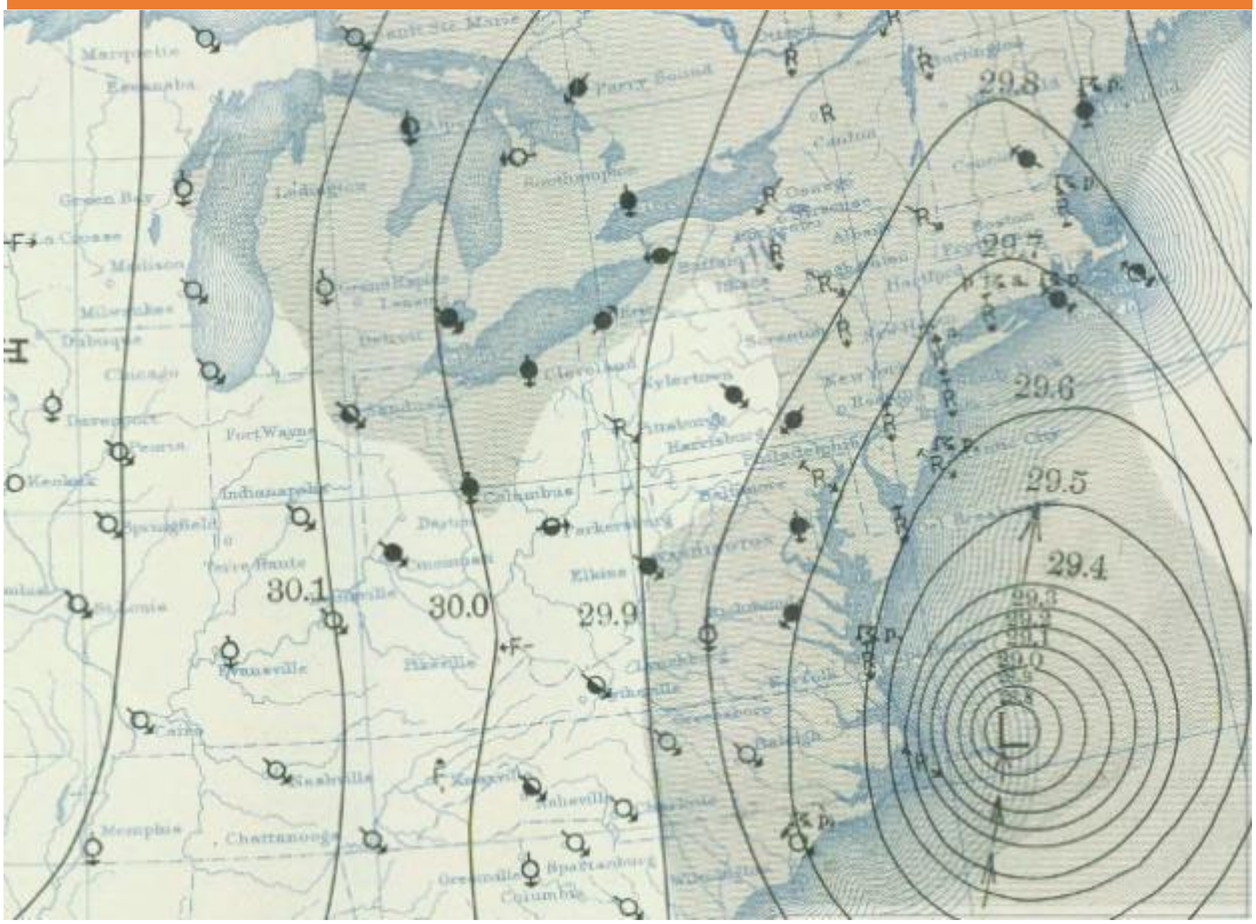
Bike lanes

Figure 2-75 Elm City Cycle Map



Section 3.0 Coastal Flood Hazards

New Haven Long Wharf Flood Protection Study



Historical Surface Weather Map of the Hurricane of 1938 (the 1938 New England Hurricane) on September 9, 1938

3.0 COASTAL FLOOD HAZARDS

GZA evaluated the coastal flood hazards within the project study area, including tidal and extreme flood events, under current and predicted sea level rise conditions, over the next 100 years. Extreme flood events include storm surge and waves. The Long Wharf District is vulnerable to coastal flooding due to its proximity to New Haven Harbor. New Haven Harbor is a natural estuary and hydraulically connected to Long Island Sound. The mouth of New Haven Harbor, located approximately 4 miles to the south of Long Wharf, is protected by a series of three breakwaters. The breakwaters serve to reduce Sound storm waves from entering New Haven Harbor but do not affect storm surge. However, a significant wave fetch (about 4 miles) exists between the breakwaters and Long Wharf, which can result in large storm waves along the Long Wharf shoreline.

To evaluate the coastal flood hazards affecting Long Wharf, GZA performed:

1. a metocean analysis of observed wind, wave and water level data;
2. review of published flood hazard data including the Federal Emergency Management Agency (FEMA) effective Flood Insurance Rate Map (FIRM) and the FEMA Flood Insurance Study (FIS), the National Oceanic and Atmospheric Agency (NOAA), tide gage data and the U.S. Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study (NACCS);
3. review of USACE and National Oceanic and Atmospheric Agency (NOAA) sea level rise projections; and
4. numerical hydrodynamic modeling of tides, storm surge and waves using the Advanced Circulation Model (ADCIRC) and the Simulating WAves Nearshore (SWAN) models.

The results of GZA's coastal flood hazard evaluation were used to evaluate the flood vulnerability of the study area structures and natural features.

Flood risks, in addition to tides and coastal storm surge exist in the Long Wharf area. In particular, flooding due to local intense precipitation (LIP) and stormwater run-off are a source of Area 3 flooding. LIP events often occur during storms that also include storm surge and waves. Flooding due to precipitation, including the capacity of the existing stormwater infrastructure to provide drainage, was not evaluated as part of this study; stormwater management within the Long Wharf area is being evaluated by others.

Coastal floods are also often accompanied by high winds and snow.

The following summarizes the results of GZA's coastal flood hazard evaluation.

3.1 Tides

Tides are the daily rise and fall of the Earth's waters by long-period waves that move through the oceans in response to astronomical gravitational forces predominantly exerted by the moon and sun. The tides in Long Island Sound, including New Haven Harbor, are diurnal, which means that during each lunar day (24 hours and 50 minutes) there are two high tides and two low tides. The high and low tide elevations vary during a daily tide cycle and over a lunar cycle, but are generally characterized by statistical mean values.

Tidal datums, representing statistical means, are used to identify tidal characteristics and include:

- Mean High Water (MHW), which represents the average of the two high tides over the "National Tidal Datum Epoch" (the 19 years between 1983 and 2001);
- Mean Low Water (MLW), which is the average of the two low tides over the same period;
- Mean Higher High Water (MHHW), which is the average of the higher of the two high tides during each tidal day observed over the same period;
- Mean Lower Low Water (MLLW), which is the average of the lower of the two low tides over the same time period;
- Mean Sea Level, which is the arithmetic mean of all hourly heights over the National Tidal Datum Epoch;
- The mean range of tide (MN), which is the difference between the Mean High Water and the Mean Low Water; and
- Highest Astronomical Tide (HAT), which is the highest level predicted to occur under average meteorological conditions and any combination of astronomical conditions.

Tidal datums are developed based on observed water level data during the current National Tidal Datum Epoch at NOAA tide stations (the 19-year period between 1983 and 2001). NOAA tide stations are present at New Haven and Bridgeport, Connecticut. The NOAA Bridgeport tide station has the longest period of record and, therefore, the Bridgeport station water level data is primarily used for this statistical analysis of coastal storm surge. It is noted that there is a minor difference between the New Haven and Bridgeport tidal datums. Mean sea level is approximately the same at New Haven and Bridgeport. The elevation of MHW and MHHW is about 0.3 foot (about 4 inches) lower at New Haven relative to Bridgeport and the MLW and MLLW are about 0.25 foot (about 3 inches) higher at New Haven relative to Bridgeport.

The current tide elevations, relative to the NAVD88 datum, at New Haven are presented in Table 3-3.

3.2 Sea Level Rise

Sea Level Rise (SLR) is the rise of global ocean waters. Relative sea level change (RSLC) is the change of sea level relative to the adjacent land mass and is unique to a given geographic location. RSLC is caused by several factors, including: 1) ground settlement due to post-glacial isostatic adjustment; 2) warming of ocean waters, resulting in volume expansion; 3) increase in ocean volumes due to melting Arctic and land ice; 4) ocean density gradients due to the infusion of lower density fresh water; and 5) changes to global ocean circulation patterns (e.g., the Gulf Stream and Labrador Current).

The observed RSLC at the NOAA Bridgeport station, over the last approximately 80 years, indicates a mean sea level rise trend of 2.81 millimeters (mm) per year (with a 95% confidence interval of +/- 0.45 mm per year) (2.81 mm/yr = 0.11 inch/year). Over the most recent 25 years, the measured water level data indicates that the mean rate of sea level rise is increasing.

3.3 Sea Level Rise Uncertainty

While the sea level of Long Island Sound is clearly rising, predicting the future rate of sea level rise is complex, highly uncertain, and dependent on many unknown factors (such as future emissions of greenhouse gases, rate and amount of ice melt, etc.). For planning purposes, it is prudent to consider a range of possible sea level rise outcomes. NOAA and the USACE have developed ranges of RSLC for use on federal projects in the United States. The USACE projections range from Low to Intermediate to High. The USACE Low projections are generally consistent with the observed historical rates of RSLC. Observed RSLC over recent years indicate a trend of increased rates. As indicated in Figure 3-2, recent projections adopted by NOAA indicate the potential for even higher RSLC.

The predicted sea level rise near New Haven between the years 2016 and 2116 (based on projections at NOAA tide station 8467150 at Bridgeport, CT) are summarized in Table 3-1 and Figure 3-1 below (in feet relative to the NAVD88 elevation datum). These projections were developed using the USACE Sea Level Change Curve Calculator (version 2017.42) and are based on USACE 2013/NOAA 2012 projections.

Table 3-1: Sea Level Rise Projections at NOAA Gauge 8467150 at Bridgeport, CT (feet, NAVD88)

YEAR	NOAA (LOW)	USACE (LOW)	NOAA (INT-LOW)	USACE (INT)	NOAA (INT-HIGH)	USACE (HIGH)	NOAA (HIGH)
2016	-0.02	-0.02	0.03	0.03	0.15	0.2	0.28
2041	0.19	0.19	0.41	0.41	0.88	1.08	1.42
2066	0.40	0.40	0.89	0.89	1.97	2.43	3.20
2116	0.82	0.82	2.19	2.19	5.22	6.52	8.68

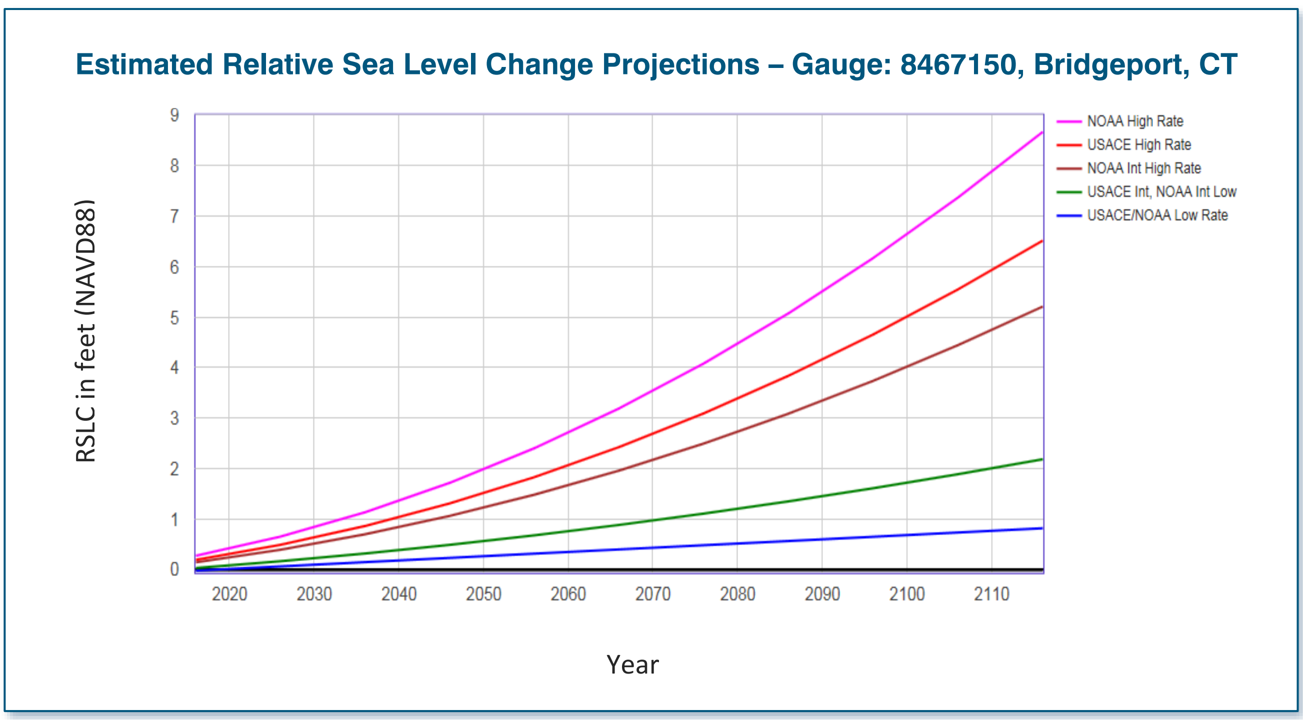


Figure 3-1: Sea Level Rise Projections (using the USACE Relative Sea Level Change Calculator for USACE2013/NOAA 2012 projections)

The NOAA sea level rise projections were revised[1] subsequent to completion of GZA's analysis and storm surge model simulations but prior to completion of the Study report. 2017 NOAA[2] projections are presented in Figure 3-2. In general, the revised projections indicate an increase in predicted sea level rise amount and likelihood. And very recent observations and modeling of accelerated ice loss from Greenland and Antarctica present concern that predictions of RSLC will change again in the future.

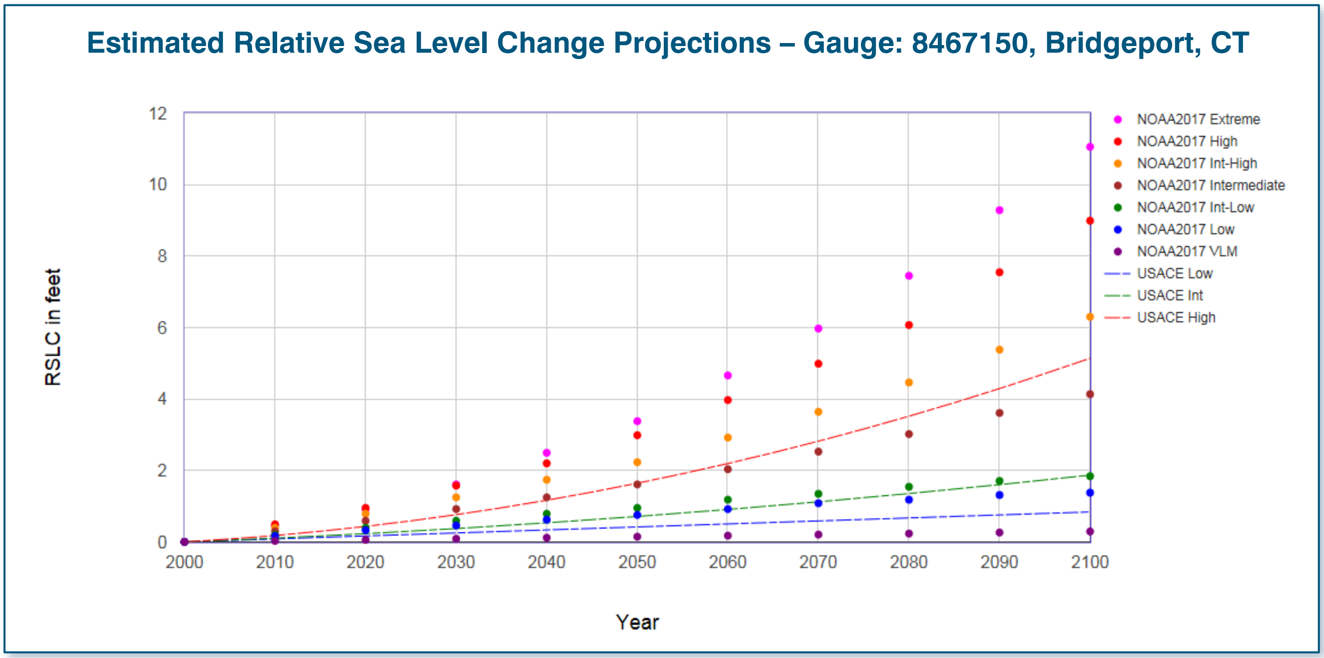


Figure 3-2: Sea Level Rise Projections (using the USACE Relative Sea Level Change Calculator for NOAA et. al 2017 projections)

Table 3-2 presents estimated exceedance probabilities associated with the six NOAA 2017 projections (Figure 3-2) for several greenhouse gas concentration trajectories (Representative Concentration Pathways) adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5). Section 5.0 discusses the selection of sea level rise projections for a risk-based decision evaluation of flood mitigation protection levels.

The 2013 USACE projections, the latest projections at the time of GZA's analyses, were used to model and evaluate flooding for the Study. The exceedance probabilities associated with the USACE projections can be approximated using Table 3-2 as a guide along with the following: USACE 2100 RSLC High (between NOAA 2017 Intermediate-High and Intermediate); USACE 2100 RSLC Intermediate (NOAA 2017 Intermediate-Low); USACE 2100 RSLC Low (between NOAA 2017 Low and VLM). At mid-century (2050) the USACE 2050 High RSLR is consistent with NOAA 2017 Intermediate; the 2050 USACE Intermediate is consistent with the NOAA 2017 Low. As an approximate guide, the 2100 USACE High RSLC projection has an unlikely to possible chance of occurrence (exceedance probabilities of 0.4% to 17%) and the USACE Intermediate RLSC projection has a possible to certain chance of occurrence (exceedance probability of 49% to 100%). The NOAA 2017 Extreme GMSL scenario is a worst case scenario. For the New Haven area, the Extreme RSLC scenario for the year 2100 is about 11 feet. Note that the

[1] "Global and Regional Sea Level Rise Scenarios for the United States"; NOAA Technical Report NOS CO-OPS 083; January, 2017

[2] The Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force, jointly convened by the U.S. Global Change Research Program (USGCRP) and the National Ocean Council (NOC), began its work in August 2015. The Task Force has focused its efforts on three primary tasks: 1) updating scenarios of global mean sea level (GMSL) rise, 2) integrating the global scenarios with regional factors contributing to sea level change for the entire U.S. coastline, and 3) incorporating these regionally appropriate scenarios within coastal risk management tools and capabilities deployed by individual agencies in support of the needs of specific stakeholder groups and user communities.

probabilities presented here are approximate; however, they are appropriate for use in understanding the risk of different sea level rise scenarios. Connecticut RSLC is higher than the global average.

Table 3-2: Probability of Exceeding Global Mean Sea Levels in 2100 for Several Representative Concentration Pathways (RCP) Scenarios (reproduced from "Global and Regional Sea Level Rise Scenarios for the United States"; NOAA Technical Report NOS CO-OPS 083; January 2017

GMSL RISE SCENARIO	RCP 2.6	RCP 4.5	RCP 8.5
LOW (0.3 M)	94%	98%	100%
INTERMEDIATE-LOW (0.5 M)	49%	73%	96%
INTERMEDIATE (1.0 M)	2%	3%	17%
INTERMEDIATE-HIGH (1.5 M)	0.4%	0.5%	1.3%
HIGH (2.0 M)	0.1%	0.1%	0.3%
EXTREME (2.5 M)	0.05%	0.05%	0.1%

Table 3-3: Tidal Elevations at Bridgeport with Sea Level Rise (using the USACE Relative Sea Level Change Calculator; feet, NAVD88)

SEA LEVEL RISE SCENARIO	2016	2041 HIGH	2041 INT	2041 LOW	2066 HIGH	2066 INT	2066 LOW	2116 HIGH	2116 INT	2116 LOW
MEAN SEA LEVEL (MSL)	-0.22	0.84	0.16	-0.01	2.01	0.64	0.2	6.1	1.94	0.62
MEAN HIGH WATER (MHW)	3.15	4.21	3.53	3.36	5.38	4.01	3.57	9.47	5.31	3.99
MEAN HIGHER-HIGH WATER (MHHW)	3.48	4.54	3.86	3.69	5.71	4.34	3.9	9.8	5.64	4.32
HIGHEST ASTRONOMICAL TIDE (HAT)	4.98	6.04	5.36	5.19	7.21	5.84	5.4	11.3	7.14	5.82
MEAN LOW WATER (MLW)	-3.60	-2.54	-2.54	-3.39	-1.37	-2.74	-3.18	2.72	-1.44	-2.76
MEAN LOWER-LOW WATER MLLW)	-3.84	-2.78	-3.46	-3.63	-1.61	-2.98	-3.42	2.48	-1.68	-3.0

3.4 Rising Tides

A reasonable estimate of the effects of RSLC on tides can be developed by linear superposition of the predicted RSLC to the current epoch tidal datums. Table 3-3 presents the current and predicted changes to the tidal datums for the New Haven area[3] due to RSLC for the years 2041, 2066 and 2116, in feet NAVD88. Figure 3.3 graphically presents the tidal datums with RSLC.

Figure 3-4 shows the limits of tidal inundation during MHHW in the year 2016 (current condition). Figures 3-5 through 3-7 show the predicted tidal inundation during MHHW due to USACE High RSLC projections for the years 2041, 2066 and 2116. Most RSLC projections do not result in significant tidal flood inundation (except local shoreline effects). The exception to this are the USACE High RSLC projections which begin to inundate the Long Wharf area between the years 2066 and 2116 (Figures 3.6 and 3.7). The USACE High RSLC projections indicate that, by the year 2116, tidal flooding would occur daily over most of Long Wharf Drive, low-lying portions of I-95 and Long Wharf areas located west of I-95, with flood inundation depths and extent similar to that which occurred during Hurricane Sandy.

Although significant tidal flood inundation is not expected in the near future, sea level rise will still affect shoreline features. These effects include: 1) a reduced shoreline land area; 2) increased beach erosion; and 3) submergence of tidal wetlands and salt marsh. It will also affect water levels at stormwater outfalls, impacting stormwater infrastructure performance.

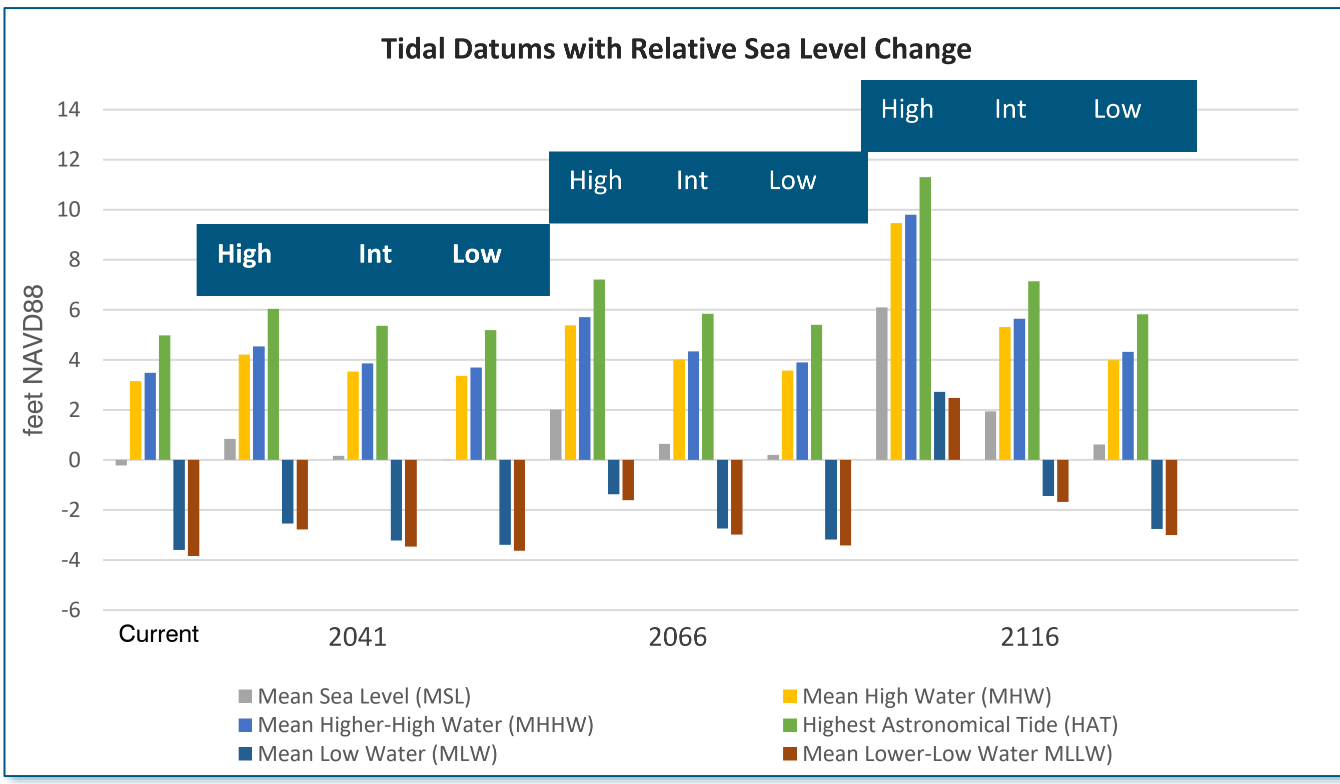


Figure 3-3: Tidal Datums with Relative Sea Level Change in Vicinity of New Haven

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[3] NOAA Bridgeport tide gage. Tidal datum analysis period of 1983 to 2001.

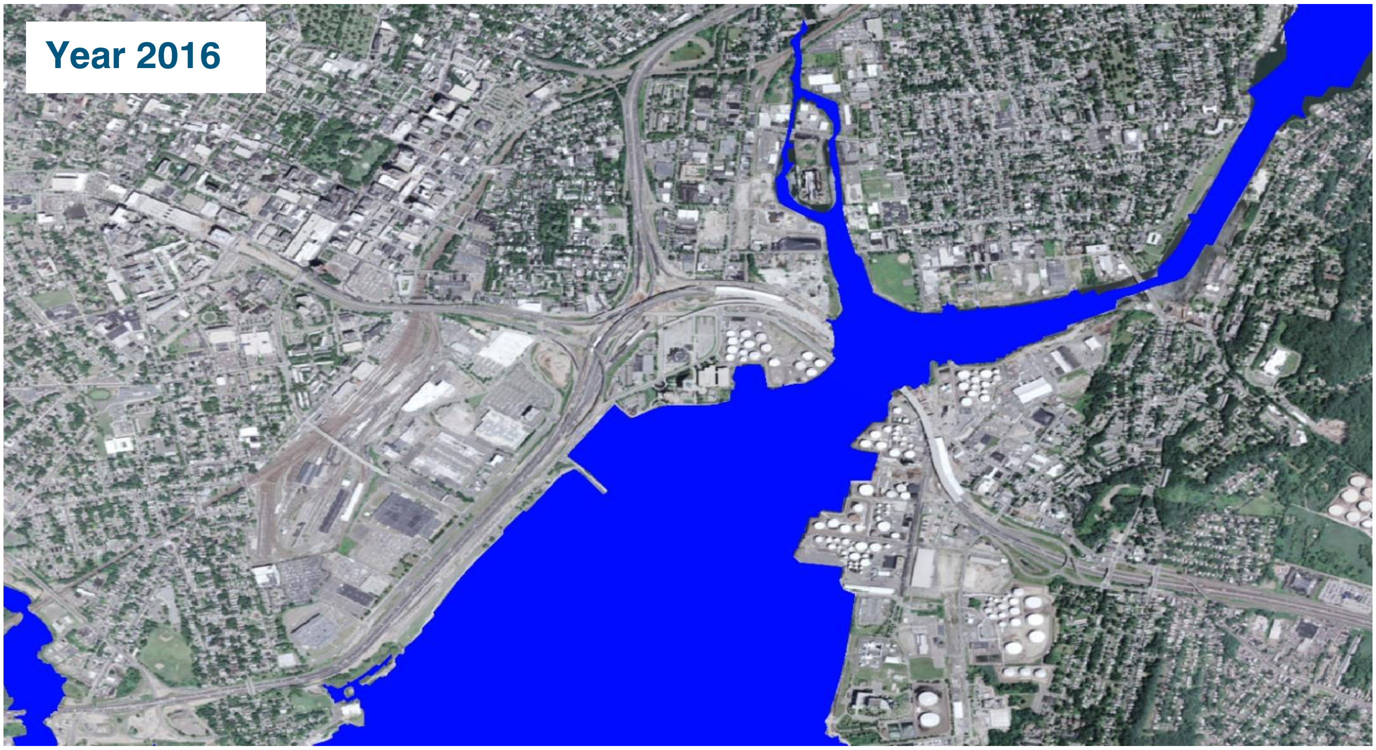


Figure 3-4: 2016 Mean Higher High Water

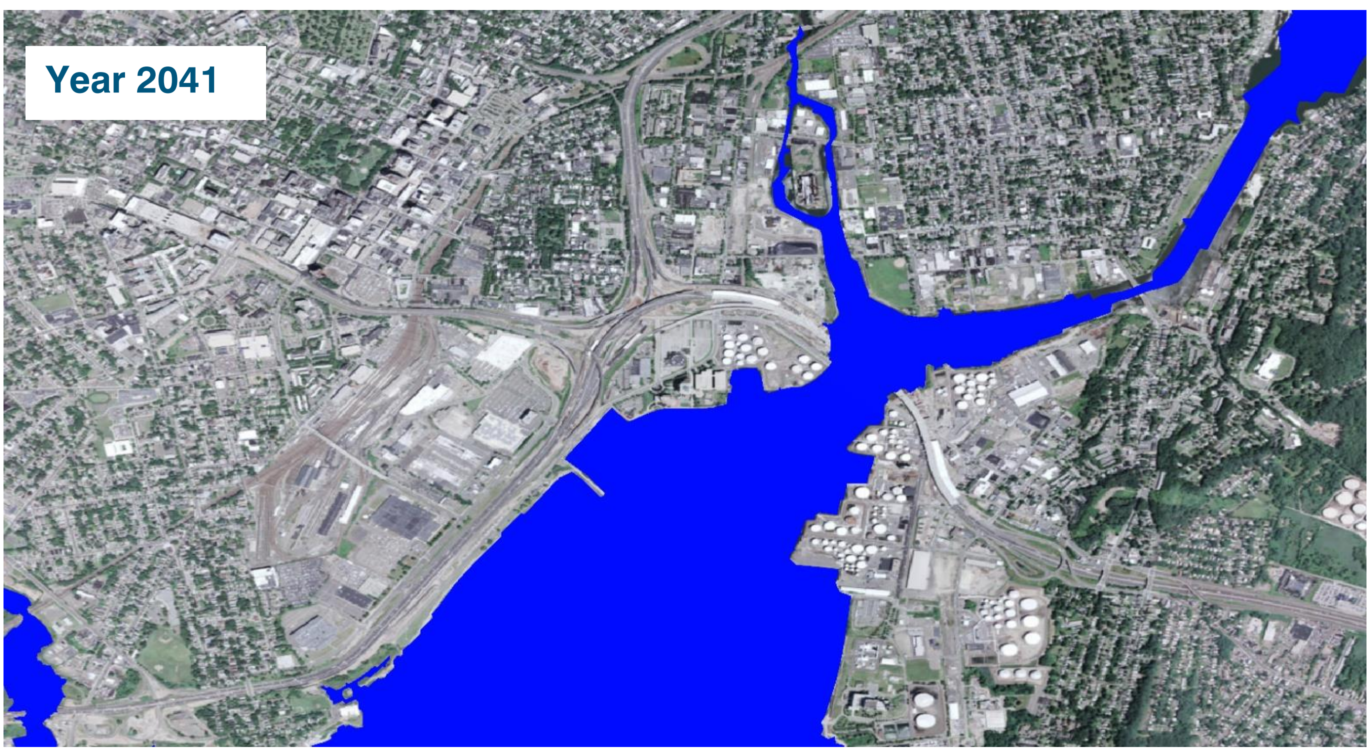


Figure 3-5: 2041 Mean Higher High Water with High SLR

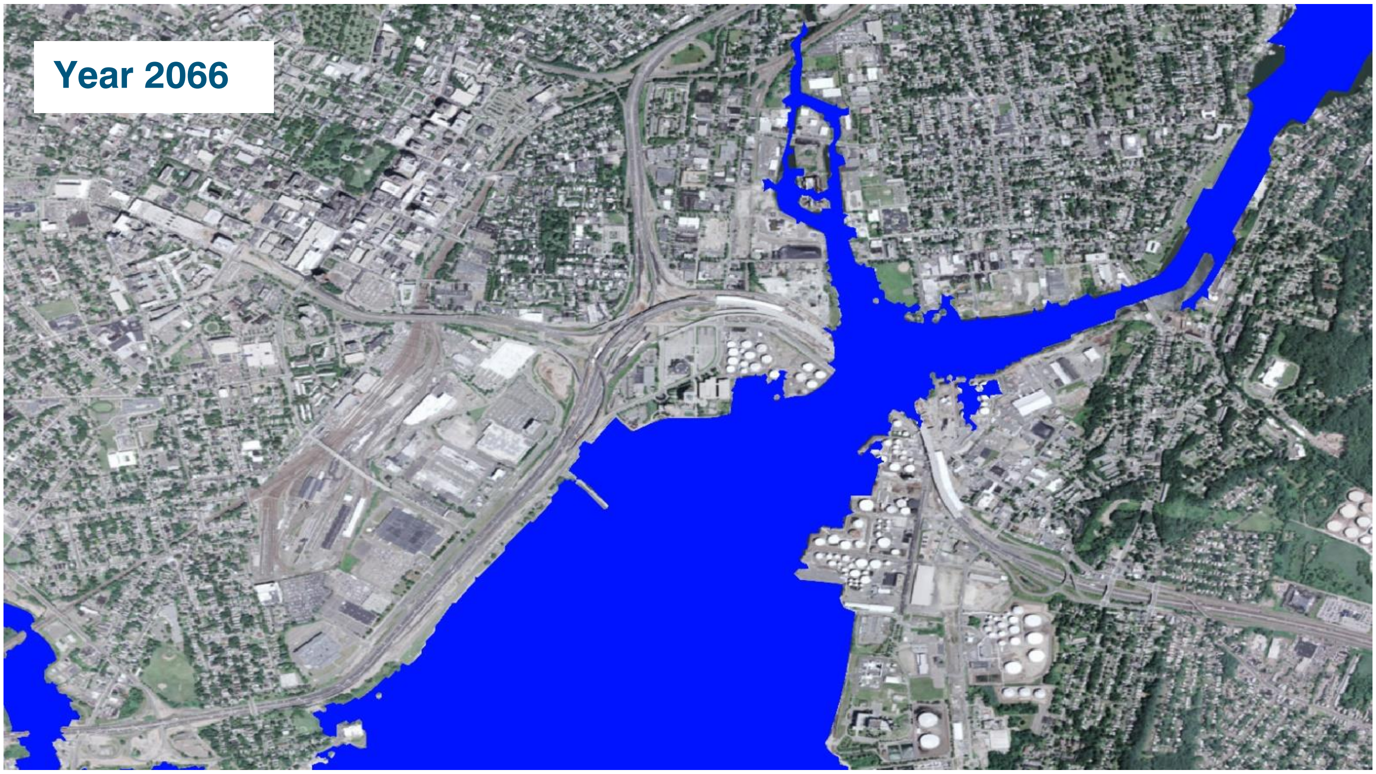


Figure 3-6: 2066 Mean Higher High Water with High SLR

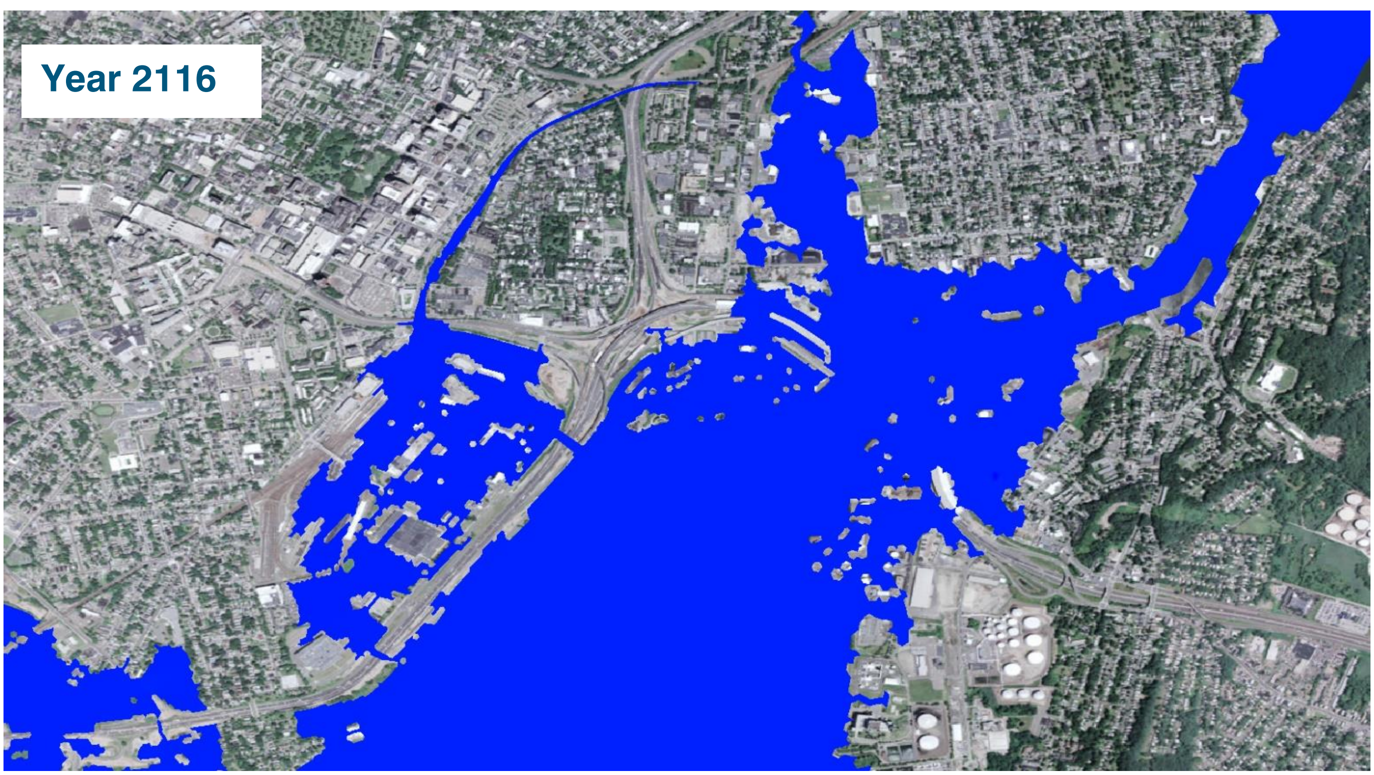


Figure 3-7: 2116 Mean Higher High Water with High SLR

3.5 Extreme Water Levels

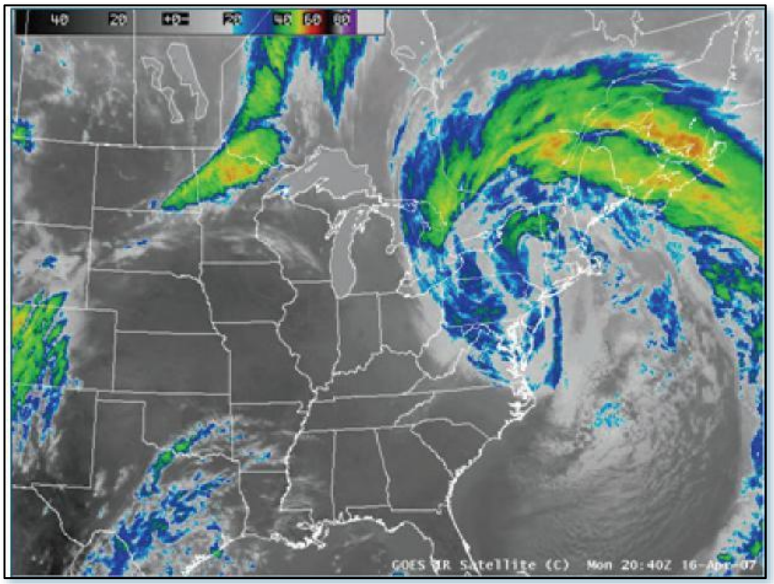


Figure 3-8: NOAA Surface Radar Map of Nor'Easter

Extreme water levels resulting from coastal storm surges at New Haven result from two types of storms: Extra-tropical storms (Nor'Easters) and tropical cyclones (Tropical Storms and Hurricanes).

Nor'Easters are relatively common in New England during the spring, winter and fall. They are less intense than hurricanes but have a large wind field and are long in duration (sometimes lasting several days). These characteristics can result in significant storm surges. This is particularly true within Long Island Sound, where the long axis of the Sound trends northeast-southwest in line with the predominant wind direction during Nor'Easters. Nor'Easters often occur in conjunction with large snowfalls, which makes emergency response and recovery much more difficult.

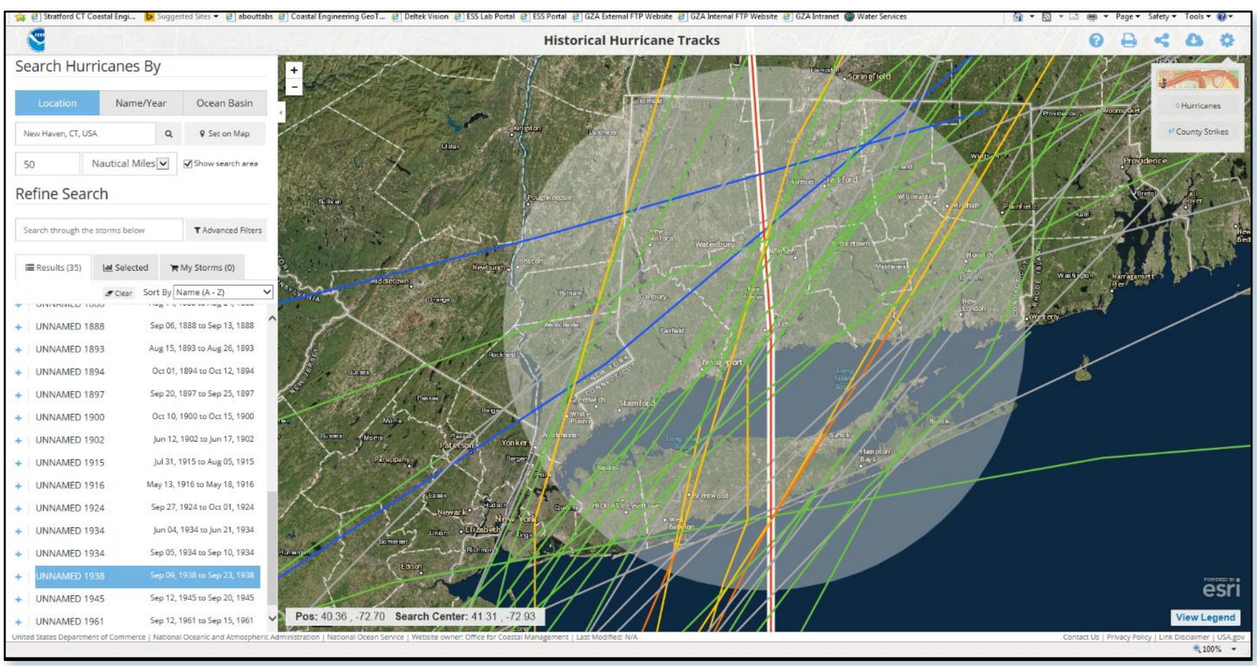


Figure 3-9: NOAA Storm Tracks for tropical cyclones, storms and hurricanes within 50 nautical miles of New Haven since 1842.

Hurricanes occur relatively infrequently in New England. Hurricanes of high intensity with the tracks and landfalls necessary to cause large floods in New Haven are even rarer. However, as discussed below, hurricanes have historically resulted in the largest storm surge flooding affecting the New Haven area. Tropical cyclones, including tropical storms and hurricanes, have also resulted in the most significant rainfalls.

According to the NOAA Office for Coastal Management, 35 tropical cyclones (including hurricanes and tropical storms) have tracked within a 50-nautical mile radius of New Haven since the mid-1800s (see Figure 3-9 for storm tracks). The most intense hurricane of record in the vicinity of New Haven is the Hurricane of 1938 (track highlighted in Figure 3-9). According to NOAA, this hurricane was a Category 3 intensity at landfall along the Connecticut coast. There were also several high intensity hurricanes during the 1800s and early 1900s that made landfall along Long Island, although details about their intensity are limited.

Of the 35 tropical cyclones, 5 hurricanes and tropical storms passed within a 50-nautical mile radius of New Haven during the last 25 years. These storms are listed below (with maximum track intensities indicated):

- Beryl, Tropical Storm, 1994
- Bertha, Category 3 Hurricane, 1996
- Floyd, Category 4 Hurricane, 1999
- Hanna, Category 1 Hurricane, 2008
- Irene, Category 3 Hurricane, 2011

Although these hurricanes reached intensities as high as Category 4 at some point over their storm track, the storm intensities decreased significantly over the colder New England waters.

Hurricane Sandy, although its landfall was over 200 nautical miles south of New Haven, was one of the most significant flood events in Connecticut due to its very large windfield. Sandy's storm surge when combined with tides, caused water levels to reach Elevation 12.3 feet MLLW (Elevation 8.6 feet NAVD88) in the vicinity of Long Wharf.

Table 3-4: NOAA Station Top Ten Water Levels (in feet above MHHW)

STATION	NAME	1	2	3	4	5
8461490	New London[1]	9/21/1938 7.53 feet	8/31/1954 6.53 feet	10/30/2012 4.89	11/25/1950 4.53 feet	9/14/1944 4.03 feet
		6	7	8	9	10
		9/12/1960 3.83 feet	11/7/1953 3.73 feet	10/31/1991 3.42 feet	8/28/2011 3.39 feet	11/12/1968 3.33 feet
		1	2	3	4	5
8467150	Bridgeport[2]	10/30/2012 5.72	8/28/2011 4.72	12/11/1992 4.72	10/31/1991 4.06	10/25/1980 3.67
		6	7	8	9	10
		3/29/1984 3.29	9/27/1985 3.27	10/19/1996 3.21	11/12/1968 3.20	4/16/2007 3.19

Notes:
1. Station data since 1938.
2. Station data since 1964.

Figure 3-10 shows FEMA's Sandy Storm Surge Maximum Extent based on field-verified high-water marks and FEMA modeling.

Table 3-4 summarizes the top ten water levels at the NOAA New London and Bridgeport tide stations relative to MHHW. The highest observed water levels resulted from hurricanes, with the highest documented flood water level observed during the Hurricane of 1938. The Hurricane of 1938 would likely have a stillwater[4] flood elevation at New Haven on the order of 11 feet to 12 feet NAVD88 were it to happen today.

Flood probability is discussed below in Section 3.6. The flood levels resulting from the Hurricane of 1938 in the vicinity of New Haven would be consistent with a probability on the order of 80-year to 500-year return period (1.25% to 0.2% annual chance), today. Further, the type of storm representative of the 1% and 0.2% annual chance (100-year and 500-year return period) floods in the vicinity of New Haven are expected to be similar high intensity hurricanes. The higher probability floods (e.g., 2-year to 80-year return period floods) are expected to be either tropical storms, lower intensity hurricanes or Nor'Easters.

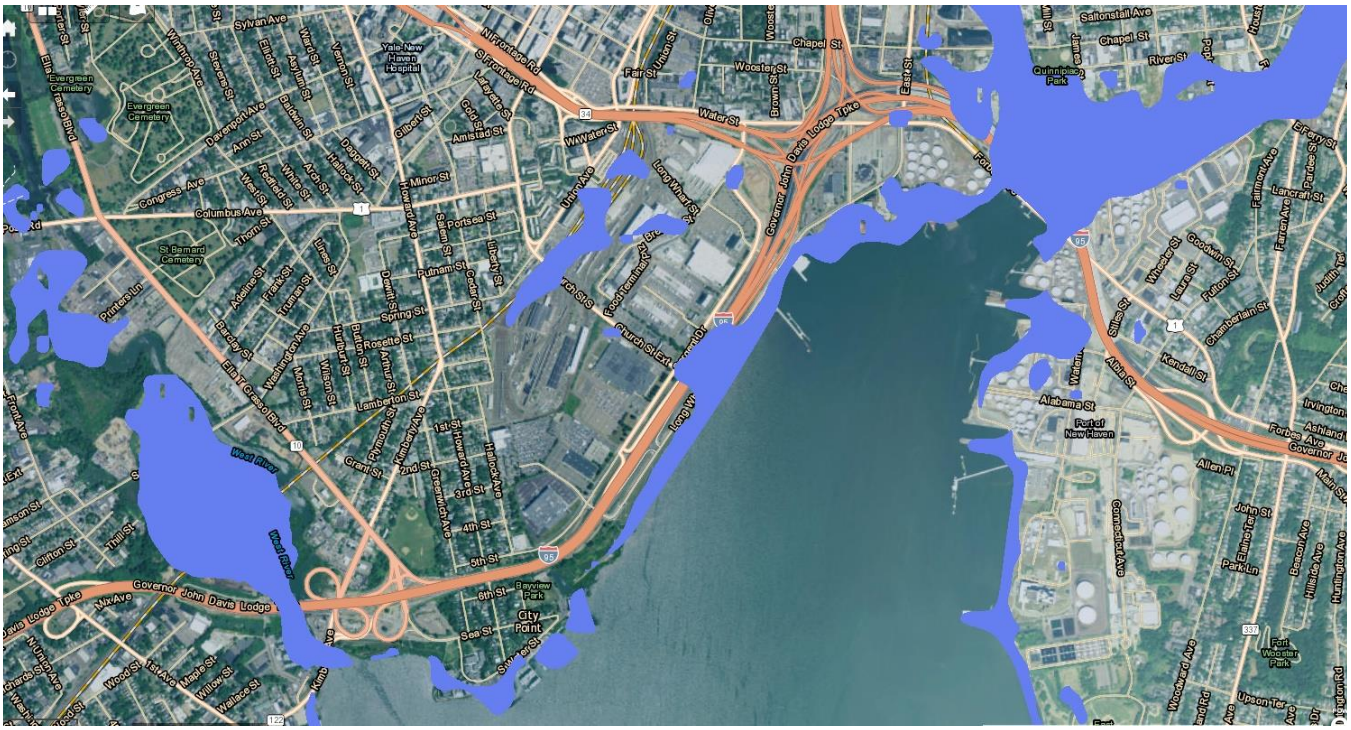


Figure 3-10: FEMA Hurricane Sandy Storm Surge Extent

3.6 Predicting Coastal Flood Probability

Flood hazard mitigation planning requires characterizing flooding in terms of risk, specifically associating different flood levels with a probability of occurrence. Flood probabilities are typically described in terms of the annual exceedance probability. For example, the 1% annual exceedance probability elevation has, in any given year, a 1/100 chance of being met or exceeded. This flood is also known as the 100-year return period flood. There are several publicly-available, industry-accepted sources of flood probability data for the New Haven vicinity. These include:

1. Statistical analysis of the NOAA Bridgeport and New Haven tide station water level data: Statistical analysis of the NOAA Bridgeport tide station water level data provides an indication of the recurrence interval of flooding based on an approximately 80-year period of record. The gage at New Haven has too brief a period of record for extrapolating extreme water levels.

[4] Stillwater refers to the water level, not including wave effects.

2. FEMA Flood Insurance Study and Rate Maps: FEMA has characterized the current flood hazard within New Haven for the purposes of the National Flood Insurance Program (NFIP). FEMA uses the 1% annual exceedance probability (100-year return period) flood event to characterize flood risk, presented on Flood Insurance Rate Maps (FIRMs), for purposes of the National Flood Insurance Program. FEMA also presents the 0.2% annual chance flood inundation limits on these maps. Figure 3-11 presents the effective (i.e., currently applicable) FEMA Flood Insurance Rate Map (FIRM) flood limits and elevations, used to calculate flood insurance rates for Long Wharf. As indicated on this figure, most of the Long Wharf District, with the exception of I-95, is inundated under a 1% annual exceedance probability flood.
3. The USACE North Atlantic Coast Comprehensive Study (NACCS): The USACE performed extensive regional coastal flood hazard analyses after Hurricane Sandy (the North Atlantic Coast Comprehensive Study). These analyses utilized statistical interpretation of storm meteorological parameters, numerical computer modeling of storm surge and waves, and statistical analysis (e.g., Joint Probability Method-Optimum Sampling, Empirical Simulation Technique) to characterize regional flood hazards.

3.7 FEMA Flood Insurance Study

The FEMA FIRM for Long Wharf is Panel 0909C0441J, effective date of July 8, 2013. The effective FEMA flood hazard zones and Base Flood Elevations (BFE) (feet, NAVD88) are shown on Figure 3-11. The FEMA BFE is the 1% annual exceedance probability flood and has the components of stillwater elevation plus wave set-up (where present) plus a portion of wave height. In conditions with waves, the BFE effectively represents the water level associated with the wave crest elevation. Under certain conditions, the BFE may also represent the elevation of wave overtopping or run-up.

FEMA used statistical analysis of historic tide gage data (Regional Frequency Analysis using L-Moments) to develop the coastal stillwater elevation flood-frequency relationship. Water level data from three NOAA tide gages (New London, New Haven and Bridgeport) were linearly interpolated to all coastal transects in New Haven County. FEMA coastal transects were located for coastal hydrologic and hydraulic analyses perpendicular to the shoreline. Two transects (20 and 21) were developed for Long Wharf (transect 20 crosses the middle of the Long Wharf Park and transect 21 crossed the Long Wharf Maritime Center). Topographic data (ground surface elevation and bathymetry) used for the current New Haven County FEMA FIS and FIRMs was developed using 2006 LiDAR and NOAA National Ocean Service (NOS) Hydrographic Data Base (NOSHDB) and Hydrographic Meta Data Base (HSMDB) (NOAA, May 2010; converted from MLLW to NAVD88).

Next Page: Figure 3-11: FEMA Flood Insurance Rate Map Flood Hazard Zones and Base Flood Elevations


Legend
Study Area
Flood Hazard Boundaries
Other Boundaries
Line Type
Limit Lines
SFHA / Flood Zone Boundary
Flood Hazard Zones
Zone Type
1% Annual Chance Flood Hazard
Regulatory Floodway
Special Floodway
Area of Undetermined Flood Hazard
0.2% Annual Chance Flood Hazard
Future Conditions 1% Annual Chance Flood Hazard
Area with Reduced Risk Due to Levee
Zone: AE
BFE: 13'
Zone: AE
BFE: 11'
Zone: AE
BFE: 12'
Zone: AE
BFE: 11'
Zone: VE
BFE: 16'
Zone: VE
BFE: 13'
New Haven Harbor
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Deep water wave heights and periods were developed using analytical methods, based on wind velocity developed from statistical analysis ("Peaks Over Threshold") of measured wind data at the Tweed Airport/New Haven. Wave setup was estimated empirically using the Direct Integration Method (DIM). Nearshore and overland wave heights were generally considered depth-limited, with the wave height equal to 0.78 the water depth and the wave crest 70% of the total wave height above the stillwater level. Overland wave heights diminish due to energy dissipation and can also regenerate in open fetch areas. Overland wave propagation was calculated by FEMA using the WHAFIS program.

Areas of the coastline subject to significant wave effects (e.g., velocity, wave forces) are referred to as coastal high hazard zones. The USACE has established a 3-foot breaking wave as the criterion for identifying the limit of the FEMA VE Zone coastal high hazard zone, as it was determined to be the minimum wave size wave capable of causing major damage to conventional wood frame or brick veneer. For advisory purposes, a Limit of Moderate Wave Action (LiMWA) was established by FEMA to indicate areas subject to moderate wave action, which has also resulted in some structural damage. The LiMWA represents the approximate landward limit of the 1.5-foot breaking wave. These areas are referred to as Coastal AE Zones. The effects of wave hazards within the Coastal AE Zone are similar to, but less severe, than VE Zones.

As Figure 3-11 presents, the FEMA BFE ranges from Elevation 13 in the coastal high hazard VE Zone to Elevations 11 to 12 in the AE Zone. The VE Zone extends along the Long Wharf shoreline. In the northeast corner of the study area (the Maritime Center development area), the FEMA coastal high hazard VE BFE is 16 feet and the AE zone is 13 feet. The range in AE Zone elevations reflects variation in dissipating and regenerating wave heights within the area west of I-95. FEMA-predicted flood elevations for other return period floods are presented in Table 3-5. Values presented represent stillwater levels, except in parenthesis which represent Total Water Level (stillwater plus wave set-up).

3.8 NOAA and GZA Water Level Analysis

NOAA statistically analyzed annual water level data at the NOAA Bridgeport and New London tide gages using the Generalized Extreme Value (GEV) probability distribution. The results are shown in Figure 3-12 (relative to meters above MHHW). The 95% confidence intervals are also shown.

GZA independently performed similar statistical analyses with comparable results (presented in Table 3-5). Values presented represent stillwater levels.

Figure 3-12: NOAA Annual Exceedance Probability Curve for the Bridgeport Station

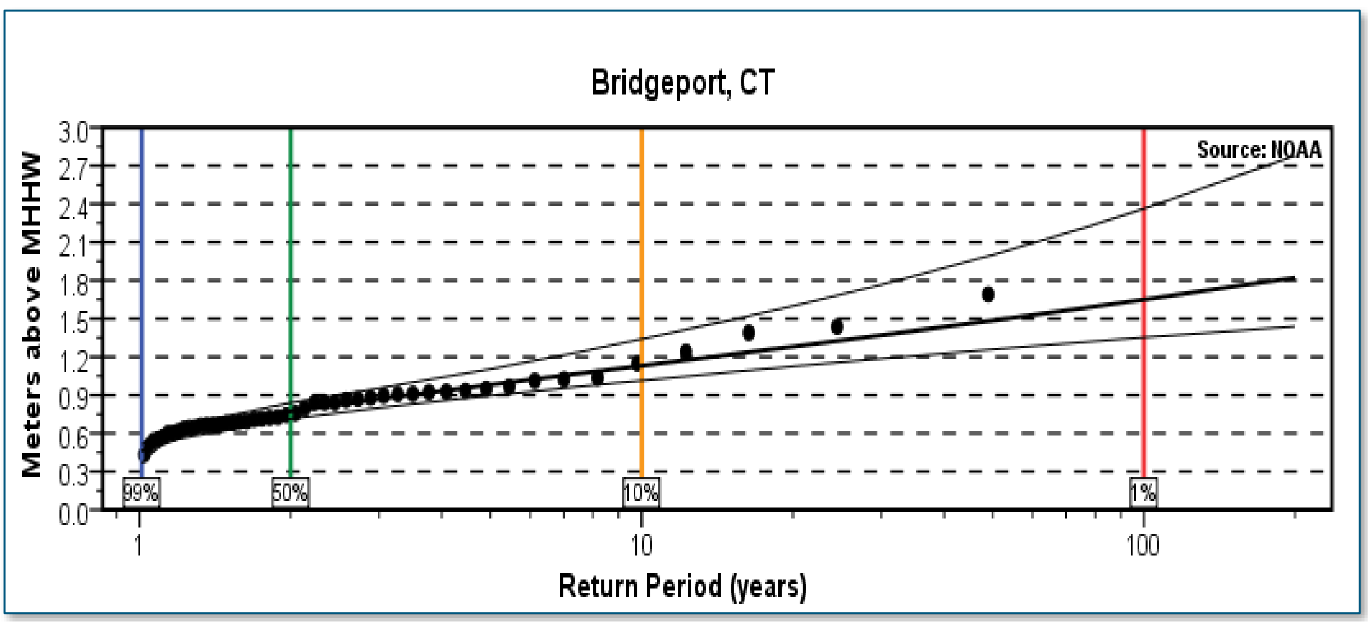


Figure 3-13: USACE NACCS Save Point Locations

3.9 USACE North Atlantic Coast Comprehensive Study

The results of the USACE NACCS are available at specific "save point" locations. Figure 3-13 shows the locations of "save points" within New Haven Harbor, close to Long Wharf. USACE-predicted Total Water Level data, including the stillwater elevation plus wave setup, are available at these locations.

Due to the updated methodology used by the USACE, the flood hazard data developed by the USACE NACCS are expected to be indicative of what future editions of the FEMA FIS and FIRMs will be for New Haven. USACE-predicted flood elevations are presented in Table 3-5.

3.10 Summary of Predicted Flood Elevations and Probabilities

Table 3-5 summarizes the predicted flood probabilities and corresponding flood elevations near the Long Wharf shoreline, from several sources, under current climate conditions as well as reflecting the estimated effect of RSLC on flood levels. Similar to tides, a reasonable estimation of the effects of RSLC on storm surge stillwater elevations can be developed by linear superposition of the predicted RSLR.[5] The FEMA values shown in Table 3-5 are for Transect 20. The USACE values are for "save point" 8134.

Table 3-5: Summary of Predicted Flood Elevations and Probabilities for the Years 2016, 2041, 2066 and 2116; UB and LB indicate lower and upper bounds, respectively. In feet, NAVD88 – see report text for explanation.

RETURN PERIOD	1-YR	2-YR	5-YR	10-YR	20-YR	50-YR	100-YR	200-YR	500-YR	1,000-YR
2016:										
NOAA MEAN	4.8	5.9	6.7	7.2	7.7	8.2	8.8	9.3		
NOAA UB	4.8	6.2	7.0	7.8	8.7	10.0	11.2	12.5		
NOAA LB	4.8	5.7	6.4	6.7	7.1	7.5	7.8	8.1		
FEMA				6.9		8.3	8.9 (10.9)		10.5	
USACE MEAN	5.4	6.3	7.5	8.3	9.2	10.5	11.7	13.1	15.1	16.6
USACE UB	8.4	9.3	10.5	11.3	12.2	13.5	14.7	16.1	18.1	19.6
USACE LB	2.4	3.3	4.5	5.3	6.2	7.5	8.7	10.1	12.1	13.6
2041:										
USACE MEAN (LOW SLR)	5.6	6.5	7.7	8.5	9.4	10.7	11.9	13.3	15.3	16.8
USACE MEAN (INT SLR)	5.8	6.7	7.9	8.7	9.6	10.9	12.1	13.5	15.5	17
USACE MEAN (HIGH SLR)	6.3	7.2	8.4	9.2	10.1	11.4	12.6	14.0	16.0	17.5

[5] Note that the hydrodynamic effects of increased water levels due to RSLR was evaluated by GZA through the use of hydrodynamic computer model flood simulations.

Table 3-5 cont.: Summary of Predicted Flood Elevations and Probabilities for the Years 2016, 2041, 2066 and 2116. In feet, NAVD88.

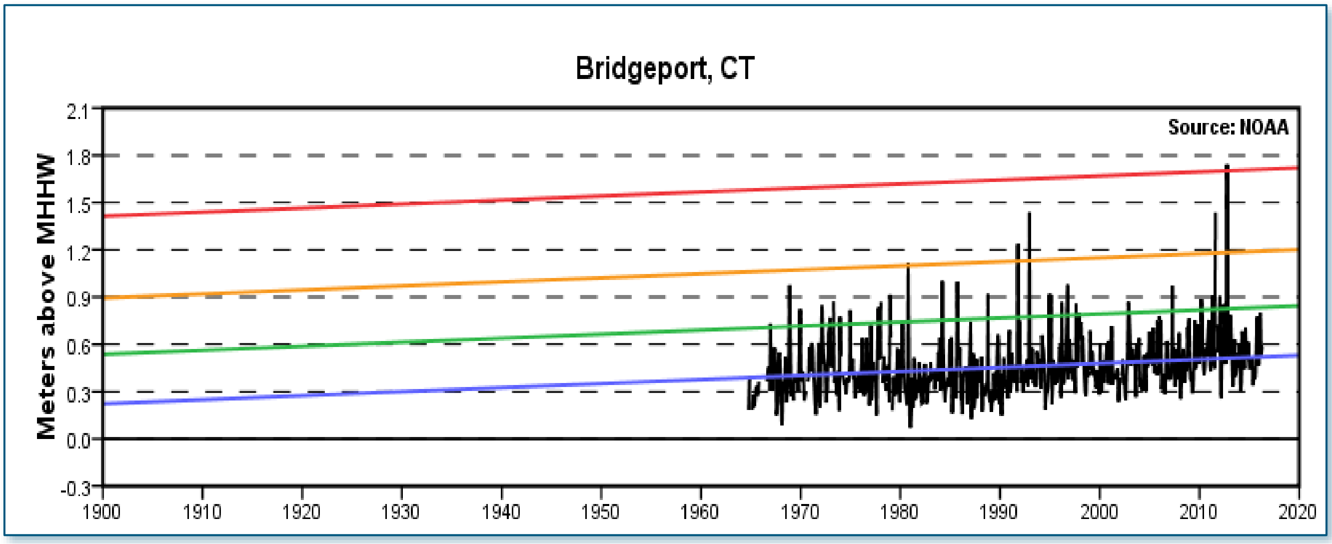
2066:	1-YR	2-YR	5-YR	10-YR	20-YR	50-YR	100-YR	200-YR	500-YR	1,000-YR
USACE MEAN (LOW SLR)	5.8	6.7	7.9	8.7	9.6	10.9	12.1	13.5	15.5	17
USACE MEAN (INT SLR)	6.3	7.2	8.4	9.2	10.1	11.4	12.6	14	16	17.5
USACE MEAN (HIGH SLR)	7.6	8.5	9.7	10.5	11.4	12.7	13.9	15.3	17.3	18.8
2116:										
USACE MEAN (LOW SLR)	6.2	7.1	8.3	9.1	10	11.3	12.5	13.9	15.9	17.4
USACE MEAN (INT SLR)	7.6	8.5	9.7	10.5	11.4	12.7	13.9	15.3	17.3	18.8
USACE MEAN (HIGH SLR)	11.7	12.6	13.8	14.6	15.5	16.8	18.0	19.4	21.4	22.9

Note that the USACE values and the FEMA 100-year return period (1% annual chance) value in parenthesis represents the Total Water Level (stillwater plus wave setup). The FEMA stillwater levels at transect 21 (Regional Maritime Center) are similar; however, the 100-year return period (1% annual chance) Total Water Levels are higher (Elevation 12.5 feet NAVD88), due to the different shoreline characteristics there. Also note that FEMA predicts a wave set-up for the 100-year return period flood of about 2 feet using the empirical DIM. GZA's numerical modeling indicates wave set-up on the order of 0.25 to 0.5 foot, which is expected (based on the methodologies used to be consistent with USACE NACCS.

3.11 Effect of Sea Level Rise of Flood Elevations

NOAA statistically analyzed monthly water level data to reflect the effect of past RSLC of flood elevations associated with different annual exceedance probability levels (see Figure 3-14). The monthly extreme probability levels include a MSL trend of 2.56 mm/year RSLR with a 95% confidence interval of +/-0.58 mm/yr based on the years 1964 to 2006 (0.84 foot per 100 years) – approximately consistent with the USACE Low projection. Table 3-5 shows the estimated effect of future RSLC on the USACE NACCS-predicted annual exceedance flood elevations for different projections of RSLC.

Figure 3-14: NOAA Water Levels with Exceedance Probability Curves for the Bridgeport Station
See Figure 3-15 for legend



3.12 Seasonality of Coastal Flood Hazard

NOAA statistically analyzed water level data on a monthly basis showing the seasonal variability of coastal flood risk. The results are presented in Figure 3-15 for the NOAA Bridgeport tide gage (relative to meters above MHHW).

As shown on Figure 3-15, the greatest flood risk is during the late Summer, Fall and Winter which includes tropical storms, hurricanes and Nor'Easters. The probability of extreme flooding during late Spring and Summer is low.

3.13 Uncertainty and Flood Probability

There is no "absolutely correct" prediction of flood probability; rather, there are a range of probabilities (and corresponding flood elevations) that reflect different prediction methods, error, and uncertainty. For example, statistical extrapolation of the NOAA Bridgeport tide gage data has significant uncertainty for predicting floods beyond the 20 to 50-year return period floods due to the limited period of record. The FEMA stillwater flood projections for New Haven, which were also developed using statistical extrapolation of tide gage data, have similar uncertainty. The USACE NACCS utilized the "state-of-the-practice" methodology; however, there is still significant uncertainty relative to meteorological parameter characterization, methodology and model error. Figure 3-16 presents the statistical mean, and upper and lower bounds (95% confidence intervals) of the USACE NACCS flood-frequency relationship.

Figure 3-15: NOAA Seasonal Variation of Exceedance Probability Curve for the Bridgeport Station

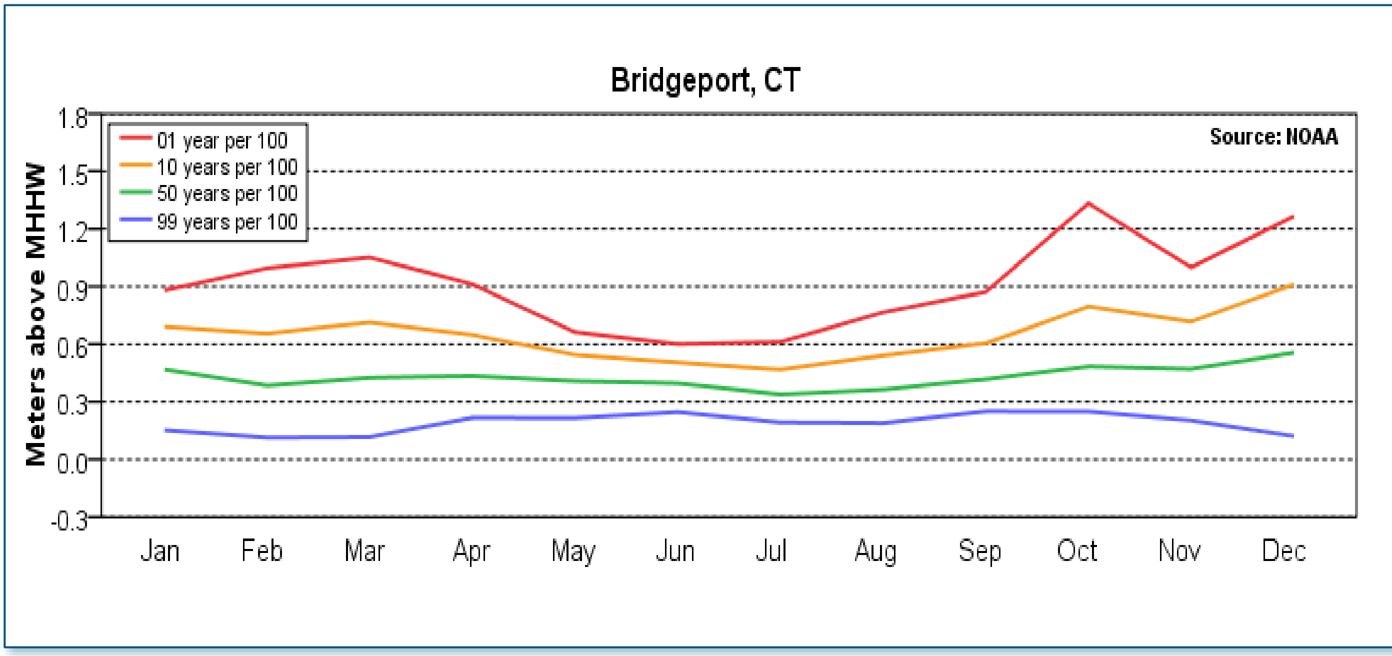
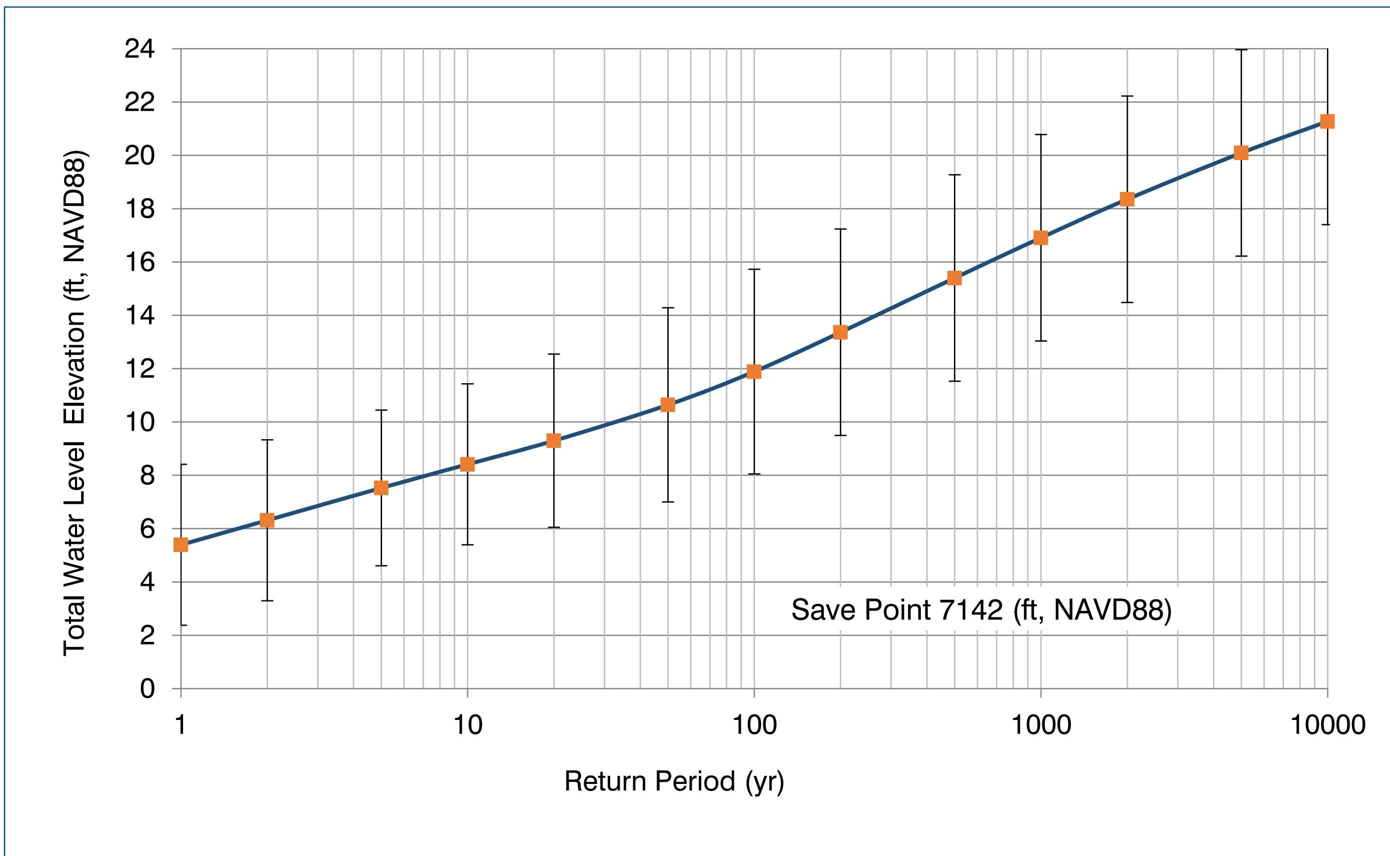


Figure 3-16: Flood Frequency Curve Base of USACE North Atlantic Coast Comprehensive Study near Long Wharf Shoreline for the year 2016. Mean, upper and lower bounds shown.



3.14 GZA Numerical Flood Model Simulations

GZA performed flood simulations using numerical hydrodynamic models of tides and storm surge as well as wave models. The coastal floods corresponding to tidal flow, the 100-year return period flood (1% annual exceedance probability) and the 500-year return period flood (0.2% annual exceedance probability) were modeled. The model simulations were performed using the two-dimensional, hydrodynamic ADvanced CIRCulation model (ADCIRC). Waves were modeled using the Simulating WAves Nearshore (SWAN) model.

The purpose of GZA's model simulations was to evaluate flooding hydrodynamically and temporally, reflecting the current topographic and shoreline setting and to provide input for evaluating flood mitigation alternatives.

3.14.1 Model Storm Surge Simulations

The ADCIRC storm surge flood simulation methodology utilized a robust, but simplified approach and included: 1) creation of a local area, high resolution model mesh; 2) development of synthetic hydrographs representative of storm types associated with the 100-year and 500-year return period floods (1% and 0.2% annual exceedance probability); 3) utilization of the USACE NACCS-predicted peak stillwater elevations at the model boundary to develop the peak hydrograph water level; and 4) stressing the model with the synthetic hydrograph and model domain wind field. This approach provides the benefits of numerical hydrodynamic models, approximating scenario-based simulations, but also ties the overall flood hazard definition (model boundary water levels) to those developed by the USACE NACCS. GZA model validation was performed for tidal conditions. Additional model checks were performed by comparison of GZA model output to representative NACCS output for save points located within the model domain.

A high resolution ADCIRC mesh was developed to represent the detailed topographic features in Long Wharf. The mesh covers Long Wharf and New Haven Harbor, and extends approximately 5 miles off the coast (location of the open boundary) (Figure 3-17). The mesh consists of 176,108 finite elements, and the grid resolution at the Long Wharf District shoreline is approximately 10 to 20 meters (Figure 3-18).

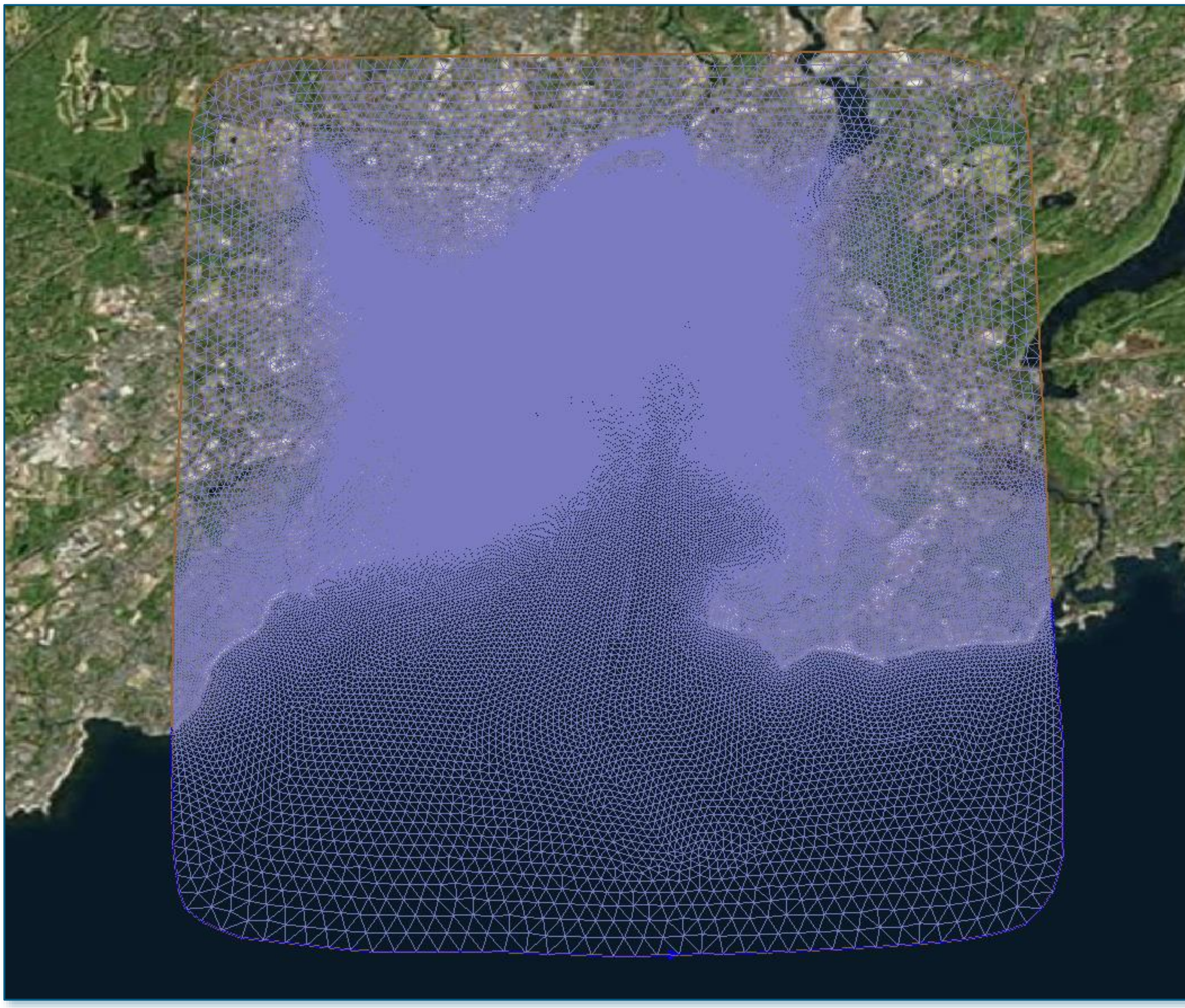
ADCIRC is a two-dimensional, depth integrated, barotropic, time-dependent, long wave hydrodynamic circulation model, and can be applied to domains in deep oceans, the continental shelf, near-shore, and small-scale estuarine systems.

USACE Low, Intermediate and High scenarios were simulated for the years 25, 50 and 100 years from 2016. RSLC was added to antecedent water levels and the synthetic hydrograph. The simulations were performed for tidal flow, the 100-year return period flood (1% annual exceedance probability) and the 500-year return period flood (0.2% annual exceedance probability). Table 3-6 presents the flood modeling scenarios analyzed for the Study. The specific simulations identified in Table 3.6 were performed to cover the full range of RSLC projections based on peak flood elevations.

Table 3-6: Flood Modeling Scenarios

Year	SLR Scenario	Modeling Scenario
2016	No SLR	Tides
		100-year return period (2 hydrographs)
		500-year return period
2041	High SLR	Tides
		100-year return period
		500-year return period
	Intermediate SLR	-
		-
		-
	Low SLR	-
		-
2066	High SLR	Tides
		-
		-
	Intermediate SLR	-
		-
		-
	Low SLR	-
		100-year return period
		500-year return period
2116	High SLR	Tides
		100-year return period
		500-year return period
	Intermediate SLR	-
		100-year return period
		500-year return period
	Low SLR	Tides
		100-year return period
		-

3.14.2 Model Storm Surge Simulation Hydrographs



The depth and extent of flooding west of I-95 is partially dependent upon the shape and duration of the synthetic (and actual) water level hydrograph since the I-95 underpasses constrict flow into Area 3. A sensitivity analysis was performed for the 2016 100-year return period flood (1% annual exceedance probability) simulation using hydrographs representative of: 1) an intense hurricane with a narrow, peaked hydrograph; and 2) a hydrograph representative of a large Nor'Easter (also similar to observed Sandy hydrograph). The hydrographs had the same peak flood elevation but different shapes. The latter results in a greater amount of flooding west of I-95, since the duration of peak flooding (several tide cycles) and the total volume of flood water are greater. The latter is also expected to be representative of less intense storms associated with probabilities that are greater than the 100-year return period (1% annual exceedance probability). The former, which is expected to be more indicative of the type of storms associated with 100-year and 500-year return period floods at New Haven, has lower flood elevations (+/- 1 foot) west of I-95 since the duration of peak flooding is relatively short (4 to 6 hours). The flood simulations for the 100-year and 500-year return period (1% and 0.2% annual exceedance probability) floods, presented in this Study, assume a hurricane hydrograph, conservatively sequenced to align with high tide.

However, the observed sensitivity to hydrograph shape indicates that future simulations of higher probability events, which could include Nor'Easters, should conservatively utilize the appropriate hydrograph.

Figure 3-18: High Resolution Mesh Used for Flood Model Simulations at Long Wharf

3.14.3 Wind Intensity Analysis

Hourly, 1 and/or 2-minute average wind data at the Tweed New Haven Airport was downloaded from the National Climatic Data Center (NCDC). The record covers 1948 to 1969, 1973 to 1999, 2004 to 2016, a total of 61 years, from two separate datasets provided by NCDC. Extreme value statistical analysis was performed by GZA.
The predicted wind-frequency curve (Figure 3-19) was based on the best fit using a Generalized Extreme Value (GEV) distribution. Directional wind speeds were not evaluated and the wind was conservatively modeled from a southerly direction to maximize fetch and wind set-up. The modeled wind speeds are summarized in Table 3-7.

The recommended design 1 and 2-minute sustained and 3-second (Gust) wind speeds for various annual recurrence intervals are listed in the Tables 3-7 and 3-8. In comparison, the Hurricane of 1938 had observed sustained wind speeds at landfall between Bridgeport and New Haven of about 115 mph.

Table 3-7: Summary of Sustained Wind Speed at New Haven Based on Return Period

RETURN PERIOD (YEAR)	WIND SPEED AT TWEED NEW HAVEN AIRPORT	
	(mph)	(m/s)
10	56	25.0
25	68	30.4
50	78	34.9
100	88	39.3
500	119	53.2

Table 3-8: 3-Second Wind Gust Speeds at New Haven (based on ASCE 7-10)

RETURN PERIOD (YEAR)	ASCE 7-10 3-SECOND GUSTS	
	(mph)	(m/s)
10	77	34.4
25	87	38.9
50	94	42.0
100	101	45.2

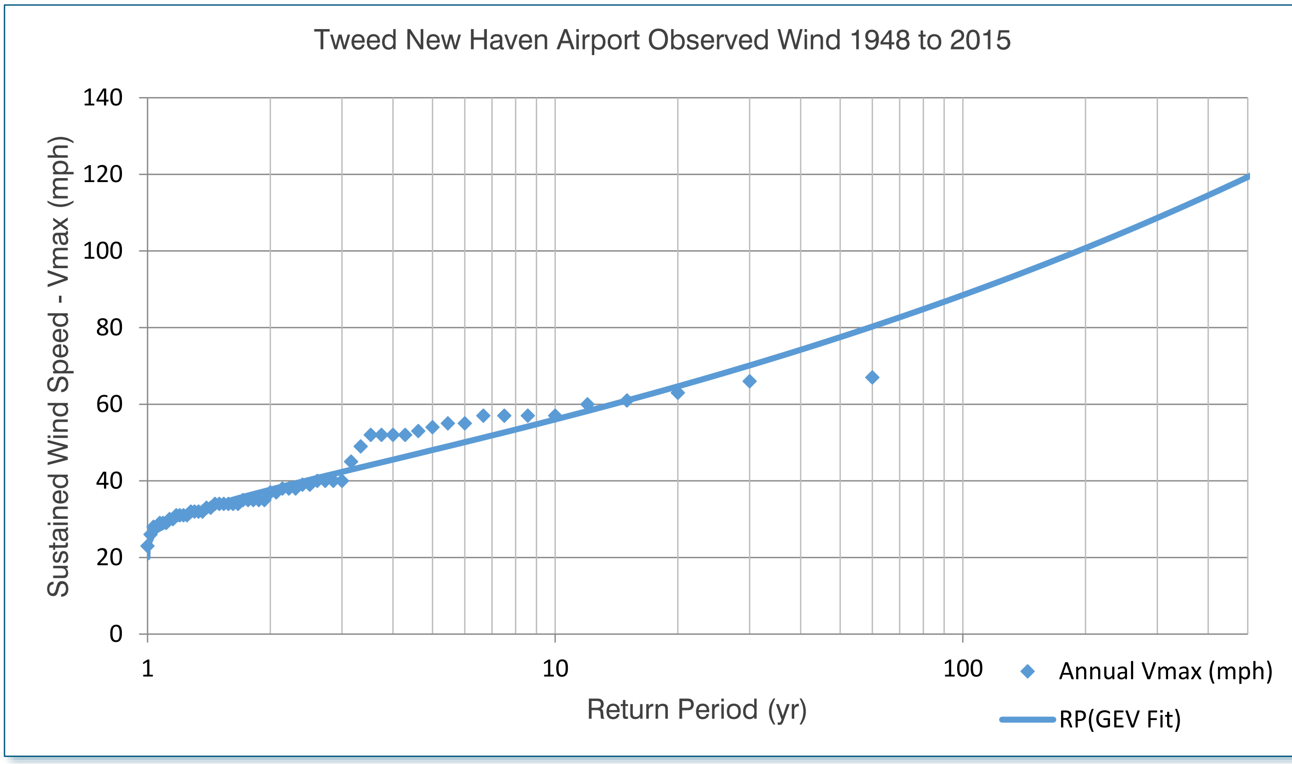


Figure 3-19: Statistical Analysis of Wind Data at Tweed New Haven Airport

3.14.4 Model Storm Surge Simulation Results

The model simulation results are presented on the following figures. It is noted that the water elevations presented on these figures are higher than those established by FEMA. The reason is that the USACE NACCS-predicted water elevations (used for the model simulations) are higher than those predicted by FEMA (see Table 3.5).

- Figures 3-20 and 3-21 present the simulation results for the 2016 100-year return period and 500-year return period (1% and 0.2% annual exceedance probabilities) peak flood inundation and elevations, respectively.
- Figures 3-22 and 3-23 present the simulation results for the 2116 100-year return period and 500-year return period (1% and 0.2% annual exceedance probabilities) peak flood inundation and elevation, respectively. These figures present conditions assuming the USACE High RSLC projections.
- Figures 3-24 through 3-28 present hourly time steps around the peak 2016 500-year return flood to demonstrate temporally how flood inundation propagates inland:
  - Hour 20:00. As the storm surge water levels rise to levels greater than the shoreline elevations, they begin to propagate across Long Wharf Drive and beneath the Canal Dock Road 1-95 underpass (Figure 3-27). The shoreline is inundated including the land area around The Sound School. The Canal Dock Road grade elevation, across from the underpass is a low point (about Elevation 7 feet NAVD88).
  - Hour 21:00. The storm surge elevation continues to rise, to about water Elevation 10 to 11 feet NAVD88 to the east to about Elevation 8 feet NAVD88 inland of I-95. The inland areas to the west-northwest of

the Canal Dock Road I-95 underpass begin to flood, including the area around the Pirelli Building and IKEA parking. Most of Long Wharf Drive is flooded. Flood levels have risen higher than much of the perimeter shoreline structures along the Long Wharf Maritime Center. The southern I-95 on-off ramps to Long Wharf Drive are flooded. The Long Wharf Drive I-95 underpass is inundated and areas to the northwest of the underpass are flooded.

- Hour 22:00. The storm surge continues to rise, to about water Elevation 12 to 13 feet NAVD88 to the east to about Elevation 10 feet NAVD88 inland of I-95. Much of the commercial and industrial inland area of Long Wharf is flooded. The railyard is starting to experience significant flooding. Flooding from Area 3 begins to propagate along the rail line underpass beneath Route 34 to the north. The Long Wharf Maritime Center and adjacent building areas are flooded. The central, low-lying portion of I-95 is flooded.

- Hour 23:00. The storm surge continues to rise, to about water Elevation 13 to 14 feet NAVD88 to the east to about Elevation 12 feet NAVD88 inland. The conditions are similar to Hour 22:00, except to a greater degree (greater extent and deeper water). All of the commercial and industrial inland area of Long Wharf is flooded. The railyard is flooded. The project study area located north of Union Avenue is starting to flood. The Long Wharf Maritime Center area is completely flooded. Much of I-95 is flooded, including the low-lying area beneath the Howard Avenue bridge.

- Hour 24:00. Near peak flood elevation. The conditions are similar to Hour 23:00, except to a greater degree (greater extent and deeper water). All of the commercial and industrial inland area of Long Wharf is flooded. The railyard is flooded. The project study area located north of Union Avenue is extensively flooded. The Long Wharf Maritime Center area is completely flooded. Much of I-95 is flooded, including the low-lying area beneath the Howard Avenue bridge.

Following Pages - Figure 3-20 through 3-29: Figure 3-20 presents the predicted 2016 100-year return period water elevation. Figure 3-21 presents the predicted 2016 500-year return period water elevation. Figure 3-22 presents the predicted 2116 100-year return period water elevation. Figure 3-23 presents the predicted 2116 500-year return period water elevation. Figures 3-24 through 3-28 present time steps during the storm surge to demonstrate flooding dynamically. Figure 3-29 indicates the major entry points to flooding of Long Wharf areas located west of I-95.

Figure 3-20


Legend
Study Area
2016 Max Flood-100yr
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
New Haven Harbor
Elm St
State St
Chapel St
East St
Water St
Forbes Ave
CT 34
Union Ave
Columbus Ave
Church St S
Hamilton St
Canal Dock Rd
Spring St
Long Wharf Dr
Sargent Dr
Howard Ave
5th St
Ella T Grasso Blvd
Kimberly Ave
Sea St
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Figure 3-21

Legend
Study Area
2016 Max Flood-500yr
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
Elm St
State St
Chapel St
East St
Water St
Forbes Ave
CT-34
Union Ave
Brewery St
Hamilton St
Columbus Ave
Church St S
Canal Dock Rd
Spring St
Long Wharf Dr
Sargent Dr
Howard Ave
New Haven Harbor
5th St
Ella T Grasso Blvd
Kimberly Ave
Sea St
5
34
1
91
95
122
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0
375
750
1,500
Feet
N

Figure 3-22

Legend
Study Area
2116 Max Flood-100yr HSLR
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
Chapel St
Water St
Forbes Ave
Union Ave
Columbus Ave
Church St S
Spring St
Howard Ave
Sargent Dr
Long Wharf Dr
Canal Dock Rd
Hamilton St
Brewery St
State St
Elm St
East St
5th St
Sea St
Kimberly Ave
Ella T Grasso Blvd
CT-34
New Haven Harbor
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Figure 3-23


Legend
Study Area
2116 Max Flood-500yr HSLR
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
Elm St
State St
Chapel St
East St
Water St
Forbes Ave
Union Ave
Brewery St
Hamilton St
Columbus Ave
Church St S
Canal Dock Rd
Spring St
Long Wharf Dr
Sargent Dr
Howard Ave
New Haven Harbor
5th St
Ella T Grasso Blvd
Kimberly Ave
Sea St
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Figure 3-24


Legend
Study Area
2016 500yr (20:00)
Water Level (ft)
<5
5 - 10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
>20
New Haven Harbor
Chapel St
Water St
Forbes Ave
Columbus Ave
Church St S
Union Ave
Spring St
Howard Ave
Canal Dock Rd
Long Wharf Dr
Sargent Dr
Hamilton St
East St
Elm St
State St
5th St
Sea St
Ella T Grasso Blvd
Kimberly Ave
Hamden
East Haven
West Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Figure 3-25


Legend
Study Area
2016 500yr (21:00)
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
New Haven Harbor
Chapel St
Water St
Forbes Ave
Columbus Ave
Church St S
Union Ave
Spring St
Howard Ave
Sargent Dr
Long Wharf Dr
Canal Dock Rd
Hamilton St
East St
State St
Elm St
5th St
Sea St
Kimberly Ave
Ella T Grasso Blvd
CT-34
34
5
1
91
95
122
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Figure 3-26


Legend
Study Area
2016 500yr (22:00)
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
New Haven
Harbor
Chapel St
Water St
Forbes Ave
Union Ave
Columbus Ave
Church St S
Spring St
Howard Ave
Canal Dock Rd
Long Wharf Dr
Sargent Dr
Hamilton St
East St
State St
Elm St
CT-34
5th St
Sea St
Ella T Grasso Blvd
Kimberly Ave
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0
375
750
1,500
Feet
N

Figure 3-27


Legend
Study Area
2016 500yr (23:00)
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
New Haven
Harbor
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

Figure 3-28


Legend
Study Area
2016 500yr (24:00)
Water Level (ft)
<10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
>22
New Haven
Harbor
Chapel St
Water St
Forbes Ave
Union Ave
Columbus Ave
Church St S
Spring St
Howard Ave
Canal Dock Rd
Long Wharf Dr
Sargent Dr
Hamilton St
East St
State St
Elm St
5th St
Sea St
Ella T Grasso Blvd
Kimberly Ave
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500
Feet
N

Figure 3-29


Legend
Study Area
Water Intrusion Points
1
2
3
4
5
New Haven Harbor
Chapel St
Water St
Forbes Ave
Davenport Ave
York St
State St
Elm St
East St
Union Ave
Church St S
Columbus Ave
Spring St
Howard Ave
Sargent Dr
Long Wharf Dr
Hamilton St
5th St
Sea St
Kimberly Ave
Ella T Grasso Blvd
CT-34
34
1
5
91
95
122
Hamden
West Haven
East Haven
Milford
Branford
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA,
0 375 750 1,500 Feet
N

3.15 USACE NACCS Model Comparison

GZA's ADCIRC model storm surge simulations are coupled at the model domain boundary (in Long Island Sound) with peak flood elevations developed in the NACCS and with GZA-developed synthetic hydrographs and model domain wind field. GZA model output was compared to USACE NACCS output for representative NACCS "save points" located within GZA's model domain:

Table 3-9: Model Output Comparison to USACE NACCS Save Point Data

NACCS SAVE POINT	LONGITUDE	LATITUDE	100-YEAR FLOOD ELEVATION			500-YEAR FLOOD ELEVATION	
			NACCS	Simulated (Nor'easter)	Simulated (Hurricane)	NACCS	Simulated (Hurricane)
7142	-72.916667	41.293333	11.9	12.0	12.3	15.4	15.6
8134	-72.91656	41.28833	11.7	11.9	12.2	15.1	15.5
271	-72.913031	41.286843	11.6	11.9	12.2	15.1	15.4
8133	-72.91975	41.2801	11.5	11.8	12.0	14.9	15.3

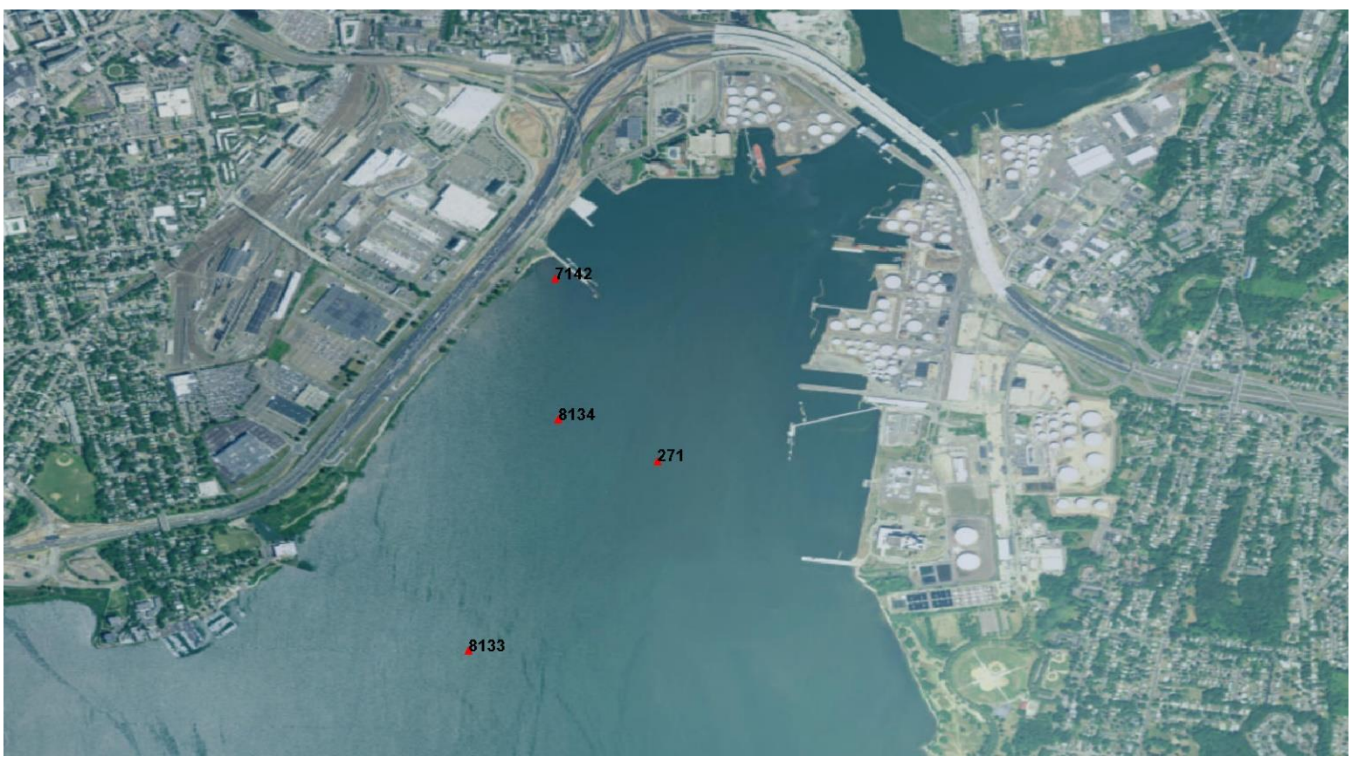


Figure 3-30: Model Output Comparison USACE NACCS Save Point Locations

As shown in Table 3-9, there is good comparison between GZA's model results and USACE NACCS. Both analyses use similar numerical models but different input methodologies. Also, the resolution of GZA's model is greater than that used by NACCS. Note that GZA's results represent stillwater elevations and USACE NACCS represents total water levels (stillwater plus wave setup). GZA modeled wave setup using the SWAN wave model and the results are presented later in this section. In general, GZA results conservatively (but marginally) exceed the NACCS mean values for nearshore flood elevation, on the order of 0.1 foot to 0.5 foot. This difference is considered by GZA to be acceptable for planning purposes and well within the uncertainties associated with predicting flood-frequency relationships and sea level rise.

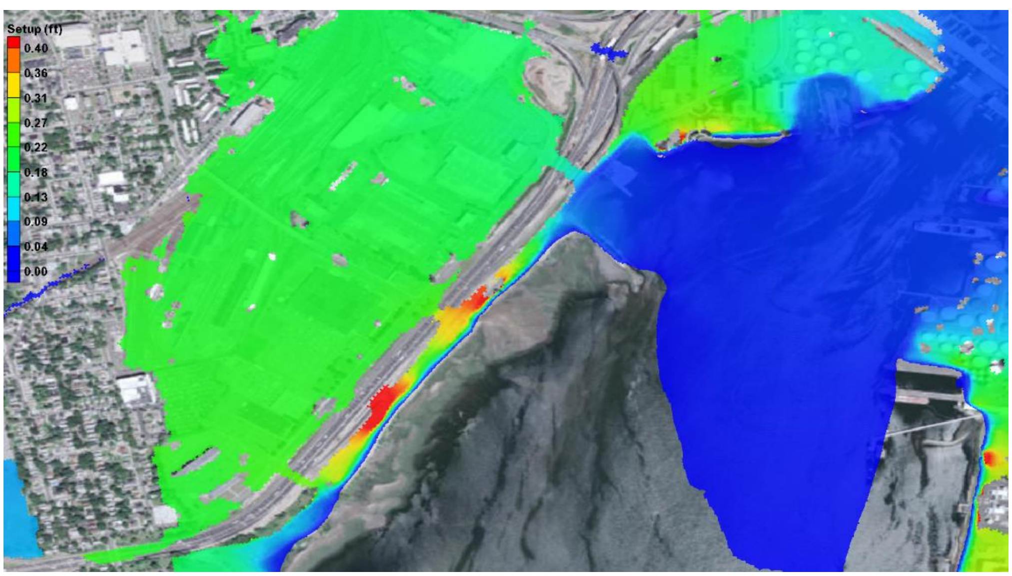
3.15.1 Extreme Wave Conditions

Wind-generated waves contribute to coastal flooding in three major ways: 1) by increasing the water surface elevation as wave trains travel onshore; 2) damaging structures with wave-induced loads; and 3) eroding shorelines. They can also cause significant damage to wetlands vegetation. Therefore, it is important to predict the wave conditions that may occur during coastal storms. While the largest waves will occur along the Long Wharf shoreline, waves can also occur within flood-inundated interior areas. Wave heights greater than 3 feet can result in significant building damage and beach erosion, while wave heights between 1.5 and 3 feet can result in moderate building damage and erosion.

GZA performed computer simulations using the SWAN wave model, for the 2016 100-year return period flood. Wind and model boundary waves were applied from a southerly direction to maximize fetch within New Haven Harbor. Predicted significant wave heights are presented in Figure 3-32. During the 2016 100-year return period (1% annual chance), wave heights reach approximately 5 feet at the southern project site near the Long Wharf Nature Preserve. Wave heights decrease moving north, reaching approximately 4 feet to the north of the pier and along the shoreline structures at the Long Wharf Maritime Center. The sheltering effects of I-95 prevents waves from propagating into Area 3. However, with the regenerative forces of winds, wave heights reach approximately 1 to 2 feet in Area 3.

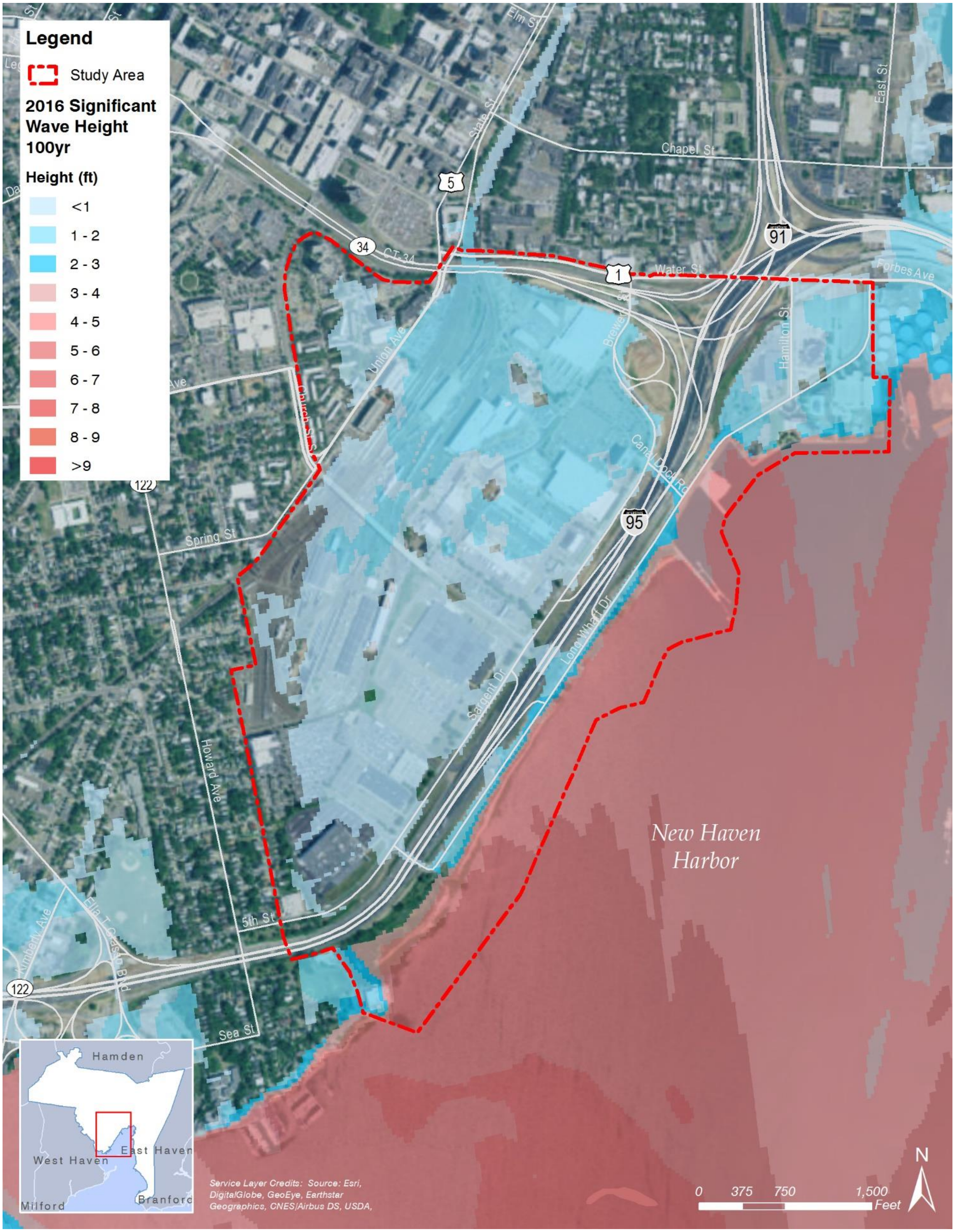
Wave setup is the increase in the total stillwater elevation against a barrier (dunes, bluffs or structure) caused by breaking waves[6]. GZA modeled wave setup using the SWAN model (see Figure 3-31) and predicted wave setup values along the Long Wharf shoreline (exclusive of wave runup) on the order of 0.2 to 0.5 foot during the 100-year return period (1% annual chance) flood.

Figure 3-31: Modeled Wave Setup Values along the Long Wharf Shoreline



[6] As waves break, they transfer momentum to the water column causing an increase in the total water elevation.

Figure 3-32: 2016 100-year return period Significant Wave Height (feet)



3.15.1 Nearshore Wind Wave Climate

Wave climate is defined as the distribution of wave parameters (wave height, wave period and wave direction) averaged over a defined time interval at a particular location (Wiegel, 1964). Evaluating site-specific wave climate is important for resiliency projects in coastal environments, in particular "Living Shorelines

GZA hindcasted nearshore wave conditions using the wind wave generation models recommended in the Shore Protection Manual (1984). The wind data were gathered from the Tweed Airport at New Haven, CT over a 68-year period (1948 – 2017). Wind data was split into 22.5-degree sectors based on wind direction. A separate wave fetch and average water depth was determined for each directional bin to calculate wave heights. Wave heights were then summed for all wave directions to determine the total number of occurrences of each wave height and the percentage of time each wave height was exceeded to create a wave frequency curve.

For the Long Wharf project area, the wave hindcast statistics were performed at two locations as presented in Figure 3-33. Figures 3-34 and 3-35 present the wave frequency curve for the two locations within the project site. GZA also performed statistical analysis within each directional bin (Figures 3-36 and 3-37). This information will be used to determine the need for attenuating wave energy before waves reach the toe of the proposed marsh enhancement areas. Research conducted by Shafer (Shafer et. Al, 2003) identifies a threshold for wave height for marsh survivability and successful growth based on observations at 8 different sites that represent healthy, eroding and eroded marsh conditions. Shafer uses 20-percent exceedance wave height ($H_{20\%}$) as the wave height comparison basis for the different project sites and determines that natural and created coastal wetlands can tolerate a $H_{20\%}$ of 0.14m (0.46ft).

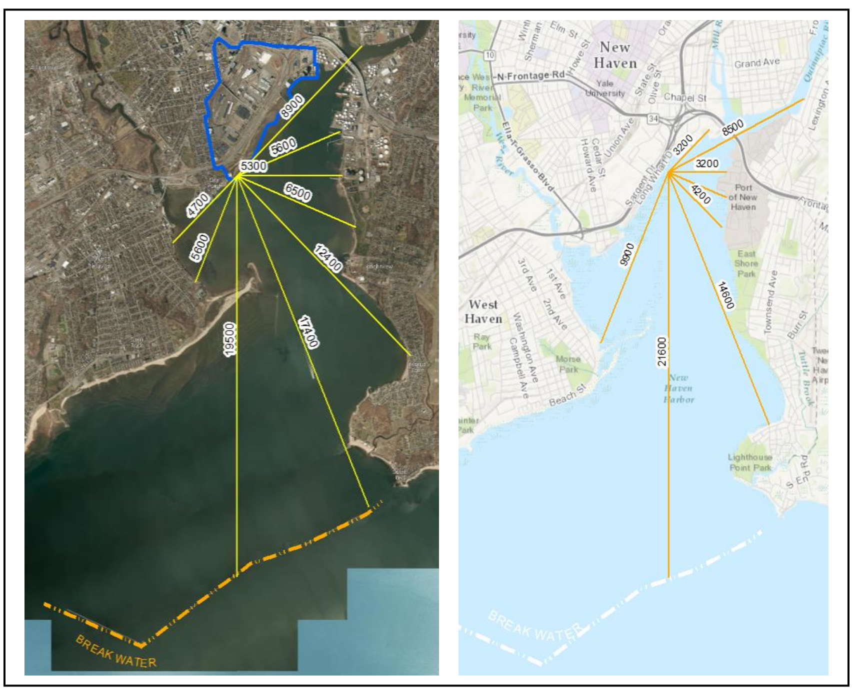


Figure 3-33: Nearshore Wave Hindcast Statistic Locations with Fetch Distances at each Directional Bin

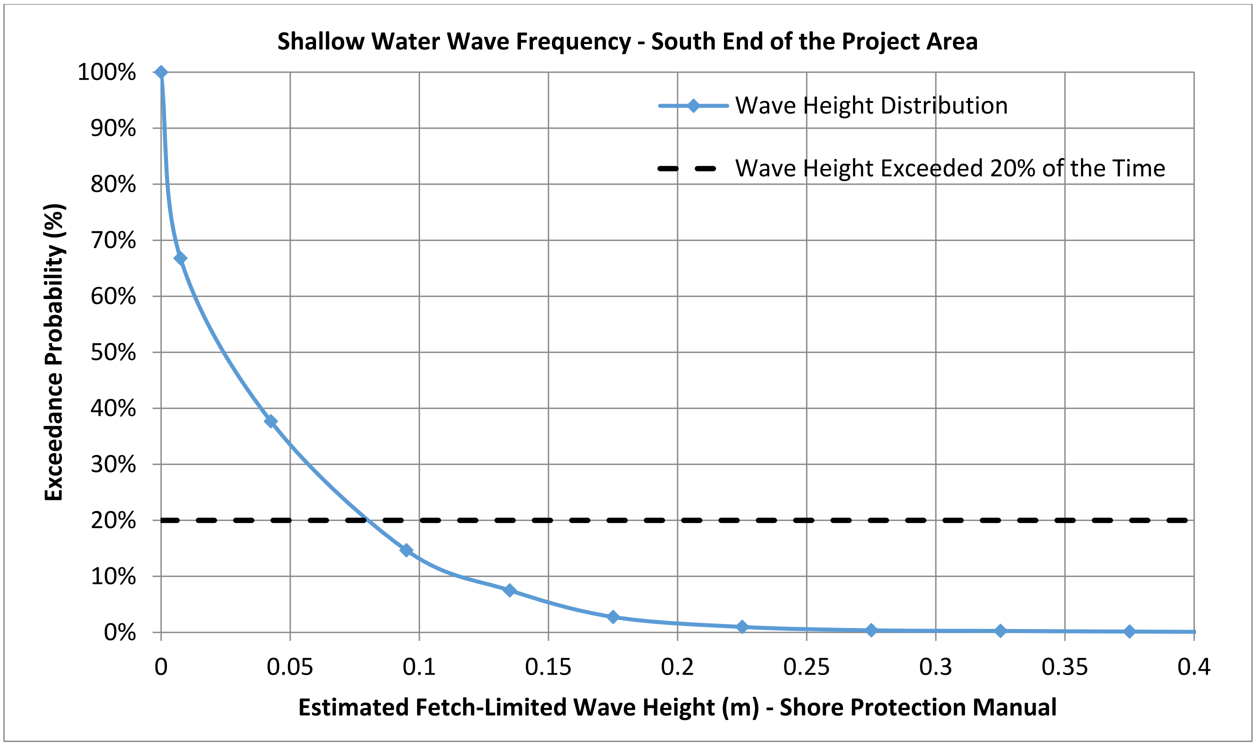


Figure 3-34: Nearshore Wave Frequency at the Southern End of the Project Area

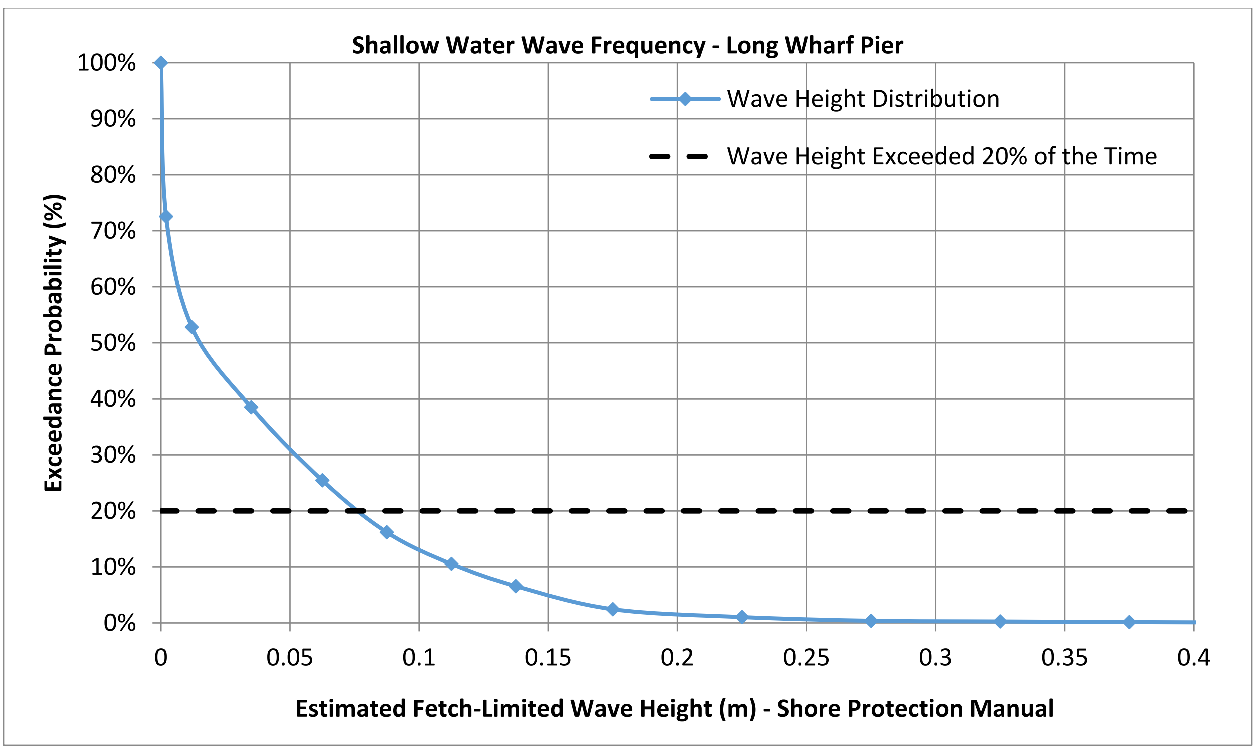


Figure 3-35: Nearshore Wave Frequency at Long Wharf Pier

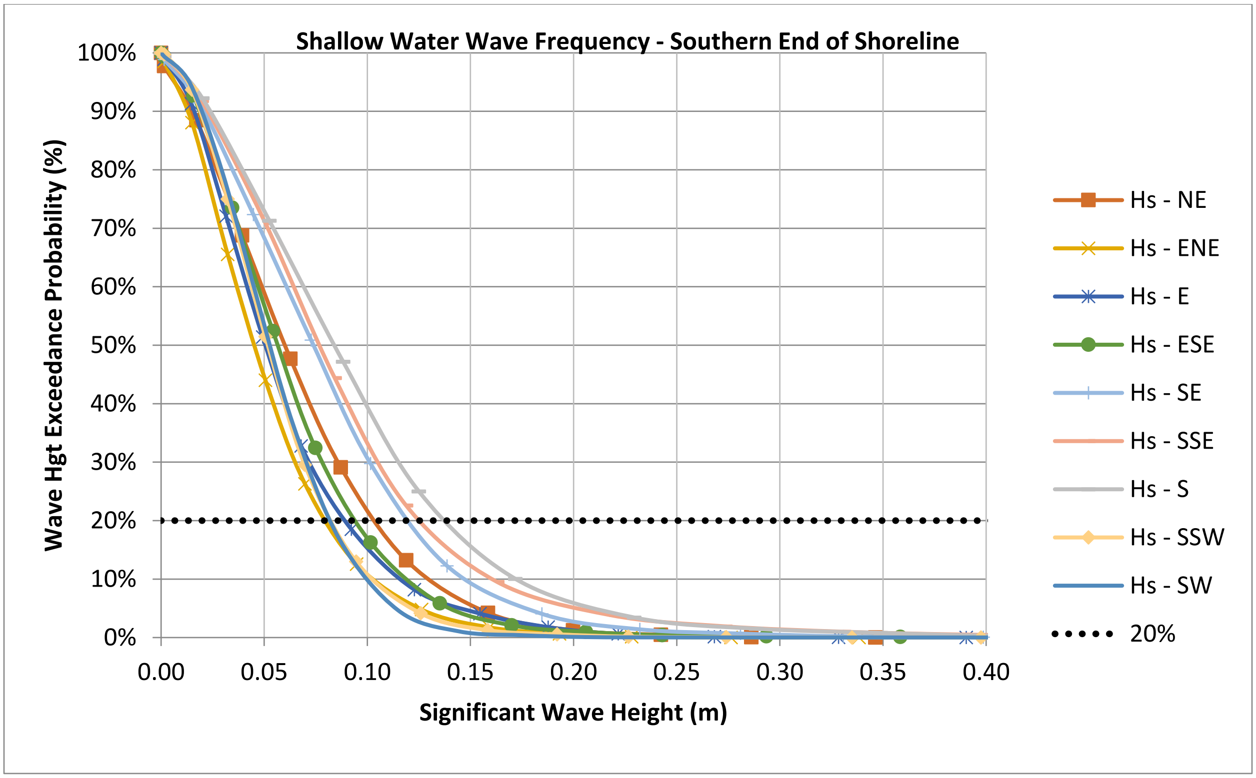


Figure 3-36: Nearshore Wave Frequency for each Directional Bin at the Southern End of the Project Area

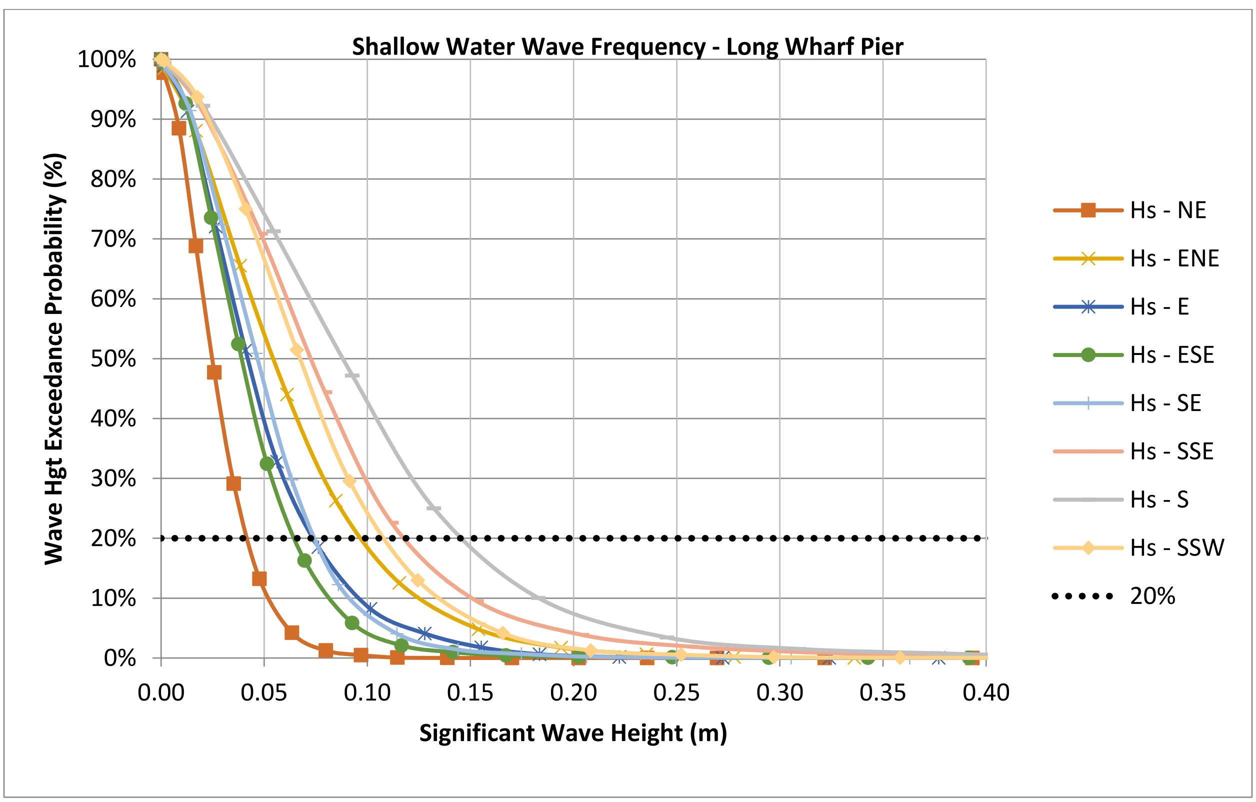


Figure 3-37: Nearshore Wave Frequency for each Directional Bin at Long Wharf Pier

3.16 Summary of Coastal Flood Hazards

The Long Wharf area is exposed to New Haven Harbor and Long Island Sound. Its location along New Haven Harbor makes it vulnerable to coastal flooding, including storm surge and waves. Flood elevations, and their associated probability of occurrence, have been analyzed by several public agencies including FEMA. NOAA and the USACE. The recent USACE North Atlantic Coast Comprehensive Study (NACCS) represents the most robust coastal flood hazard public study of the region currently available. This study, which is based on detailed model simulations and statistical analysis, predicts higher flood elevations than those presented on the effective FEMA FIRMs; however, the NACCS is expected to be reflective of what future revisions of the FEMA FIRM will likely indicate for this area (due to the methodology used by the USACE). GZA performed high resolution numerical flood model simulations (based on NACCS boundary model input) to dynamically evaluate the flooding across the Long Wharf area in detail. Model simulations were also performed by GZA to evaluate the effects of sea level rise on the coastal flood hazard.

Two key flood hazard planning benchmarks (the 100-year and 500-year return period flood events) are evaluated in detail. Both of these flood events are expected to result from tropical cyclones (hurricanes). The only historical, documented flood event analogous to the 100-year return period flood is the Hurricane of 1938, a hurricane that would be as devastating today as it was in 1938. There is no documented, historical flood event equal to the predicted 500-year return period flood. This flood would be catastrophic with significant damage of all Long Wharf structures and shoreline. Both of these flood events will occur coincident with high winds (likely sustained winds of 100 mph and greater) and heavy precipitation (with both additional river and stormwater flooding).

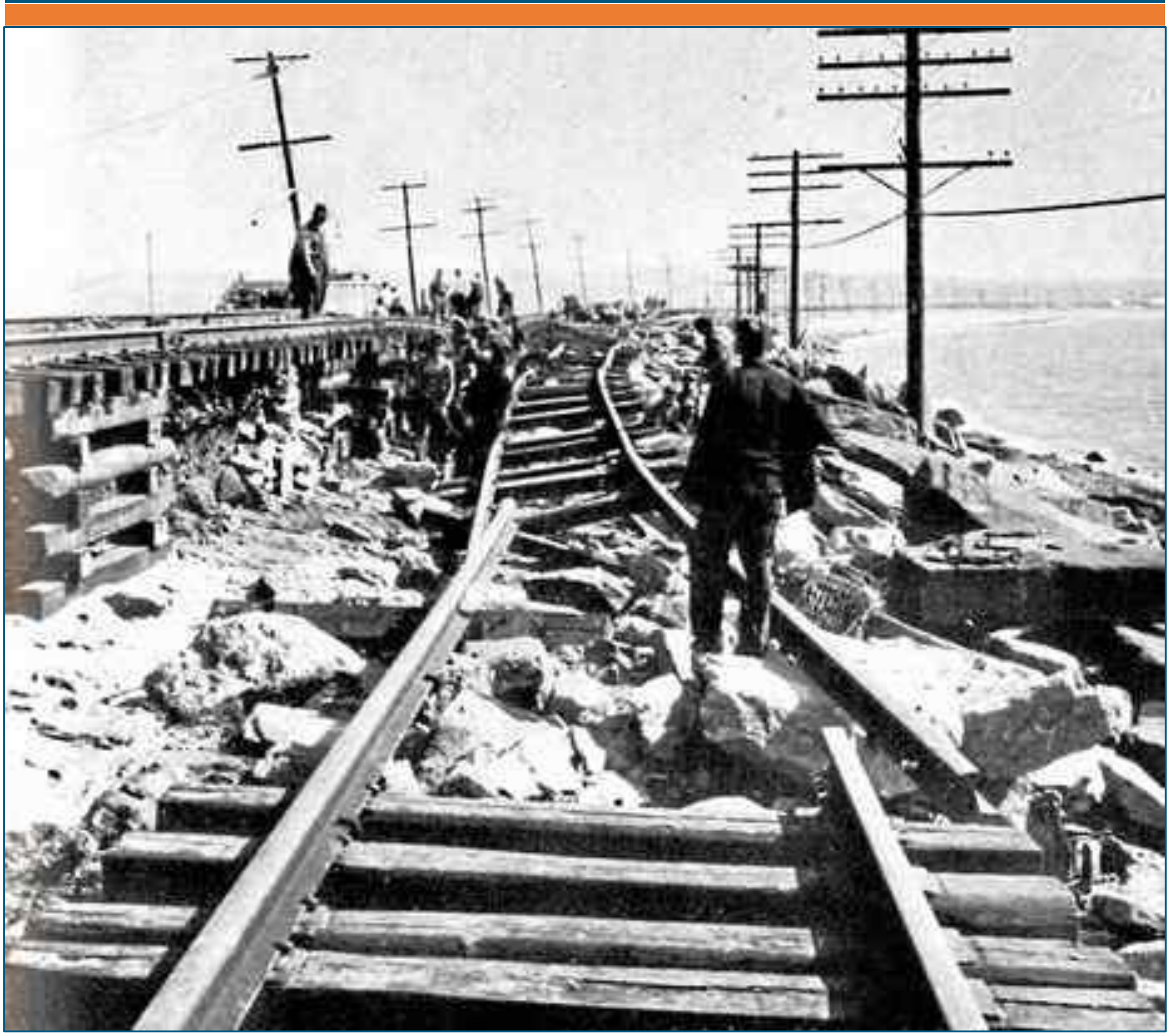
This Study addresses coastal flooding, including tides, storm surge and waves, in detail. Local intense precipitation that may occur coincident with storm surge is also a flood risk, including the performance of the stormwater infrastructure and management of rainwater. An evaluation of stormwater infrastructure is being performed by others.

Coincident rainfall will also increase river flow. The study area numerical model domain includes the downstream portions of several rivers including the Mill River, the Quinnipiac River and the West River. The downstream portions of these rivers are tidally influenced and flood water levels are controlled predominantly by the storm surge elevations within the Harbor. Therefore, river flow will not contribute significantly to flood levels within New Haven Harbor nor the adjacent Long Wharf areas. Coastal flooding may, however, cause backwater conditions increasing river flood elevations upstream.

Sea level rise over the next 50 years is predicted to be between 0.4 foot and 3.2 feet. The effect of sea level rise will be to increase both the frequency and floodwater elevation of coastal flood events. Under the High sea level rise projections utilized by the USACE, by the year 2116, tidal flooding of the Long Wharf will also occur (similar to that observed during Hurricane Sandy, but on a twice-daily basis).

Section 4.0 Flood Vulnerability

New Haven Long Wharf Flood Protection Study



The tide tore away the railroad tracks in New Haven. Ref. New Haven Register 9/21/13, article by Ed Stannard. "The 1938 hurricane was truly the 'perfect storm.' It moved onshore in Milford at about 3:00 p.m. that Wednesday. Most of Connecticut was on the dangerous right-hand sector where the storm's circulation combines with the storm's northward motion to enhance the force of the wind," by Dr. Mel Goldstein.

4.0 FLOOD VULNERABILITY

GZA evaluated the vulnerability to coastal flooding of the Long Wharf District assets located within Areas 1, 2 and 3, including the New Haven Rail Yard (including Amtrak, Metro-North and Shoreline East), the commercial and industrial buildings located west of I-95, the Long Wharf Maritime Center and surrounding buildings, the Long Wharf shoreline and the City of New Haven Housing Authority and Police Station.
The vulnerability of Long Wharf area roadways and utilities is also discussed.

Flood vulnerability was evaluated by comparing the predicted flooding to the existing site conditions and facilities. GZA's flood model simulations, which were coupled to the USACE NACCS results, predicted the flood inundation limits and water levels used for the vulnerability evaluation. The following presents a coastal flood hazard profile and ground surface elevation at each area. Google Earth™ images (shown with GZA's flood simulation results) are presented to assist visualization of the predicted flood impacts at each of the Study areas.

Recommended Sea Level Rise and Extreme Flood Elevations:

As presented in Section 3, there is both a range of flood elevations associated with different annual exceedance probabilities, based on the methodology and data used, and significant uncertainty associated with these elevations. There are also multiple projections of RSLC, each with different likelihoods of occurrence. The appropriate selection of flood elevations and sea level rise projections for evaluation of vulnerability and mitigation measures is dependent upon multiple factors, including expected loss, the criticality of the facilities being considered, the duration of the planning horizon, thresholds or tipping points in the human or natural systems of concern, and risk tolerance. The effective FEMA FIRMs and FIS are utilized for purposes of the National Flood Insurance Program. At New Haven, the FIS and FIRMs have methodological limitations. Due to these methodological limitations, use of the NACCS results is, in our opinion, a better source of coastal flood risk data at New Haven. Therefore, these values (or GZA model results developed using NACCS data) are recommended for assessing the current flood risk.

Section 3 presents a discussion of sea level rise projections. The predicted sea level rise near New Haven between the years 2016 and 2116 (based on projections at NOAA tide station 8467150 at Bridgeport, CT) were developed using the USACE Sea Level Change Curve Calculator (version 2017.42) and are based on USACE 2013/NOAA 2012 projections. Specifically, the USACE (Low, Intermediate and High) projections were used for GZAs model simulations. The NOAA sea level rise projections were revised subsequent to completion of GZA's analysis and storm surge model simulations but prior to completion of the Study report. The revised NOAA projections (discussed in Section 3) include: VLM, Low, Intermediate-Low, Intermediate, Intermediate-High, High and Extreme. The variance between the NOAA, 2017 projections increases significantly by mid-century. The report "Global and Regional Sea Level Rise Scenarios for the United States"; NOAA Technical Report NOS CO-OPS 083; January 2017 (NOAA, 2017) presents general guidance about selection of projections for planning purposes. One planning approach is to: 1) use a scientifically plausible, but currently low expected likelihood of occurrence as a planning upper bound; and 2) define a mid-range scenario as a baseline for planning, such as adaptation plans covering the next three decades (2050). These projections would bound a planning "envelope". The NOAA, 2017 Intermediate-Low scenario has a high predicted probability (49% to 96%). The NOAA, 2017 Intermediate scenario has a low to moderate probability (2% to 17%). The NOAA, 2017 Intermediate-High scenario currently has a very low expected exceedance probability (0.4% to 1.3%). Based on their estimated likelihood of occurrence: 1) the NOAA, 2017 Intermediate-Low scenario (49% to 96%) has a possible to near certain expected chance of occurrence and should be a minimum, lower bound; 2) the NOAA, 2017 Intermediate scenario (2% to 17% by 2100) has an unlikely to possible expected chance of occurrence and is considered an appropriate mid-range planning scenario; and 3) the NOAA, 2017 Intermediate-High (0.4% to 1.3% by 2100) is considered an upper bound.

For comparison, the following presents a comparison of the USACE and NOAA 2017 RSLC scenarios (from 2040 to 2100):

Year 2040:

NOAA, 2017 Intermediate-Low:	0.79 foot
NOAA, 2017 Intermediate:	1.25 feet
NOAA, 2017 Intermediate-High:	1.74 feet
USACE Intermediate:	0.54 foot
USACE High:	1.17 feet

Year 2050:

NOAA, 2017 Intermediate-Low:	0.95 foot
NOAA, 2017 Intermediate:	1.61 feet
NOAA, 2017 Intermediate-High:	2.23 feet
USACE Intermediate:	0.71 foot
USACE High:	1.64 feet

Year 2070:

NOAA, 2017 Intermediate-Low:	1.35 feet
NOAA, 2017 Intermediate:	2.53 feet
NOAA, 2017 Intermediate-High:	3.64 feet
USACE Intermediate:	1.12 feet
USACE High:	2.82 feet

Year 2100:

NOAA, 2017 Intermediate-Low:	1.84 feet
NOAA, 2017 Intermediate:	4.13 feet
NOAA, 2017 Intermediate-High:	6.30 feet
USACE Intermediate:	1.87 feet
USACE High:	5.14 feet

The State of Connecticut, in PA 13-179, "An Act Concerning the Permitting of Certain Coastal Structures by the Department of Energy and Environmental Protection" references NOAA CPO-1 report (an earlier NOAA report, dated December 2012) and requires that State and Municipal Plans of Conservation and Development, Civil Preparedness Plans and Municipal Hazard Mitigation Plans must "consider" the sea level change scenarios from the NOAA CPO-1 report. PA 13.179 also charged the University of Connecticut, Department of Marine Science to update the NOAA CPO-1 projections every 10 years based on local conditions and the state of the science.

Based on verbal communication with the University of Connecticut, we understand that forthcoming updates to the NOAA COP-1 projections will result in recommendations as follows: 1) for mid-range planning, assume that sea level will be 1.7 feet higher than the national tidal datum in Long Island Sound by the year 2050 (relative to the year 2000); 2) planners should be aware that the rate of sea level is expected to continue to increase, with a 3.25 feet rise in sea level by 2100; and 3) greenhouse gas emissions will be monitored and new assessments will be developed at decadal intervals.

In consideration of all of the information presented above, it is recommended that the USACE High RSLC Scenario be considered for evaluation of future risk and adaptation strategies for this project. It is also recommended that the USACE Intermediate RSLC Scenario be considered as having a very high (possible to near certain) likelihood of occurrence.

4.1 Area 1

Area 1 is a low lying coastal zone with both natural and shoreline protection features. From land to shore, Area 1 includes Long Wharf Drive, Long Wharf Park, Long Wharf Pier and the Canal Dock Boat House on the northern end, and the Veterans Memorial Park and Long Wharf Nature Preserve on the southern end. Area 1 also contains critical utilities (e.g., sanitary sewer main along Long Wharf Drive).

Attachment 2 presents Existing Conditions plans and sections with tide and flood water elevations indicated.

Area 1 Coastal Flood Hazard Profile

Flooding Mechanisms:

Tides:

The mean tide range at Long Wharf is approximately 6.2 feet. The tides are semidiurnal at New Haven, and the shoreline floods twice-daily with tidal circulation currents within the Harbor. Based on GZA's tide circulation modeling, tidal current velocities are low and non-erosive. The current MHHW (Elevation 3.1 feet NAVD88) floods the tidal flats and marsh and encroaches on the beaches, the toe of the revetments and the bulkheads. Upland areas are not, currently, tidally flooded. Tidal flooding of upland areas will occur if future tides exceed the crest elevations of the existing revetments and beaches (about Elevation 6 to 8 feet NAVD88). Assuming the USACE High RSLC projection, this condition could occur during high tides around the year 2070.

During low tides (MLLW -3.6 feet NAVD88), about 400 to 600 feet of tidal flat is exposed (to beyond the end of Long Wharf Pier).

The nearshore beach morphology is affected by discharge from the main stormwater outfalls, with the creation of large sediment deltas and localized high velocity flow at outfalls.

The shoreline within the Long Wharf Nature Preserve includes patches of beach, a large area of regularly flooded tidal marsh, and marsh drainage channels. The area of regularly flooded marsh extends to in front of the Veterans Memorial Park.

Storm Surge:

Flooding of Area 1 from coastal storm surge occurs relatively infrequently. As presented in Section 3.0, once storm surge flood elevations exceed the ground surface elevations along the shoreline, they will begin to flood areas that stay dry during the regular tidal cycle. This condition begins when floodwaters rise to about Elevation 6 to 8 feet NAVD88. This condition currently has an estimated return period of 2 to 10 years (10% to 50% annual exceedance probability). By the year 2041, this condition has an estimated return period of 1 year (near 100% annual exceedance probability), meaning that by this time some upland flooding will likely occur on average at least once a year.

Waves:

The shoreline is exposed to relatively large, erosive waves during storm events (as evidenced by its inclusion within a FEMA VE Zone). During the 2016 100-year return period (1% annual exceedance probability) flood, waves along the Long Wharf shoreline are predicted to range from about 3 feet to 5 feet in height (significant wave height). These waves will occur coincident with storm surge, meaning that they will break along the upper portions of the beach and within certain upland areas. Waves along the Long Wharf shoreline during non-storm conditions are typically 2 feet or less in height and are attenuated by the mud flats.

Flood Hazard Profile:

The entire Area 1 is located within the FEMA Special Flood Hazard Area. The effective FEMA Flood Insurance Rate Map (FIRM) indicates that seaward of Long Wharf Drive, the shoreline is a coastal high hazard area with a BFEs between of 13 feet and 16 feet NAVD88 and wave heights 3 feet or greater. The FEMA FIRM also indicates that Long Wharf Drive and the I-95 on and off-ramps are inundated during the 100-year return period (1% annual exceedance probability) flood with a BFE of 11 feet NAVD88 and wave heights between 1.5 and 3 feet.

A summary of predicted coastal storm surge flood elevations within Area 1, based on NACCs results are:

- Year 2016; 100-year return period:
  - Ground Surface Elevation: 3(+/- MHW) to 13 feet NAVD88
  - Flood Stillwater Elevation: +/- 12 feet NAVD88
  - Approximate Flood Depth: +/-0 to 9 feet
- Year 2016; 500-year return period:
  - Flood Stillwater Elevation: +/- 15.5 feet NAVD88
  - Approximate Flood Depth: +/- 2.5 to 12.5 feet
- Year 2041; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 13 feet NAVD88
  - Approximate Flood Depth: +/- 0 to 10 feet
- Year 2041; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 12.5 feet NAVD88
  - Approximate Flood Depth: +/- 0 to 9.5 feet
- Year 2066; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 14 feet NAVD88
  - Approximate Flood Depth: +/- 1 to 11 feet
- Year 2066; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 13 feet NAVD88
  - Approximate Flood Depth: +/- 0 to 10 feet
- Year 2116; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 18.5 feet NAVD88
  - Approximate Flood Depth: +/- 5.5 to 15.5 feet
- Year 2116; 100-year return period (Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 14 feet NAVD88
  - Approximate Flood Depth: +/- 1 to 11 feet

The predicted significant wave heights associated with the 2016 100-year return period flood along the Area 1 shoreline can be as high as 5 feet. Higher waves are mostly prominent in the southern portion of Area 1, near the Long Wharf Nature Preserve and they gradually attenuate toward the northern end of the site. The existing tidal flats and revetment work as important wave attenuation mechanisms, reducing the wave energy by breaking them before waves propagate inland (except during high storm surge water levels). By the year 2041, due to the increase in storm surge depth wave heights along the Area 1 shoreline during a 100-year return period flood could increase to 8 feet in height.

Area 1 Coastal Flood Vulnerability

Natural and Built Shoreline Features (Beaches, Marsh, Tidal Flats, Revetments and Piers):

The natural shoreline features are vulnerable to the coastal processes that occur during both tidal and storm floods and waves. These processes include: 1) changes to the water regime of tidal marshes due to sea level rise; 2) storm damage to marsh vegetation; and 3) erosion and sediment transport of sand beaches due to wave effects.

Tide water level datums will increase with sea level rise. MHHW is predicted to increase: Year 2041 Elevation 3.6 to 4.2 feet NAVD88; Year 2066 Elevation 4.1 to 5.4 feet NAVD88; and Year 2116 Elevation 5.3 to 9.5 feet NAVD88. MLLW is predicted to increase: Year 2041 Elevation -3.2 to -2.5 feet NAVD88; Year 2066 Elevation -2.7 to -1.3 feet NAVD88; and Year 2116 Elevation -1.4 to 2.2 feet NAVD88.

Figure 4.1 shows the current marsh and beach water regime at the Long Wharf Nature Reserve (Connecticut SLAMM model[1]). As shown in this figure, the area currently consists of regularly flooded marsh and estuarine beach (including tidal flat).

Figure 4-1: Connecticut SLAMM Model Current Conditions

[1] Sea Level Rise Affecting Marshes Model (SLAMM); http://longislandsoundstudy.net/research-monitoring/slamm/

Figure 4.2 shows the SLAMM predicted land cover for a condition of 2.5 feet of sea level rise (approximately reflecting USACE High RSLC projection by the year 2066 and USACE Intermediate RSLC projection by the year 2116). The area still consists of regularly flooded marsh and estuarine beach, but with a reduced area of beach and reduced tidal flat exposed at low tide.

Figure 4-2: Connecticut SLAMM Model +/- 2.5 feet Sea Level Rise

Figure 4.3 shows the SLAMM-predicted land cover for a condition of 2.5 feet of sea level rise for the area of Long Wharf Park. As shown here, the beach is effectively lost to open water under this condition.

Figure 4.4 shows the SLAMM model predicted land cover for a condition of about 5.6 feet of sea level rise (approximately reflecting USACE High RSLC projection by the year 2100). The Long Wharf Nature Preserve is predicted to still maintain an area (although reduced) of regularly flooded marsh. The estuarine beach is gone within this area (during all tides) and replaced with open water. Localized areas of former marsh have been replaced with tidal flat. Some upland areas are flooded.

The natural shoreline features are also vulnerable to storm-related damages, in particular: 1) effects of wave-induced currents on marsh vegetation; and 2) erosion of beaches and upland slopes. Erosion of these beach and upland slopes can also result in damage to shoreline protection revetments and underground utilities beneath and adjacent to upland slope areas.

Although there is not a large amount of research data currently available on the individual driving mechanisms effecting wetlands vegetation (e.g., colonization on mud flats), current velocities due to waves (i.e., drag forces) and sediment scouring clearly effect plant survival and colonization on bare flats. The natural tidal marshes can also be affected during storm flood conditions due to sediment deposition (of adjacent beach sand) into the marshes. Marshes are also affected by boat wake.

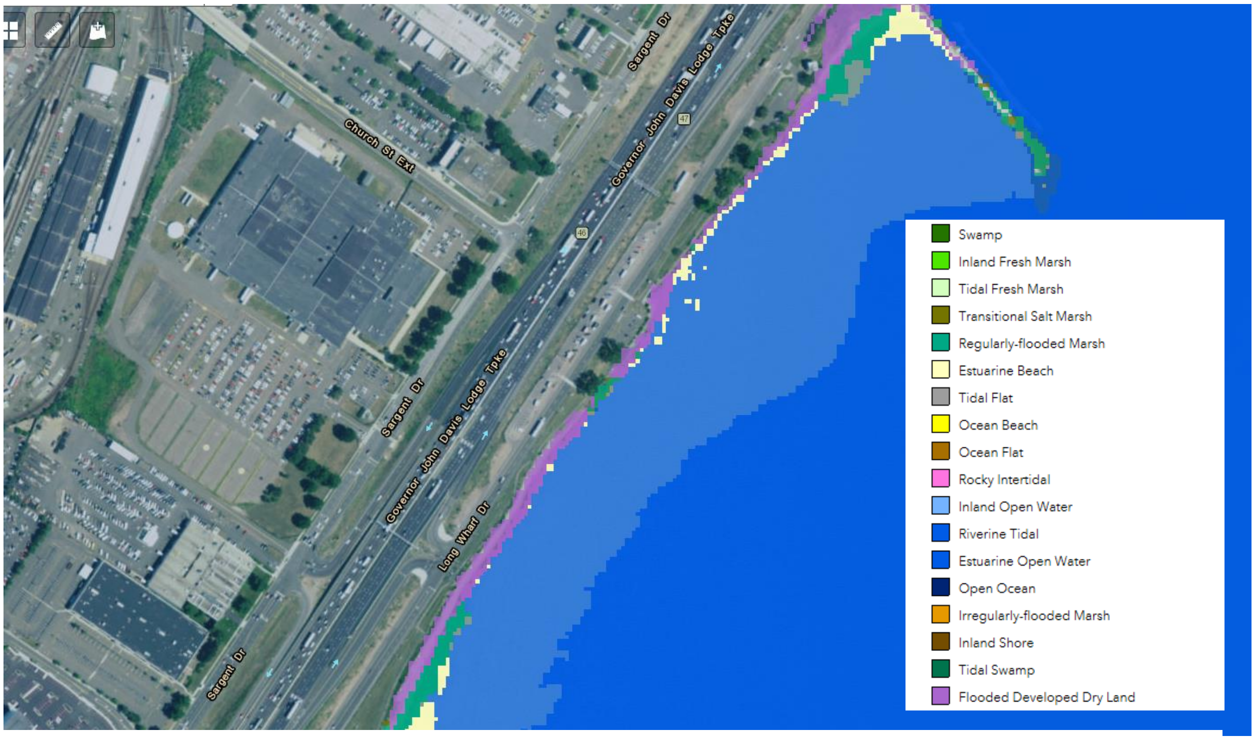


Figure 4-3: Connecticut SLAMM Model +/- 2.5 feet Sea Level Rise

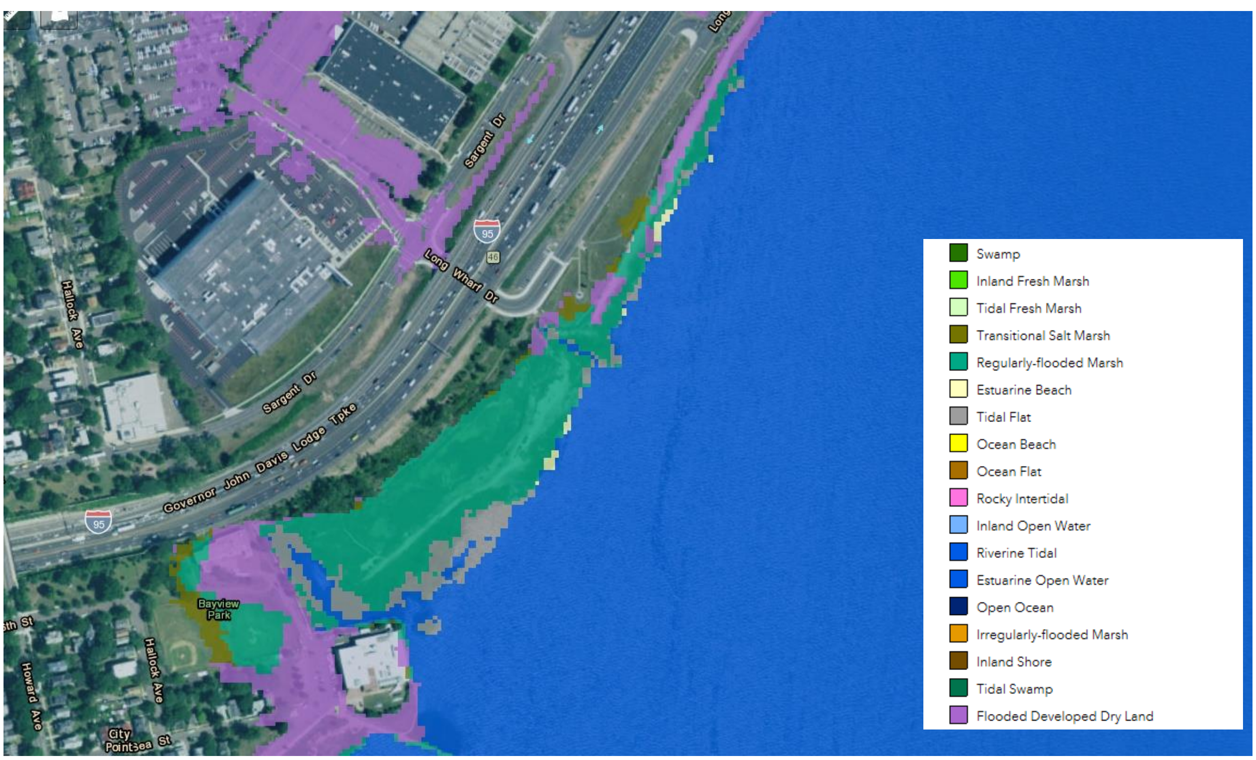


Figure 4-4: Connecticut SLAMM Model +/- 5.6 feet Sea Level Rise

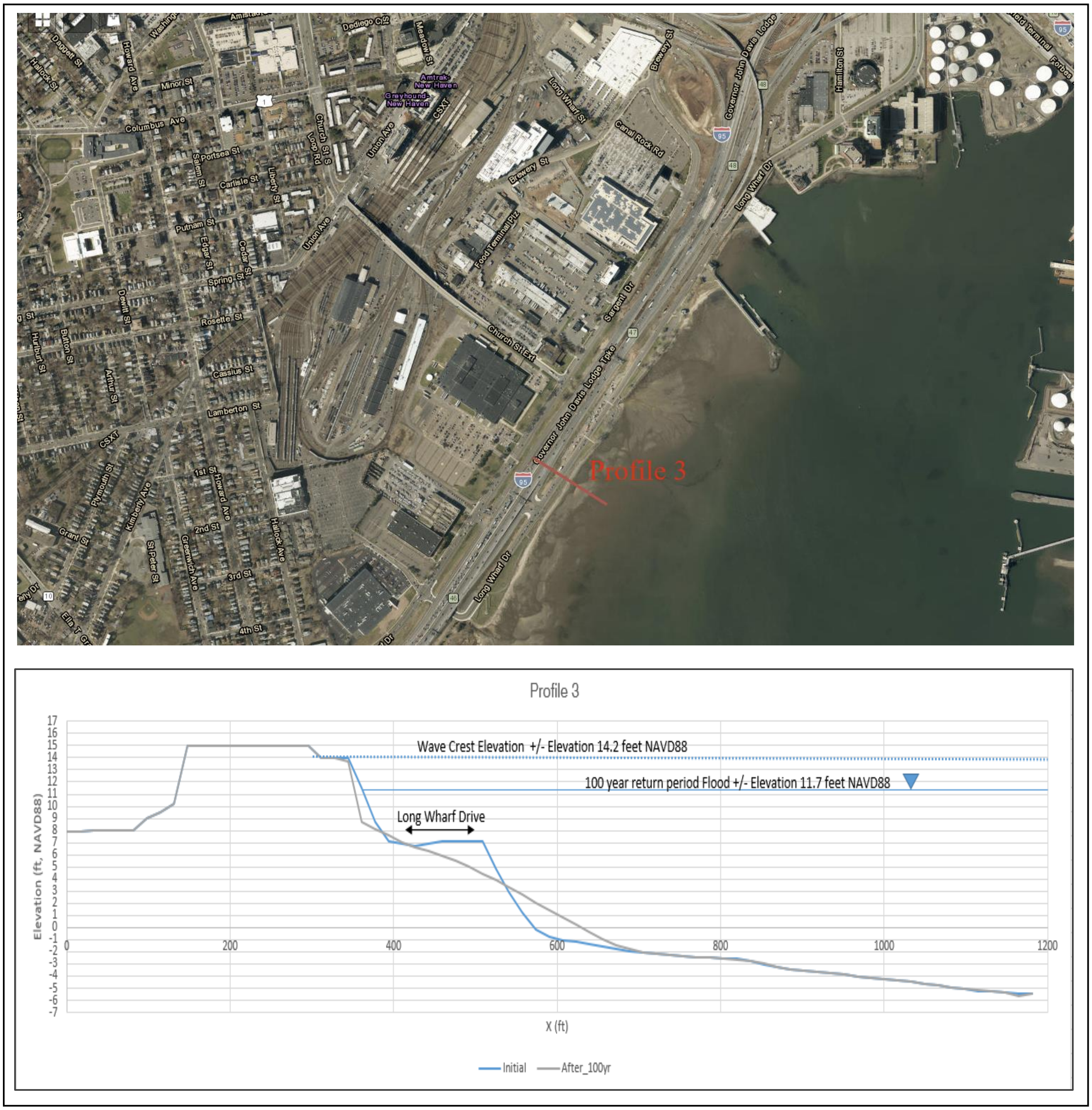


Figure 4-5: Shoreline Change Prediction for Unprotected Slope during 100-year return period flood using XBeach

A preliminary evaluation of shoreline transformation due to erosion during the 2016 100-year return period (1% annual chance) flood was performed using the sediment transport model XBeach. Figure 4.5 shows the existing shoreline and the predicted shoreline change for an unprotected shore at Profile 3. Although this preliminary analysis is very conservative (the model assumes an erosive sand stratum), the results imply that unprotected upland shoreline slopes, including roadways and utilities, are vulnerable to damage. This is consistent with observation of shoreline damage during Hurricanes Sandy and Irene, which were much less intense storms than the 100-year return period flood event.

More importantly, it is consistent with shoreline scour observed during the Hurricane of 1938, which is closer to a 100-year return period flood event. The existing revetments are also, similarly, vulnerable to damage. Maintenance and reconstruction of the existing damaged revetments with adequately-sized stone will allow these structures to provide better shoreline protection and minimize erosion and scour. Damage to the shoreline features will become both greater and more frequent in the future as sea level rise increases storm surge elevations and wave heights.

A damage evaluation of Long Wharf Pier was not performed as part of this study. The LiDAR data indicates that the deck/crest elevation of the pier (which is constructed on a quarry stone jetty) is at about Elevation 8 feet NAVD88. The jetty has parallel timber piers and docks for vessel berthing. Based on predicted flood elevations by the USACE, the pier is predicted to be inundated during the 10-year return period (10% annual exceedance probability). The 100-year return period significant wave heights at the pier are on the order of 4 to 5 feet. Although a detailed analysis has not been performed to support this conclusion, preliminarily it is expected that the 2016 100-year return period (annual exceedance probability) flood and wave action will result in some damage to the jetty (e.g., some stone displacement) and extensive damage or destruction of the timber structures (piers, docks and buildings).

Upland Developed Areas:

The upland, developed portions of Area 1 are susceptible to coastal flooding once coastal storm surge flood elevations exceed about 6 to 8 feet NAVD88. Currently (2016), this is predicted to occur with a return period of 2 years to 10 years (i.e., 10% to 50% annual exceedance probability). Floodwater inundates Long Wharf Drive when rising to elevations of approximately 8 to 10 feet NAVD88. Currently, this is predicted to occur with a return period floods of 10 years to 50 years (i.e., 10% to 2% annual exceedance probability). By 2041, the probability of flooding Long Wharf Drive increases to 5 to 20 years (20% to 5% annual exceedance probability).

Figures 4-6 and 4-7 and 4-8 and 4-9 show conceptual representations of the predicted flooding associated with the 2016 100-year and 500-year return period floods, respectively.

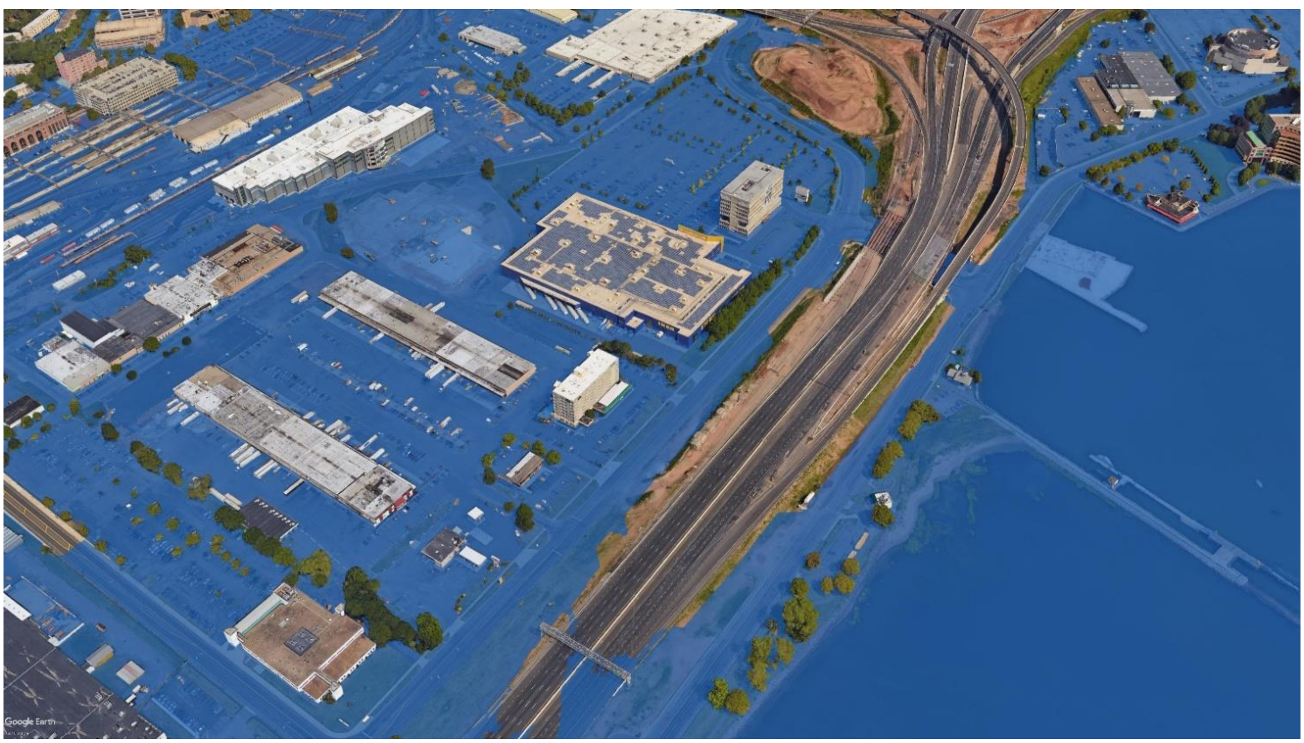


Figure 4-6: 2016 100-year Return Period Flood Inundation at Areas 1 and 3, North of Church Street

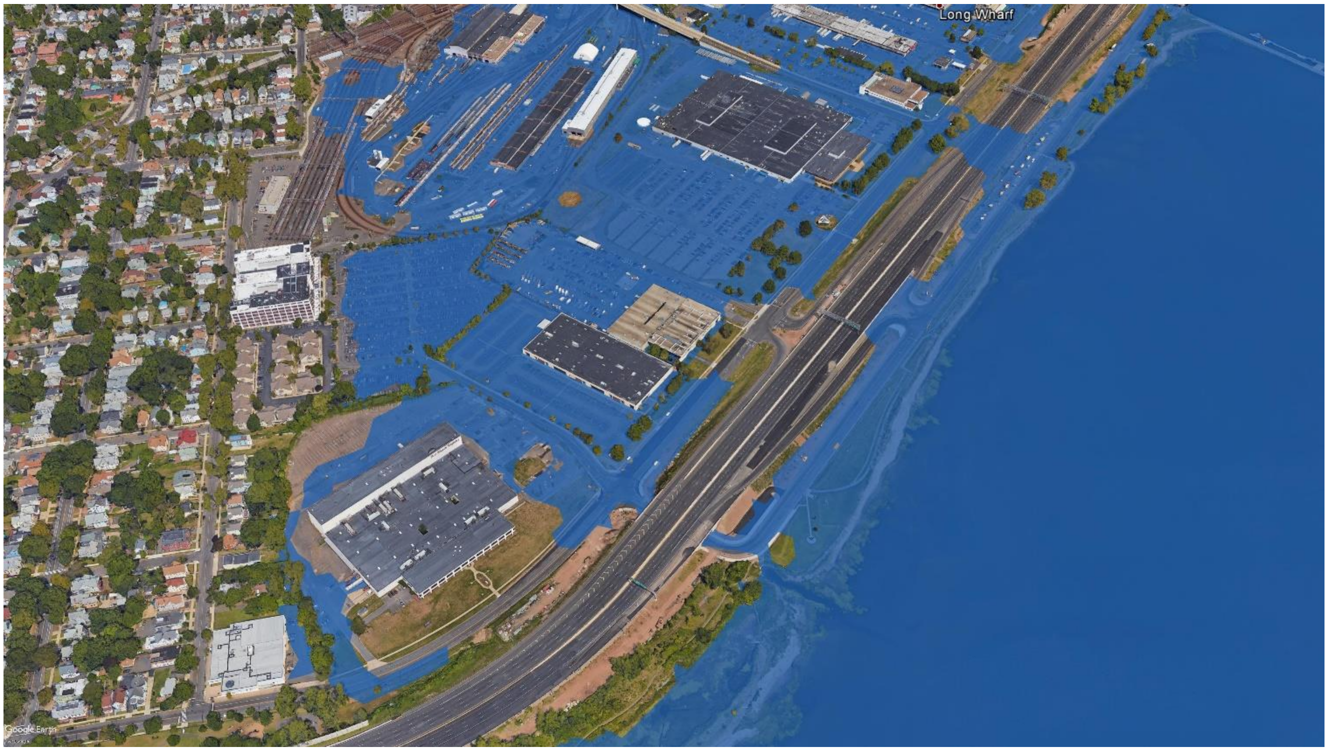


Figure 4-7: 2016 100-year Return Period Flood Inundation at Areas 1 and 3, South of Church Street

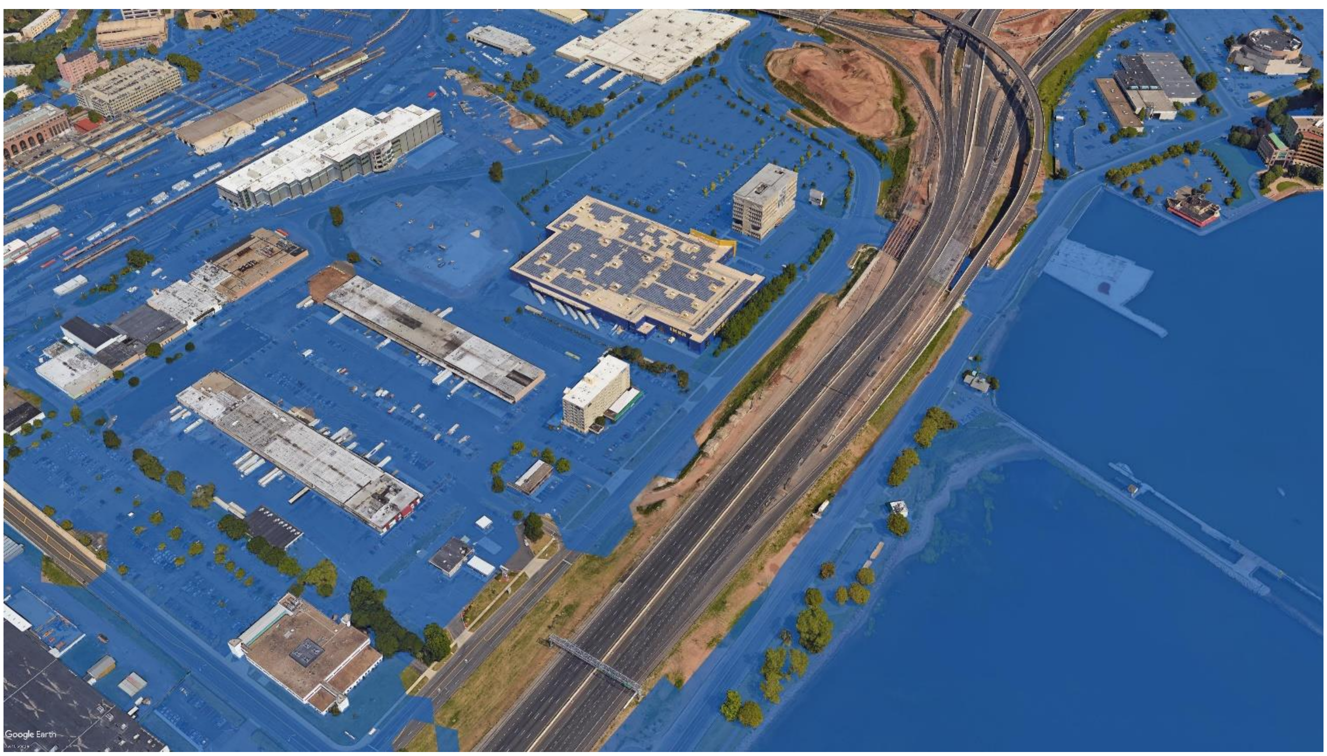
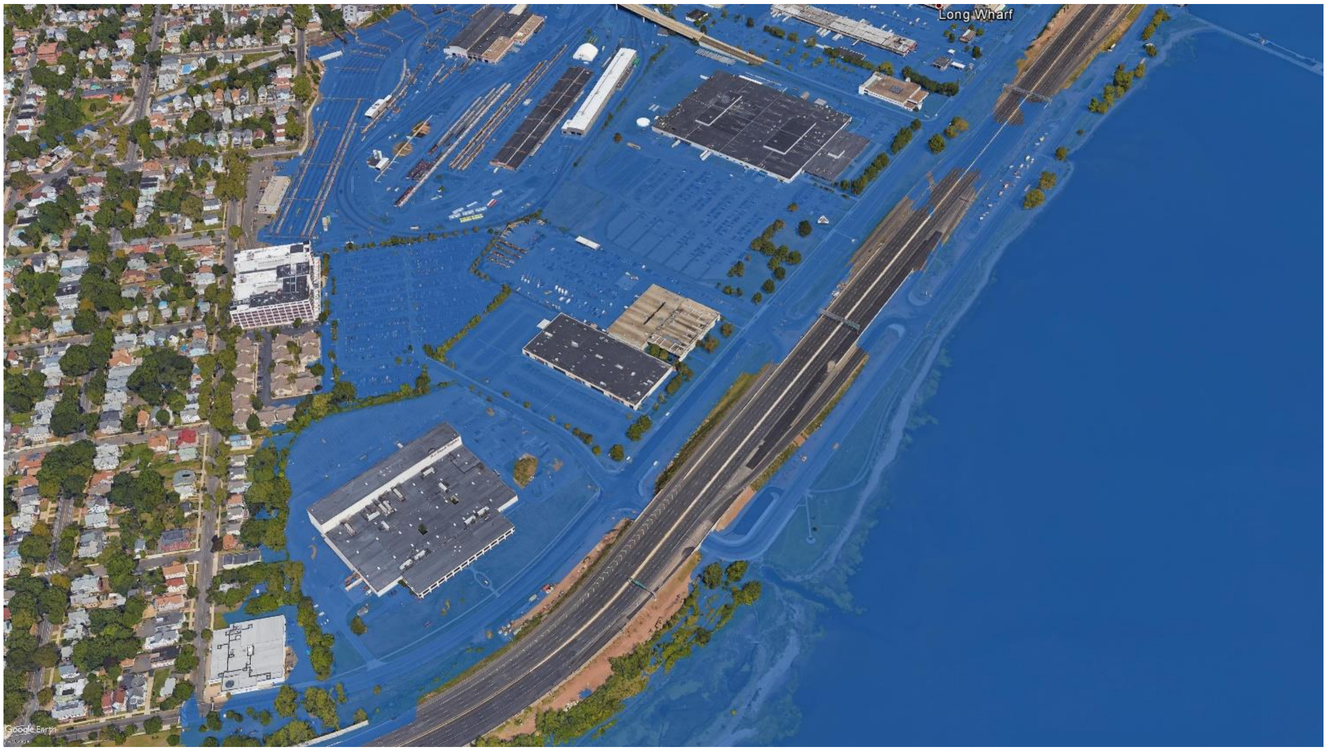


Figure 4-8: 2016 500-year Return Period Flood Inundation at Areas 1 and 3, North of Church Street

Figure 4-9: 2016 500-year Return Period Flood Inundation at Areas 1 and 3, South of Church



Street

4.2 Area 2

Area 2 is a developed area (Long Wharf Maritime Center, Sportech Venues, Long Wharf Drive offices and the City of New Haven Sewage Treatment Pump Station) with a hardened shoreline. A combined storm-sewer outfall is also located near the pump station. Area 2 has open exposure to flooding and waves from New Haven Harbor. Area 2 consists of commercial buildings, a portion of the Long Wharf Drive (before it turns into East Street), and the southern portion of the I-91 and I-95 intersection. The Area 2 shoreline mostly consists of steel sheetpile, stone bulkheads and quarry stone revetment. The shoreline (shore protection and adjacent walkway) elevation, based on available LiDAR, ranges from: 1) southwest corner near Long Wharf Drive at Elevation 5 to 6 feet NAVD88; 2) south-facing bulkhead and revetment at Elevation 10 feet NAVD88; and 3) southeast corner along concrete bulkhead at Elevation 8 feet NAVD88. The average ground surface elevation within the commercially developed area ranges between approximately 9 to 11 feet NAVD88. The ground surface elevation is higher at the highway embankment, which has roadway elevations of up to about 36 feet NAVD88.

Area 2 Coastal Flood Hazard Profile

<u>Flooding Mechanisms:</u>

Area 2 is at risk of coastal flooding caused by the tides, storm surge and wave impacts. A summary of predicted coastal storm surge flood elevations within Area 2, based on NACCs flood hazard results are:

Tidal Flooding:

The area is not currently vulnerable to tidal flooding and, based on the shoreline elevations, will not be vulnerable to tidal flooding except for the USACE High RSLC projection (MSL 6.1 feet NAVD88 and MHHW 9.5 feet NAVD88 for the years between 2066 and 2116).

Storm Surge:

Flooding of Area 2 from coastal storm surge is predicted to have a relatively high probability of occurrence. As presented in Section 3.0, once storm surge flood elevations exceed the ground surface elevations within the commercially developed areas (Elevations 9 feet to 11 feet NAVD88), these areas will be inundated.

<u>Flood Hazard Profile:</u>

The entire Area 2 is located within the FEMA Special Flood Hazard Area, indicating that it is vulnerable to flooding due to the 100-year return period (1% annual chance) FEMA Base Flood. The effective FEMA Flood Insurance Rate Map (FIRM) indicates that the southern and western shoreline is within a coastal high hazard area with a BFE of 16 feet NAVD88. On the westernmost portion of the shoreline, Area 2 is still in a high velocity flood zone; however, the BFE is lower at 13 feet NAVD88. The high velocity zone across the entire shoreline penetrates about 30 to 60 feet inland at which point wave heights dissipate and the flood hazard transitions to an AE Zone and BFE of 13 feet NAVD88.

A summary of predicted coastal storm surge stillwater flood elevations based on GZA's numerical modeling are presented below:

- Year 2016; 100-year return period:
  - Ground Surface Elevation: 6 to 11 feet NAVD88
  - Flood Stillwater Elevation: +/- 12 feet NAVD88
  - Approximate Flood Depth: +/- 1 to 6 feet
- Year 2016; 500-year return period:
  - Flood Stillwater Elevation: +/- 15.5 feet NAVD88
  - Approximate Flood Depth: +/- 4.5 to 9.5 feet
- Year 2041; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 13 feet NAVD88
  - Approximate Flood Depth: +/- 2 to 7 feet

- Year 2041; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 12.5 feet NAVD88
  - Approximate Flood Depth: +/- 1.5 to 6.5 feet
- Year 2066; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 14 feet NAVD88
  - Approximate Flood Depth: +/- 3 to 8 feet
- Year 2066; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 13 feet NAVD88
  - Approximate Flood Depth: +/- 2 to 7 feet
- Year 2116; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 18.5 feet NAVD88
  - Approximate Flood Depth: +/- 7.5 to 12.5 feet
- Year 2116; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 14/5 feet NAVD88
  - Approximate Flood Depth: +/- 3.5 to 8.5 feet

Waves seaward of the Area 2 shoreline structures during the 2016 100-year return period flood are on the order of 4 feet significant wave height.

Area 2 Coastal Flood Vulnerability

Flooding of the shoreline features, including flood inundation and wave overtopping, will occur at the southwest corner of Area 2 once flood elevations are above about 6 feet NAVD88 (estimated 2 year return period [50% annual exceedance probability]). Flood inundation will be localized and limited to these areas until flood elevations exceed about 8 feet NAVD88 (10-year return period [10% annual exceedance probability]). Flood inundation will become widespread once flood elevations reach about 10 to 11 feet (100-year return period [1% annual exceedance probability) flood.

Flood inundation of Area 2 starts at two locations: from the eastern shoreline in front of the Long Wharf Garage and the parking lot behind Lenny and Joe's Fish Tale on the western end of Area 2. When floodwaters rise to approximately 10 feet-NAVD88, Area 2 starts getting inundated from the southern shoreline facing New Haven Harbor.

The area is vulnerable to flood damage of buildings, building contents, vehicles and exterior landscaped and parking areas due to floodwaters, wave action and salt corrosion. The building structures located near the shoreline (e.g., Lenny and Joe's Fish Tale) have some exposure to waves greater than 3 feet. Overall, however, the shoreline structures (consisting of bulkhead and revetment) appear robust relative to flood damage.

The ground surface elevation around the East Street Pump Station is 10 feet NAVD88. The FEMA BFE at the pump station is AE Zone Elevation 16 feet NAVD88, consisting of a stillwater elevation of 8.9 feet NAVD88 and a wave overtopping flood elevation of 16 feet.

Area 2 businesses are a significant contributor to New Haven's tax base.

Figures 4-10 and 4-11 show conceptual representations of the predicted flooding associated with the 2016 100-year and 500-year return period floods, respectively.

Area 2 Effect of Sea Level Rise

Sea level rise will increase the probability of flooding in the future. The likelihood of experiencing flood elevations exceeding 8 feet NAVD88, currently about the 10-year return period (10% annual exceedance probability per NACCS), will increase to about the 2 to 5-year return period (50% to 20% annual exceedance probability) by the year 2041; a 1 to 5-year return period (100% to 20% annual exceedance probability) by the year 2066 and likely annually by the year 2116.

Figure 4-10: 100-year Return Period Flood Inundation at Area 2 in 2016

Figure 4-11: 500-year Return Period Flood Inundation at Area 2 in 2016

4.3 Area 3 Industrial/Commercial/Residential

Area 3 is developed and includes: 1) the commercial and industrial properties located to west of I-95; 2) the rail yard; and 3) residential and City properties. Area 3 is located inland and to the west of I-95. The industrial/commercial area includes signature companies such as IKEA, Assa Abloy, Sargent Manufacturing, Jordan's Furniture, etc. as well as the New Haven Food Terminal and the U.S. Postal Building. Located to the north of the rail tracks are the City of New Haven Police Department and the City of New Haven Public Housing (residential). The ground surface elevation in the industrial/commercial/residential area ranges from about Elevation 8 to 11 feet.

Area 3 Industrial/Commercial/Residential Coastal Flood Hazard Profile

Flooding Mechanisms:

Storm Surge:

Area 3 industrial/commercial/residential areas are susceptible to flooding due to coastal storm surge. Most coastal flood events will be accompanied by precipitation including heavy snow during winter Nor'Easters and rain during both tropical cyclones and Nor'Easters.

GZA's flood simulations indicate that flooding initially enters Area 3 via the I-95 underpasses and (under high enough floods) over the central, low-lying portion of I-95. As presented in Section 3.0, once storm surge flood elevations exceed the ground surface elevations along the shoreline and along Long Wharf Drive, they will begin to flood areas to the west of I-95 (principally via flood inundation at the two major Long Wharf I-95 underpasses). This condition begins when floodwaters rise to about Elevation 8 feet NAVD88. Once flood elevations exceed about 9 feet, floodwaters will propagate across the rail tracks (north of Union Station) and flood the area of the New Haven Police Station and the New Haven Housing Authority.

If flood elevations are high enough, Area 3 will also flood from floodwaters propagating from Area 2 via Water Street and through the Brewery Street underpass and I-95 near Bayview Park.

Flood Hazard Profile:

All the industrial/commercial buildings in Area 3, with the exception of New Haven Village Suites and the commercial building to the north of Village Suites, are located within the FEMA FIRM AE flood hazard zone, indicating that this area is vulnerable to flooding due to the 100-year return period flood event. The New Haven Police Station and the New Haven Housing Authority are also located within the FEMA FIRM AE flood hazard zone.

The effective FEMA FIRM indicates that the Base Flood Elevation (BFE) ranges between 11 to 12 feet NAVD88 throughout the area, consisting of a stillwater elevation of 8.9 feet NAVD88 and local wave effects. The BFE immediately landward of the I-95 is Elevation 11 feet NAVD88.

Area 3 is also vulnerable to flooding due to intense precipitation. An analysis of the area stormwater infrastructure is being performed by other and is not addressed in this report.

A summary of predicted coastal storm surge stillwater flood elevations based on GZA's numerical modeling are presented below:

- Year 2016; 100-year return period:
  - Ground Surface Elevation: 8 to 11 feet NAVD88
  - Flood Stillwater Elevation: +/- 10 to 11 feet NAVD88
  - Approximate Flood Depth: 0 to 3.0 feet
- Year 2016; 500-year return period:
  - Flood Stillwater Elevation: +/- 15 to 16 feet NAVD88
  - Approximate Flood Depth: 4 to 8 feet

- Year 2041; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/-11 to 12.5 feet NAVD88
  - Approximate Flood Depth : 3 to 4.5 feet
- Year 2041; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/-10 to 11 feet NAVD88
  - Approximate Flood Depth : 2.5 to 3 feet
- Year 2066; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 12.5 to 13.5 feet NAVD88
  - Approximate Flood Depth: 1.5 to 5.5 feet
- Year 2066; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 12.5 to 13.5 feet NAVD88
  - Approximate Flood Depth: 1.5 to 5.5 feet
- Year 2116; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 18.5 to 19 feet NAVD88
  - Approximate Flood Depth: 7.5 to 11 feet
- Year 2116; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 18.5 to 19 feet NAVD88
  - Approximate Flood Depth: 7.5 to 11 feet

The predicted waves associated with the 2016 100-year return period flood are between 1.5 and 3 feet within Area 3.

The duration of extreme flooding (e.g., 100-year return period floods) for all three study areas is expected to be less than 12 hours, with peak flooding less than 8 hours. Coincident wind speeds will be on the order of 80 mph to 120 mph.

Area 3 Industrial/Commercial/Residential Coastal Flood Vulnerability

Flood inundation will become widespread once flood elevations reach about Elevations 10 to 11 feet (100-year return period [1% annual chance) flood.

The area is vulnerable to flood damage of buildings, building contents, vehicles and exterior landscaped and parking areas due to floodwaters, waves and salt corrosion. Business disruption is also a flood-related outcome.

Figures 4-6 through 4-9 and 4-12 through 4-15 show conceptual representations of the predicted flooding associated with the 2016 100-year and 500-year return period floods, respectively.

Area 3 Industrial/Commercial/Residential Effect of Sea Level Rise

Sea level rise will increase the probability of flooding in the future. The likelihood of experiencing flood elevations exceeding 8 to 9 feet NAVD88, currently about the 10 to 20-year return period (5% to 10% annual exceedance probability), will increase to about the 5 to 10-year return period (20% to 10% annual exceedance probability) by the year 2041; a 1 to 5-year return period (100% to 20% annual exceedance probability) by the year 2066 and likely annually by the year 2116. For comparison, the flood elevation resulting from Hurricane Sandy has a return period of about 20 years (5% annual exceedance probability) based on the USACE NACCS flood frequency prediction.

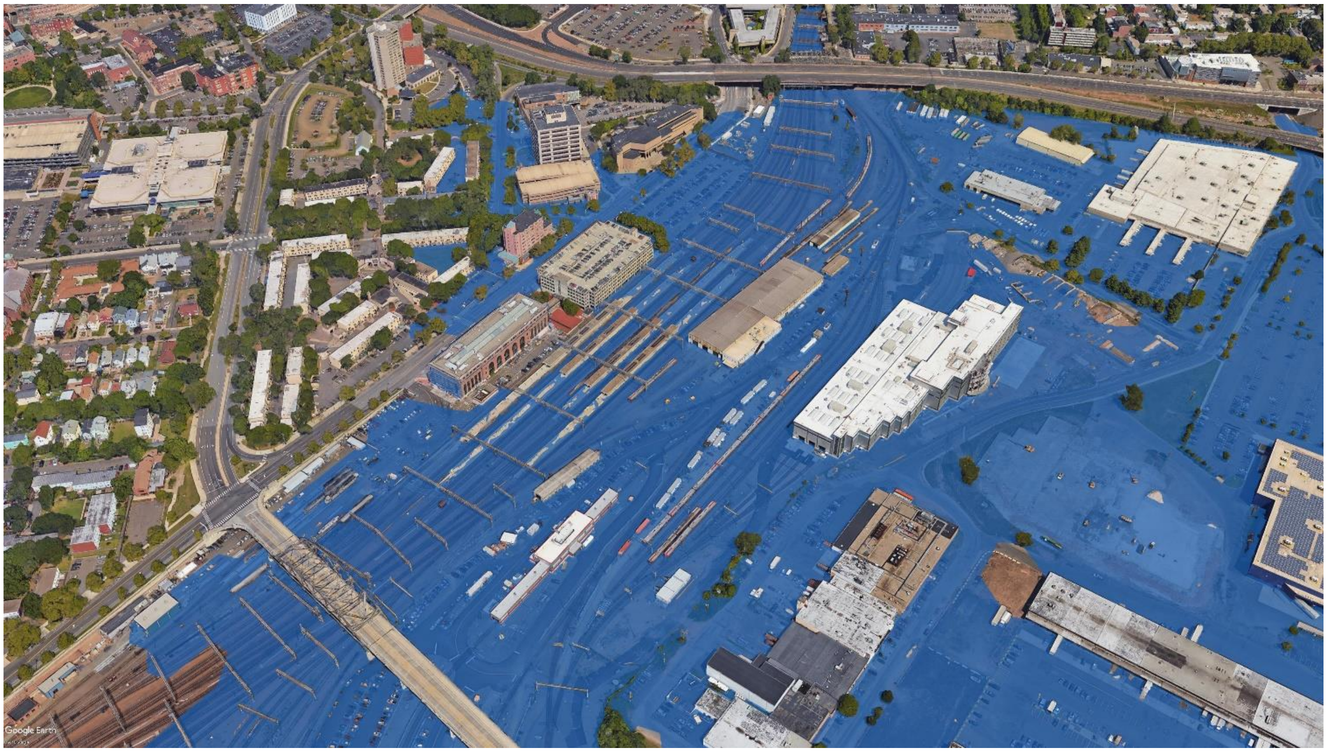


Figure 4-12: 100-year Return Period Storm Inundation at the Area 3 (North of Church Street) in 2016

Figure 4-13: 100-year Return Period Storm Inundation at Area 3 (South of Church Street) in 2016

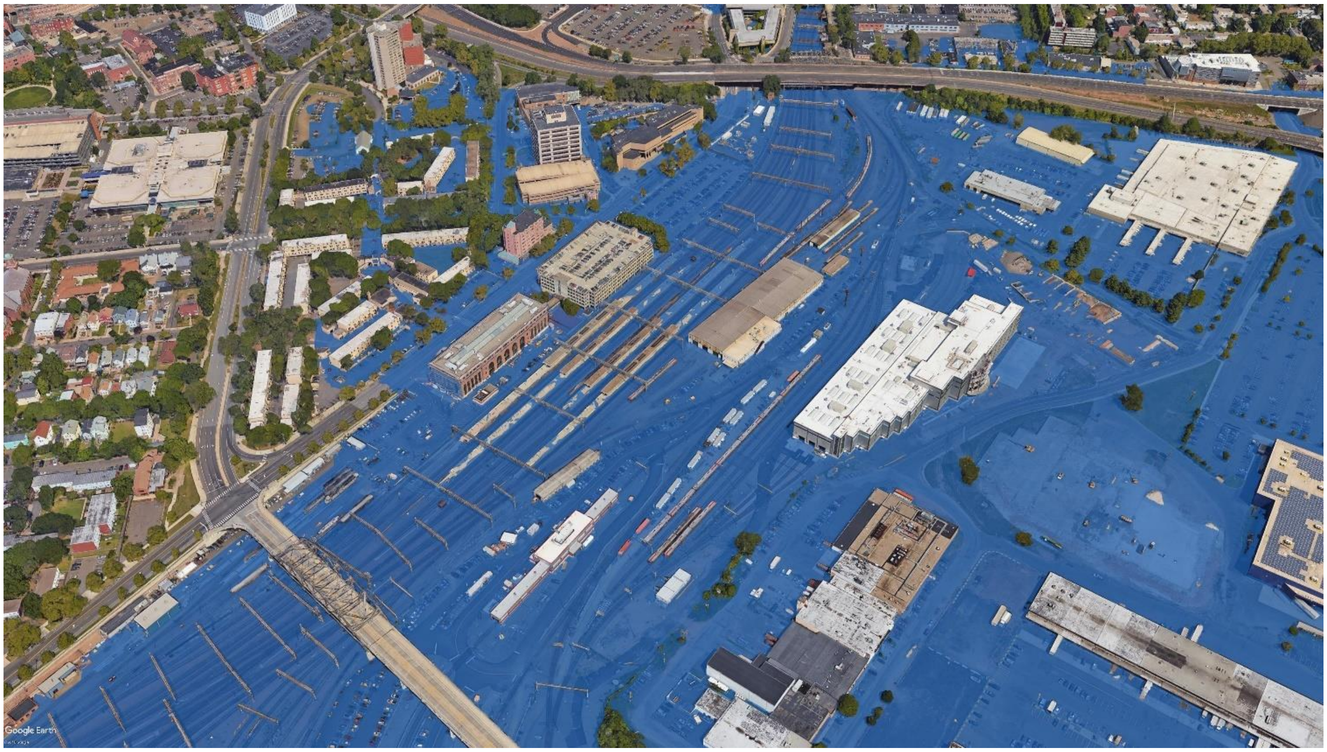


Figure 4-14: 500-year Return Period Storm Inundation at Area 3 (North of Church Street)

Figure 4-15: 500-year Return Period Storm Inundation at Area 3 (South of Church Street) in 2016

4.4 New Haven Rail Yard/Amtrak/Metro-North

The New Haven Rail Yard (located in Area 3) has existed since the late 1800's and in its current location (on filled land) since the mid-1900's. The State owns the rail platforms and stations. Today, the New Haven Rail Yard contains rail infrastructure of regional significance, including:

- Northeast Corridor mainline tracks (including electrified overhead catenary), owned by the Connecticut Department of Transportation (ConnDOT), serving:[2]
    - Amtrak Acela Express, Northeast Regional, Vermonter, and Springfield Shuttle – 46 trains per weekday, about 16,000 daily riders;
    - Metro-North Railroad (New Haven Line to Grand Central Terminal) – 90 to 100 trains per weekday, 110,000 daily riders on the entire line;
    - Shore Line East (New Haven to New London; owned by ConnDOT and operated by Amtrak) – 20 trains per weekday, 634,000 annual passengers;
    - Freight rail (two to five trains per day carrying 7.5 million metric tons of freight annually);
- The New Haven Union Station passenger rail station (owned by ConnDOT). This facility, first opened in 1920 and listed on the National Register of Historic Places, was reopened in 1985 after extensive renovations. It serves about 700,000 annual boardings and alightings on four platforms with nine tracks.
- The New Haven Rail Yard, a 74-acre ConnDOT-owned railyard serving both diesel and electric locomotives for Amtrak (including Shore Line East) and Metro-North. This also serves as a layover facility for some Metro-North and Shore Line East locomotives and cars. A new multi-story New Haven Rail Maintenance Facility (repair shop for electrical multiple-unit cars, with offices and training facilities on upper floors) was constructed between 2010 and 2013 at a cost of nearly $200 million, along with 25 new storage tracks.

Overall, capital improvements on the order of $1.2 billion have been made (or are planned) to the facility by ConnDOT. Financing for station improvements, upgrades and other capital investments comes from several sources including state, federal and rail operator funding. Relocation of the rail yard in the future is not anticipated.

Area 3 Rail Yard Coastal Flood Hazard Profile

Flooding Mechanisms:

The rail infrastructure is at risk of flooding due to: 1) localized intense precipitation (due to lack of capacity of stormwater drainage systems during heavy precipitation events); and 2) coastal flooding (saltwater inundation) during major coastal storms (due to storm surge).

Stormwater:

The rail yard has historically been flooded due to stormwater runoff discharging to the "east cut" (under Water Street Bridge where ground surface is just a few feet above Mean Sea Level), and then to the yard, and to surcharging of the stormwater infrastructure. The east cut pump station was constructed approximately 10 years ago to address stormwater issues.

[2] Sources: Amtrak Fact Sheet, Fiscal Year 2015: State of Connecticut; Transportation Fast Facts 2015, Connecticut DOT; MTA schedules accessed November 1, 2016; Connecticut State Rail Plan, Connecticut DOT, 2012; New Haven Rail Maintenance Facility Improvements FONSI, U.S. DOT, May 7, 2009; Wikipedia, accessed November 1, 2016; additional Metro-North and Amtrak data cited in Cambridge Systematics, Inc. research for Federal Highway Administration – Hurricane Sandy Adaptation and Response project.

Figure 4-16: Passenger platforms, rail yard, and maintenance facility (looking NE from station)

Figure 4-17: Passenger platforms and maintenance facility (looking SE from station)

Storm Surge:

Flooding of the rail yard from coastal storm surge occurs from flooding that has propagated to the area via the I-95 underpasses and over the central, low-lying portion of I-95. The rail yard vulnerability to coastal storm surge is due to: 1) the relatively low ground surface elevation surrounding rail yard features; and 2) overland hydraulic connectivity with shoreline flooding and New Haven Harbor during coastal flood events. As presented in Section 3.0, once storm surge flood elevations exceed the ground surface elevations along the shoreline and along Long Wharf Drive, they will begin to flood areas to the west of I-95 (via flood inundation at the two major Long Wharf I-95 underpasses). This condition begins when floodwaters rise to about Elevation 8 feet NAVD88.

If flood elevations are high enough, flooding will also propagate toward the rail yard from Area 2 via Water Street and through the Brewery Street underpass. If flood elevations are high enough, flooding will also propagate toward the rail yard over the central, low-lying portion of I-95.

GZA's modeling indicates that under coastal flood conditions (not including the effects of precipitation), the flood will flow from the yard and away from Area 3 via the east cut rail tracks (to the north) and the rail tracks (to the south-southwest).

Sea Level Rise:

As discussed in Section 3.0, RSLC will increase the effects of stormwater and coastal related flooding. Stormwater flooding will occur due to an increase in sea level at drainage system outfalls, causing the infrastructure to surcharge more frequently decreasing the performance of the infrastructure. Coastal flooding will also intensify due to increasing sea level.

<u>Flood Hazard Profile:</u>

The entire rail yard is located within the FEMA FIRM AE flood hazard zone, indicating that it is vulnerable to flooding due to the 100-year return period flood. The effective FEMA Flood Insurance Rate Map (FIRM) indicates that the Base Flood Elevation (BFE) in the rail yard area is 11 feet NAVD88. Portions of the rail yard, including part of the new ConnDOT building and parking lot are located within an area delineated with a BFE of 12 feet NAVD88). The BFE includes a FEMA stillwater elevation of 8.9 feet, with the difference between the stillwater elevation and the BFE due to wave effects.

A summary of predicted coastal storm surge stillwater flood elevations based on GZA's numerical modeling are presented below:

- Year 2016; 100-year return period:
  - Ground Surface Elevation: 3 to 10 feet NAVD88
  - Flood Stillwater Elevation: +/- 11 feet NAVD88
  - Approximate Flood Depth: +/-1 to 8 feet
- Year 2016; 500-year return period:
  - Flood Stillwater Elevation: +/- 15.5 to 16 feet NAVD88
  - Approximate Flood Depth: +/- 4 to 13 feet
- Year 2041; 100-year return period (USACE High RSLC):
  - Flood Stillwater Elevation: +/- 11 to 12.5 feet NAVD88
  - Approximate Flood Depth: +/- 1.0 to 9.5 feet
- Year 2041; 100-year return period (USACE Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 11.5 feet NAVD88
  - Approximate Flood Depth: +/- 1.5 to 5.5 feet
- Year 2066; 100-year return period (Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 11.5 feet NAVD88
  - Approximate Flood Depth: +/- 1.5 to 5.5 feet

- Year 2116; 100-year return period (Intermediate RSLC):
  - Flood Stillwater Elevation: +/- 13.2 feet NAVD88
  - Approximate Flood Depth: +/- 3.2 to 7.2 feet

The predicted waves associated with the 2016 100-year return period flood are less than 1.5 feet in the area of the rail yard.

The duration of flooding is expected to be less than 12 hours, with peak flooding less than 8 hours. Coincident wind speeds will be on the order of 80 mph to 120 mph.

Area 3 Railyard Flood Vulnerability

The rail yard is susceptible to coastal flooding once coastal storm surge stillwater elevations exceed about 8 to 9 feet NAVD88. Currently, this is predicted to occur with a return period flood of 10-year to 20-years (i.e., 5% to 10% annual exceedance probability). Extensive flooding occurs when floodwaters rise to about Elevations 9 to 10 feet NAVD88, return period floods on the order of 20-year return period to 50-year return period. RSLC will increase the probability of flooding in the future. Section 3.0 summarizes predicted probabilities reflecting RSLC.

Figures 4-12 through 4-15 show conceptual representations of the predicted flooding associated with the 2016 100-year and 500-year return period floods, respectively.

The Rail Yard is vulnerable to flood damage due to both inundation of salt water, salt spray and the effects of wind and waves. Most coastal flood events will be accompanied by precipitation including snow (possibly heavy) during winter Nor'Easters and rain (during both tropical cyclones and Nor'Easters), as well as high wind.

Coastal flooding will create the following stressors on rail infrastructure, facilities, rolling stock, and equipment:

- Displacement of tracks, ties, and interlockings;
- Scour and erosion of the rail bed;
- Blockages, washouts, and failures of culverts, outfalls, and drainage pipes;
- Erosion and failure of embankments, retaining walls, and other engineered structures;
- Failure of electrical, mechanical, signal, and communication systems including electrical substations, transformers, switches, gates, and signals (with the additional long-term accelerated deterioration if the water is contaminated with salt or other corrosive elements);
- Inundation of rolling stock (locomotives and passenger cars), maintenance-of-way equipment, and parts and equipment in rail car storage and maintenance facilities;
- Inundation of passenger terminals, platforms, tunnel passages, and parking facilities;
- Increased risk of hazardous material spills (e.g., from fuel storage tanks located in the rail yard and other materials stored in maintenance facilities on-site); and
- Flood damages of buildings, building contents, vehicles and exterior landscaped and parking areas due to floodwaters, waves and salt corrosion.

These stressors can lead to the following direct impacts:

- Short-term service disruptions from flooding and associated direct impacts on users of the system (service will typically be shut down during a major storm regardless of localized flood conditions, but disruptions may continue after the storm if floodwaters do not subside quickly);
- Longer term service disruptions due to the need to repair or replace infrastructure, facilities, rolling stock, and equipment.

Short-term and long-term service disruptions, in turn, can result in the following indirect impacts:

- Disrupted transportation services cause user (i.e., passenger) economic losses if alternative routes and modes impose additional travel time and/or cost, or if they are unable to access jobs, colleges/universities, or workforce training at all during the disruption;
- Alternative temporary infill transportation requirements.

4.5 Roadways

Local and State roadways within the Long Wharf District are vulnerable to coastal flooding. The 500-year return period is an appropriate risk level for assessing infrastructure vulnerability. Figures 4-18, 4-19 and 4-20 show the roadway flood impacts for the 500-year return period (0.2% annual exceedance probability) flood for the years 2016, 2041 and 2116, respectively. The 500-year return period flood results in loss of the use of:

- I-95 along Long Wharf at two locations (central, low-lying area across from Church Street and the low-lying area around the Howard Street Bridge);
- The Long Wharf I-95 northbound on- and off-ramps;
- The Long Wharf I-95 northbound on- and off-ramps;
- Long Wharf Drive from Sargent Drive to Chapel Street;
- The Long Wharf Drive and Canal Dock Road I-95 underpasses;
- The Brewery Street underpasses;
- Local roads around City Point, the Sound School and Bayview Park including South Water Street, the east end of Sea Street, the south end of Howard Avenue and Hallock Avenue (including side roads);
- Local Roads within Area 2, including Long Wharf Drive (East Street) and Hamilton Street;
- Route 1 (Water Street) from Forbes Avenue to the rail tracks;
- Portions of Route 34 north of Area 3;
- Sargent Drive;
- Area 3 interior roads, including Church Street east of the bridge; and
- Union Avenue, West Water Street, Meadow Street, South Orange Street and several local roads in the vicinity of the New Haven Police Department and Public Housing buildings.

Effectively, access to I-95 is not available at either Long Wharf or I-91 northbound. I-95, along Long Wharf, is constructed on an elevated embankment. However, as discussed above, I-95 has several low points (at about Elevation 10 feet NAVD88) which are vulnerable to flooding. I-95 is the principal highway connecting New York City with much of New England, including the Connecticut coast, Rhode Island and the Boston Metro Area. I-95 carries about 149,000 vehicles per day.

The roadway flood impact extent is generally similar for the 100-year return period flood, but to less flood depth.

In addition to loss of use, roadways are vulnerable to coastal flood damage due to salt (corrosion), pavement damage, drainage structure failure and scour. Note that the recent I-95 improvements (such as use of robust concrete road barriers) may affect flood inundation across low-lying highway segments.

Figure 4-18: Flood Inundation of Area Roads during 2016 500-year Return Period Flood

Figure 4-19: Flood Inundation of Area Roads during 2041 500-year Return Period Flood

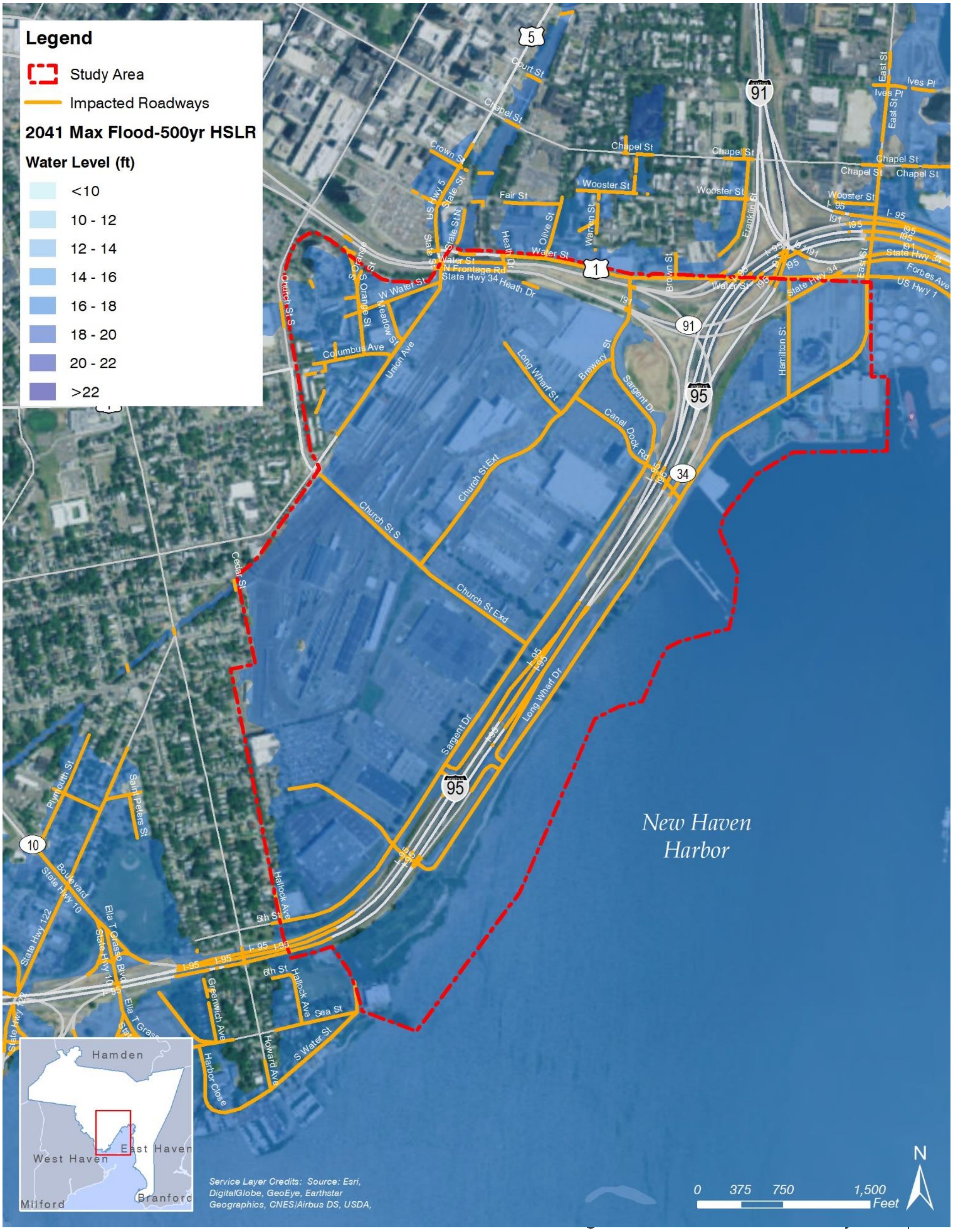
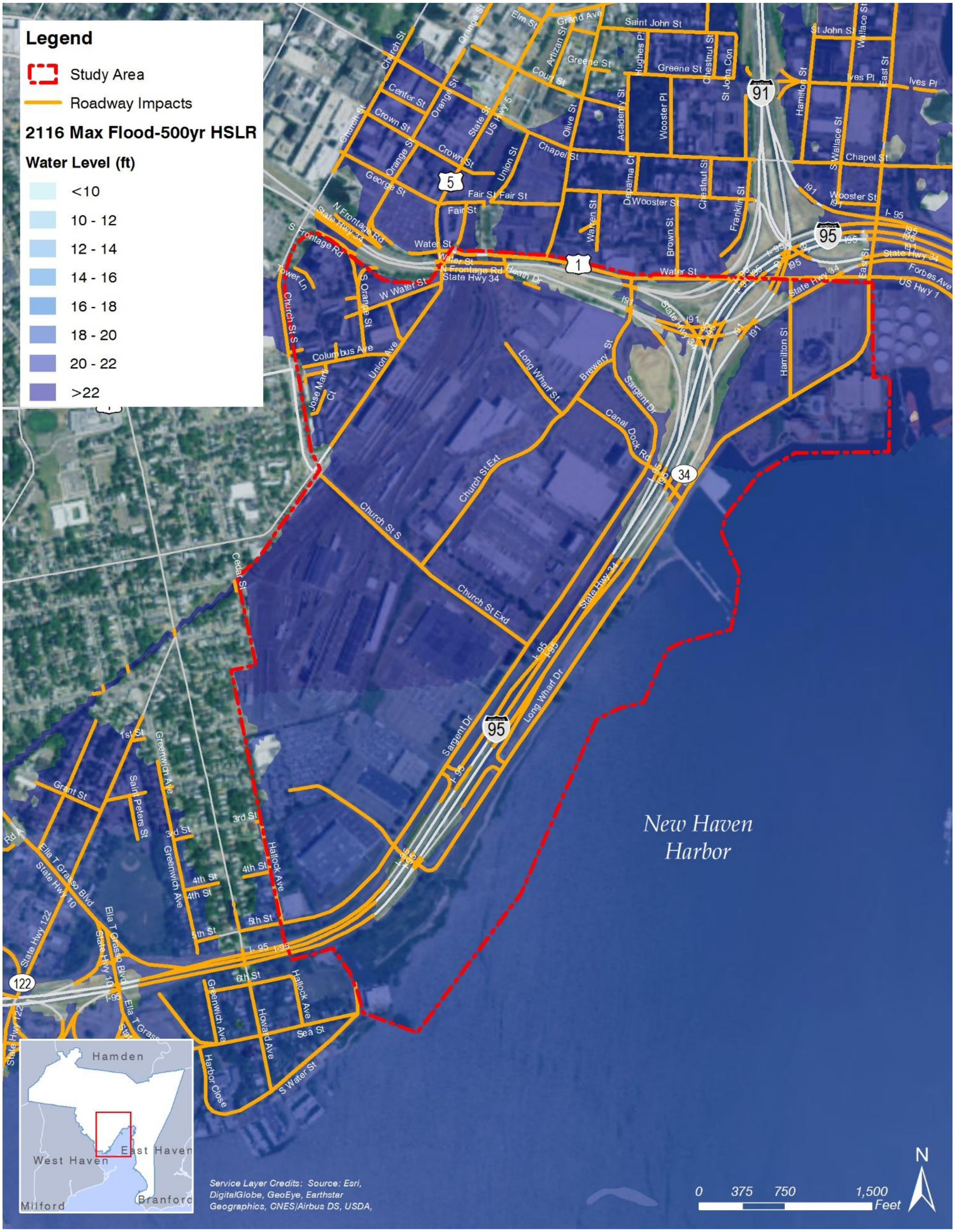


Figure 4-20: Flood Inundation of Area Roads during 2016 500-year Return Period Flood



4.6 Long Wharf District Building Flood Losses

As demonstrated during recent years by Hurricanes Irene and Sandy, the Long Wharf District is vulnerable to coastal flooding. The limits of flood inundation presented on the effective FEMA FIRMs as well as flood models performed by GZA demonstrate that much of the district is in a coastal high flood hazard zone. The effects of coastal flooding on property and business include direct costs due to loss of (or damage to) buildings, equipment, vehicles, building contents, etc. They also include indirect costs due to disruption of business and services (such as transportation, power, water, sewer, etc.).

A preliminary, approximate flood loss analysis was performed in order to get an "order-of-magnitude" idea of building flood loss exposure for the purpose of considering the benefit of flood mitigation alternatives and supporting decision-making. The analysis was performed: 1) using the results of GZA's flood modeling (which are consistent with the coastal flood hazard as determined by the USACE NACCS); and 2) using depth-damage relationships developed (and compiled) for specific building types and categories in the FEMA HAZUS-MH Loss Estimation software. The analysis estimates the Average Annualized Loss (AAL) as a base metric. The AAL is the expected loss per year if losses are averaged over many years.

The analysis has several limitations, including the following: 1) the analysis assumes that building first floor elevations are at the exterior site grades (i.e., some or all of the buildings may have an elevated first floor); 2) only building losses are estimated (i.e., losses of rail yard equipment, public infrastructure, utilities, roads, pump station equipment and natural and ecological features are not considered); 3) content value is evaluated as a percentage of building value (and is also assumed to be stored at exterior site grade levels); 4) vehicle loss (i.e., parked cars) is not included; 5) property valuation is based on available (2014 to 2015) assessor's data ($1.2 billion rail yard capital investments not reflected); 6) loss of service or productivity costs are not included; and 7) the City of New Haven Assessed Improvement Values are used.

There are a total of 86 parcels located within the Long Wharf District, including 56 structures and 30 unimproved lots. The total building Assessed Improvement Value (excluding contents) is $375 million, as shown in Table 4.1. Note that: 1) the Canal Dock Boat House (under construction) is not included; 2) value of the Long Wharf Pier and ancillary structures are not included; 3) an assessed value of about $170 million was used for the rail yard facilities (which may not fully reflect the recent capital improvements at risk); 4) an assessed value of about $11 million was carried for the Area 1 City of New Haven Sewage Facility; and 5) a value of <$1,000 was assumed (per the assessor's data) for the Area 2 City of New Haven Sewage Pump Station. Similarly, Table 4.2 presents an estimate of the content value exposure by project area. Table 4.3 summarizes the estimated AAL by area.

Table 4-1: Long Wharf District Building Improvement by Project Areas

PROJECT AREA	EXPOSURE ($1,000,000)	PERCENT OF TOTAL
AREA 1	$7	2%
AREA 2	$67	18%
AREA 3	$301	79%
TOTAL	**$375**	**100%**

Figure 4-21: Total Assessed Improvement Value by Parcel (in dollars)

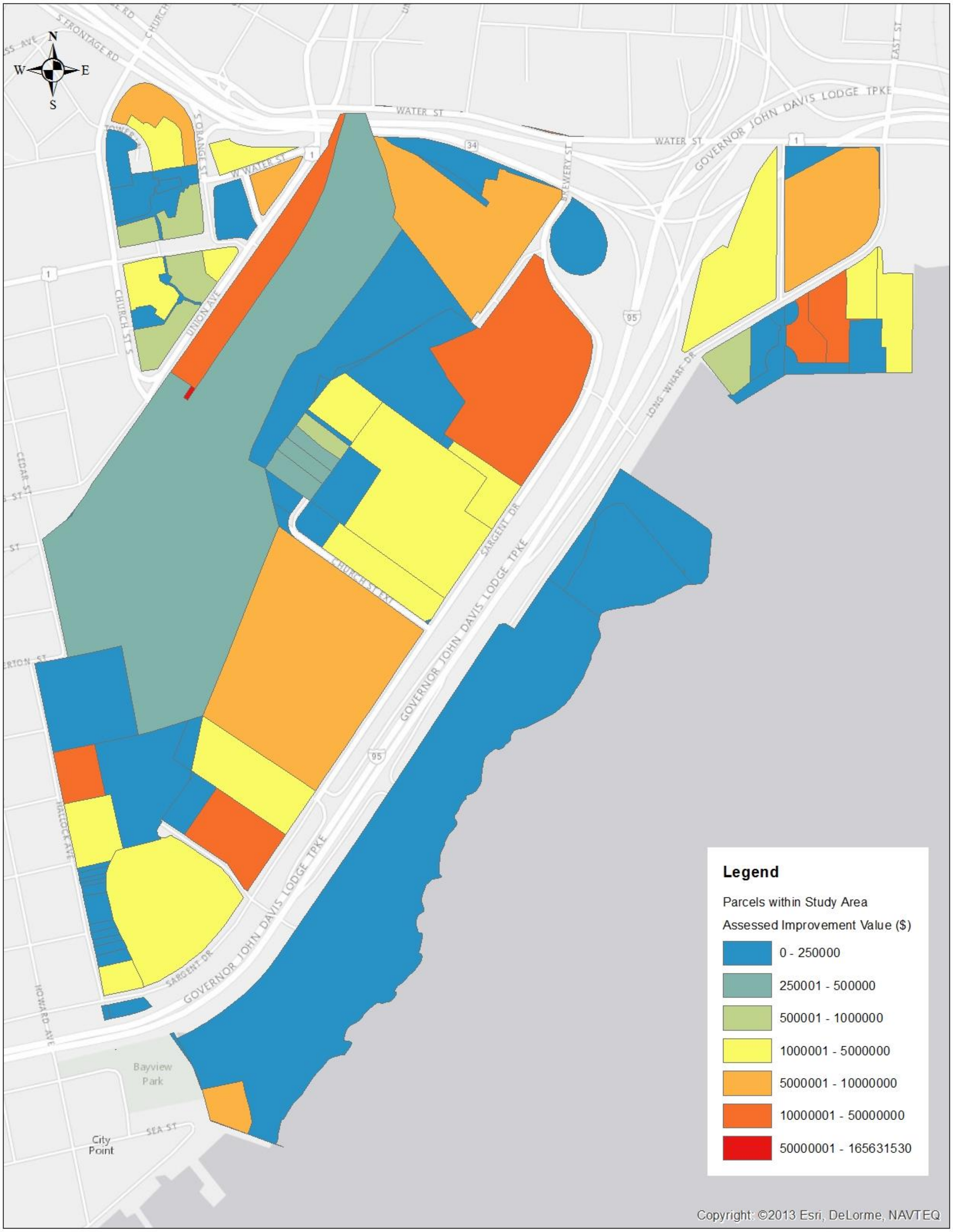


Table 4-2: Long Wharf District Content Value by Project Areas

PROJECT AREA	EXPOSURE ($1,000,000)	PERCENT OF TOTAL
AREA 1	$3.6	2%
AREA 2	$33.8	18%
AREA 3	$150.6	80%
TOTAL	**$188.1**	**100%**

Table 4-3: Averaged Annualized Structure and Content Losses by Area ($1,000)

PROJECT AREA	TOTAL STRUCTURAL LOSS	TOTAL CONTENT LOSS	TOTAL LOSS	PERCENT OF TOTAL
AREA 1	$50.0	$44.1	**$94.0**	4%
AREA 2	$404.0	$111.8	**$516.0**	20%
AREA 3	$1,259.0	$671.7	**$1,931.0**	76%
TOTAL	**$1,713.0**	**$827.6**	**$2,541.0**	**100%**

Table 4.3 summarizes the estimated AAL (based on current sea level and mean USACE NACCS flood elevations). The estimated building flood AAL for the Long Wharf District was $1,713,000[3]. This represents 1.2% of the building flood $141,000,000 AAL predicted for New Haven County by FEMA (FEMA's HAZUS Average Annualized Loss Viewer).

The distribution of estimated flood loss by area is generally similar to the exposure. Assuming a 50-year planning life cycle (and, for simplification, ignoring both sea level rise and the future value of money), the predicted 50-year building loss (based on an AAL of $2,541,000), is on the order of $127 million.

It is noted that financial loss associated with utility, roadway, sewerage treatment facilities and the railyard represent significant loss exposure as do indirect and consequential costs:

- No consequential or indirect costs have been considered.
- The assessed improvement value for the rail yard facility may significantly underestimate the loss exposure for the railyard facilities.[4]
- In addition to direct damage, disruption of rail service would result in significant losses in revenue and cost to consumers.[5]
- Failure of the sanitary sewer main (e.g., due to storm-related scour) could result in significant direct damage, disruption of service and environmental losses.
- Failure of the sanitary sewage pump stations could result in significant direct damage, disruption of service and environmental losses.

[3] For reference, the National Disaster Resilience Competition State of Connecticut Phase II Application Benefit-Cost Analysis (Attachment F) estimated reduction of Long Wharf property costs of $1.2 million (annual undiscounted value).
[4] For example, the National Disaster Resilience Competition State of Connecticut Phase II Application Benefit-Cost Analysis (Attachment F) estimated a $3.3 million in rail fleet replacement (annual undiscounted value), assuming loss of all stored rail cars.
[5] For example, the National Disaster Resilience Competition State of Connecticut Phase II Application Benefit-Cost Analysis (Attachment F) estimated a $7 thousand revenue loss (annual undiscounted value).

Therefore, the predicted building AAL of $2,541,000 may represent a lower bound of total Long Wharf District flood loss.

4.7 Long Wharf District Non-Building Flood Losses

As discussed above, there may be significant additional non-building flood loss direct costs:

Loss of land along Long Wharf Shoreline:

The land areas south of Long Wharf Pier encompasses about 45 acres (not included tidal flats). This land, including beach, wetlands and grass area would be significantly (assume about 30%) lost to erosion and sea level rise over the next 50 years. Assuming a land value of about $100,000 per acre, predicted land use cost is about $1,350,000.

Damage to existing revetment:

There is about 1,800 of existing, semi-intact to intact quarry stone revetment. Assuming: 1) a current value of the existing revetment of about $2,000,000; 2) about 10% damage during a 25-year return period flood; 50% damage during a 50-year return period flood; about 75% damage during a 100-year flood; and about 100% damage during a 500-year return period flood; 3) replacing in kind (i.e., replacing with the same stone size), the AAL is about $69,300 and the 50-year loss is about $3,465,000.

Damage to Long Wharf Pier:

The existing jetty appears to be robustly constructed. The jetty is about 650 feet long with a top concrete deck of about 10 feet width and wood railing. The end of the pier includes about 500 linear feet of timber floating docks, a timber pier and the small wood frame Amistad building. Assuming: 1) a replacement value of the decking, rails, wood pier, docks and building of about $1,000,000; 2) about 10% damage during a 25-year return period flood; 50% damage during a 50-year return period flood; about 75% damage during a 100-year flood; and about 100% damage during a 500-year return period flood; 3) replacing in kind (i.e., replacing with the same stone size), the AAL is about $23,300 and the 50-year loss is about $1,150,000. This loss is not included in benefit-cost evaluation of flood protection alternatives since none of the alternatives will affect Long Wharf Pier.

Damage to underground utilities:

The key utility relative to flood loss is the sanitary sewage main. This utility is vulnerable to scour-related damage due to its proximity to the shoreline, its high flow volume and its shallow buried depth. The length of the pipe adjacent to the shoreline is about 5,750 linear feet. About 60% of this length appear vulnerable to scour. Assuming: 1) a current replacement value of the pipe of about $4,600,000; 2) about <1% damage during a 25-year return period flood; 5% damage during a 50-year return period flood; about 50% damage during a 100-year flood; and about 90% damage during a 500-year return period flood; and 3) replacing in kind, the AAL is about $50,600 and the 50-year loss is about $2,530,000.

This cost, however, does not include costs related to: 1) loss of service; and 2) environmental damage due to an uncontrolled release of sewage. For purposes of the benefit-cost evaluation, an AAL of about $100,000 and a 50-year loss of $5,000,000 is assumed for loss of service, environmental release and environmental penalties.

Additional underground utilities include: 12-inch DIP water line; electric line; telephone; cable; and fiber optic. An approximate $1,000,000 replacement cost is assumed along with similar percent damage as the sanitary sewer. The AAL is about $11,000 and the 50-year loss is about $550,000.

Damage to roadways:

Most roadways within predicted flood areas will not experience significant wave effects and therefore, severe damage is not expected even due to low probability flood events. The exception is Long Wharf Drive adjacent to the shoreline, which could experience scour and erosion-related damage. The length of vulnerable roadway is about 4,700 linear feet. The width is about 50 feet. Assuming: 1) roadway repair costs of about $15 per square foot; 2) about <1% damage during a 25-year return period flood; 10% damage during a 50-year return period flood; about 30% damage during a 100-year flood; and about 60% damage during a 500-year return period flood; 3) replacing in kind (i.e., replacing with the same stone size), the AAL is about $27,700 and the 50-year loss is about $1,390,000.

Table 4-4 presents the estimated additional non-building losses and total AAL for Area 1. Table 4-5 presents the estimated total AAL for Areas 1, 2 and 3.

Table 4-4: Averaged Annualized Non-Building Loss for Area ($1,000)

PROJECT AREA	TOTAL LOSS	PERCENT OF TOTAL
AREA 1	$247.6	-
TOTAL AREA 1	$341.6	12%

Table 4-5: Total Averaged Annualized Building and Non-Building Loss for Area ($1,000)

PROJECT AREA	TOTAL STRUCTURAL LOSS	TOTAL CONTENT LOSS	TOTAL LOSS	PERCENT OF TOTAL
AREA 1	$297.60	$44.1	**$341.6**	12%
AREA 2	$404.0	$111.8	**$516.0**	18.5%
AREA 3	$1,259.0	$671.7	**$1,931.0**	69.5%
TOTAL	**$2,414.6**	**$827.6**	**$2,788.0**	**100%**

Due to its highly approximate nature, the "absolute" values presented above should not be relied upon. However, although highly approximate, this preliminary loss evaluation provides insight into the flood risk and benefits of flood loss mitigation:

- Although approximate, Tables 4.1 and 4.2 and Figure 4-21 indicate that the majority of the building structure and content flood loss exposure (80%) is located within Area 3 and about 20% of the building loss exposure is located within Area 2.
- Area 1 has significant land and infrastructure loss potential (Table 4.4).
- Construction and implementation of flood mitigation measures will provide significant reduction in flood loss.
- The amount of flood loss reduction is dependent upon the percentage of area protected. For example, flood protection of only Area 3 would leave about 30% residual flood risk (about $43 million over a 50-year planning life cycle) within the Long Wharf District, including roadway and infrastructure risk.
- Flood loss reduction is also dependent upon the vertical elevation of provided flood protection. Considering two scenarios:
    1. Flood protection provided to about Elevation 13 feet NAVD88 currently reduces the predicted Long Wharf District building flood loss by about 40%.
    2. Flood protection provided to about Elevation 16 feet NAVD88 currently reduces the predicted Long Wharf District building flood loss by about 90%.

- Sea level rise will reduce the amount of flood protection provided by flood mitigation measures. Considering the first scenario presented above:
    1. Flood protection provided to about Elevation 13 feet NAVD88 reduces the predicted Long Wharf District building flood loss from about 40% (today) to about 20% (50 years from now). However, it is expected that flood protection provided to Elevation 16 feet NAVD88 will be less sensitive to the effects of sea level rise.

4.8 Flood Vulnerability Summary

The Long Wharf Flood District is vulnerable to coastal flooding. Connecticut's economic losses associated with Hurricane Sandy were estimated to be about $1 billion. The coastal communities, including those in New Haven County, experienced most of Connecticut's losses. The flood elevations experienced during Hurricane Sandy have an annual exceedance probability between 2% and 5% (20-year to 50-year return period), a relatively high probability of occurrence. The Connecticut experience during Hurricane Sandy had several components that are relevant to Long Wharf. Most major roads and train lines were cancelled. At Sandy's peak, 630,000 customers lost electricity. To mitigate potential releases, sewage treatment plants were briefly shut down. As significant as these events were, Hurricane Sandy was a significantly less impactful flood event than those benchmark flood events predicted here (the 100-year and 500-year return period floods).

The Long Wharf District contains critical transportation infrastructure, including State highways (representing major north-south transportation routes) and Union Station and the Northeast Corridor mainline tracks. All of these have been determined to be vulnerable to coastal flooding. The Long Wharf District also contains numerous commercial, industrial and City assets, all of which have been determined to be vulnerable to coastal flooding. City utilities, in particular the sanitary sewage main pipeline and pump stations along Long Wharf, have been determined to be vulnerable to coastal flooding due to flood inundation, wave effects and erosion of shoreline.

A preliminary evaluation of flood losses was performed to develop an "order-of-magnitude" estimate of building flood loss exposure for consideration of the benefit of different flood mitigation alternatives and supporting decision-making. The Long Wharf District building flood losses, over a 50-year planning life cycle were predicted to be about $140 million. The benefits (i.e., prevented flood losses) of flood mitigation measures (alternatives presented in Section 5) are expected to exceed the cost of these measures by an acceptable margin.

Section 5.0 Flood Protection Strategies and Alternatives

New Haven Long Wharf Flood Protection Study

Historic Photograph of the Hurricane of 1938, from photobucket, uploaded by blackstonelib

5.0 FLOOD PROTECTION STRATEGIES AND ALTERNATIVES

As presented in Section 4.0, the Long Wharf area is highly vulnerable to coastal flooding. Section 5.0 presents and discusses flood mitigation strategies and alternatives to reduce flood risk.

Three flood resiliency strategies are commonly used in coastal environments: Retreat, Protect and Accommodate.

Retreat: Managed withdrawal from coastal areas, most often accompanied by adaptive land use and managed relocation.

Protect: A range of interventions designed to hold back flood waters to prevent flooding of developed areas and prevent erosion and loss of land.

Accommodate: Allowing flooding to occur, but protecting infrastructure, property, and natural resources from damage through permanent and interim measures implemented on an on-going basis.

A strategy of Retreat is unlikely to be acceptable in consideration of the degree of development of the Long Wharf District, including: 1) recent improvements by ConnDOT and IKEA; and 2) additional investment into the New Haven Rail Yard (implying that the facility will be present and operable for a long time into the future).

A strategy of Accommodate is already being implemented by property owners and managers within the Long Wharf District, primarily through risk management programs and compliance with existing local, State, and federal regulations.
The responsibility for, and costs of, an Accommodation strategy are borne by: 1) private property owners (e.g., through the implementation and cost of compliance with NFIP and building code regulations and post-storm repair); 2) the City of New Haven (e.g., repair and reconstruction of infrastructure and public resources); and 3) the State for the rail yard and state roads (e.g., I-95).
The costs of an Accommodation strategy will increase with sea level rise and the associated increase in the frequency and level of flooding.

A Protect strategy, such as a flood wall, is generally implemented on a large scale (e.g., by a municipality or the State) and requires significant capital investment for infrastructure, private property acquisition and/or purchase of land easements.
A Protect strategy would also require operational responsibility and long-term maintenance.
Although not accredited by FEMA as a levee, I-95, constructed as a large embankment, already provides some degree of flood protection and presents an opportunity for employing both a Protect and Accommodate strategy.

5.1 Flood Protection Alternatives

Four flood mitigation alternatives were identified, ranging in scale, strategy, implementation responsibility and cost. As discussed below, the four alternatives are not mutually exclusive and may be integrated and phased based on available funding, etc. The alternatives include:

- Alternative 1: Property-Scale Flood Protection
- Alternative 2: Municipal-Scale Temporary, Deployable Flood Protection Measures
- Alternative 3: Municipal-Scale Permanent, Deployable Flood Protection Measures
- Alternative 4: Municipal-Scale Permanent Flood and Shoreline Protection Measures

The following describes each of these alternatives. Attachment 3 provides additional detail on Alternatives 2 and 3.

Alternative 1 – Property-Scale Flood Protection

Strategy: Accommodate

Approach: This alternative involves two separate types of measures: 1) permanent flood protection (e.g., dry floodproofing) measures performed in compliance with local, State and federal building regulations; and 2) localized (building scale), deployable temporary flood protection performed for risk management and loss prevention purposes. The responsibility for this alternative is primarily that of the property owners and managers and, generally, represents the current approach to flood protection strategy in the Long Wharf District. For example, outreach meetings with Area 3 property owners and managers indicated that several were already implementing flood protection measures.

Under this approach, permanent flood protection (an approximately 5,700 linear foot long flood wall) around the railyard and ConnDOT buildings could be constructed to provide protection of the railyard facilities and would provide a cost-effective protection of these facilities.

Area Protected: Since this alternative is the responsibility of individual property owners, it can provide protection for all building property located within the Long Wharf District (excluding exterior parked vehicles). This alternative does not provide shoreline protection from erosion and scour. It does not provide flood protection for roadways or infrastructure.

Level of Protection: Not limited.

Details:

Under this approach, flood protection is provided at the individual property level. Flooding of the surrounding area, including parking areas, open spaces, roadways, etc. and along the Long Wharf shoreline will still occur. Implementation of this alternative will not result in modification of the effective FEMA Flood Insurance Rate Map (FIRM). Implementation of these measures will, however, reduce the flood risk of the individual properties as well as the cost of both National Flood Insurance and private flood insurance. The costs for implementation of this alternative are typically borne by the property owners; however, low-interest loan programs may be available to cover some of these costs. The implementation of this alternative is also typically by the property owner; however, given the close proximity of the properties it may be desirable for property owners to share resources for use of deployable temporary measures (e.g., storage facilities, subcontractors, etc.).

The elements of this flood protection approach include both:

- Regulatory Compliance Measures:
  - Elevation of buildings, structures and infrastructure; and
  - Flood-proofing of buildings and structures.
- Supplemental Risk Management Measures:
  - Use of deployable, temporary flood protection;
  - Storage and maintenance of temporary measures;
  - Emergency response plans;
  - Permanent flood wall around railyard facilities; and
  - Training and implementation.

New Haven structures are subject to compliance with local, state and federal flood regulations including building codes, zoning and other statutes. The regulatory compliance triggers for structures located within FEMA flood hazard zones include: 1) new construction; 2) substantial improvement; and 3) substantial damage. The occurrence of any of these events will require bringing buildings into compliance with regulation.

The 2016 Connecticut State Building Code includes the 2012 International Building Code and the State Building Code Connecticut Supplement and Amendments. The State Building Code also incorporates by reference ASCE 7 (Minimum Design Loads for Buildings and Other Structures) and ASCE 24 (Flood Resistant Design and Construction), which contain most of the requirements related to flood regulations. The Connecticut State Building Codes support and are consistent with the federal NFIP regulations (44CFR Parts 59 and 60). The City of New Haven also has a Flood Damage Prevention Ordinance and is the controlling flood regulation.
The Connecticut State Building Code is scheduled to be updated in 2018. This update will include significant changes to the flood regulations through incorporation of the 2015 International Residential Code (2015 IRC) and the 2015 International Building Code (2015 IBC), including ASCE 24-14 (including adoption of Coastal AE zones).

In accordance with the City of New Haven Flood Damage Prevention Ordinance, the basis for establishing special flood hazards is the FEMA Flood Insurance Study for New Haven County, Connecticut, dated July 8, 2013 and the accompanying Flood Insurance Rate Maps dated July 8, 2013 and others supporting data adopted by reference and declared to be part of the ordinance. The minimum current elevation requirements for structures located within FEMA special flood hazard zones are summarized below. The effective FEMA Base Flood Elevations (BFE) are shown on Figure 3-11 and range from Elevation 11 to 13 feet NAVD88 (VE=16 feet NAVD88 at Area 2).

Table 5-1: Design and Construction Requirements in Flood Hazard Areas

NON-RESIDENTIAL CONSTRUCTION	SPECIAL FLOOD HAZARD AREA (SFHA)	ELEVATION REQUIREMENT
MINIMUM ELEVATION OF LOWEST FLOOR (INCLUDING BASEMENT) OR LEVEL OF DRY FLOODPROOFING	Zone AE	BFE +1 foot
NEW CONSTRUCTION AND SUBSTANTIAL IMPROVEMENT	Coastal High Hazard Areas (Zone VE)	Locate 25 feet landward of the Connecticut Coastal Jurisdiction Line
MINIMUM ELEVATION OF BOTTOM OF LOWEST HORIZONTAL STRUCTURAL MEMBER	Coastal High Hazard Areas (Zone VE)	BFE + 1 feet

<u>AE Zone Standards</u>

New construction and substantial improvement of any commercial, industrial or other nonresidential structure shall have either the lowest floor, including basement, elevated to at least the FEMA Base Flood Elevation (BFE) plus 1 foot or, together with attendant utility and sanitary facilities, shall:

- Be flood proofed to the BFE plus 1 foot so the structure is watertight with walls substantially impermeable to the passage of water.
- Have structural components capable of resisting hydrostatic and hydrodynamic loads and the effects of buoyancy.
- Electrical, plumbing, machinery or other utility equipment that services the structure must be elevated to or

above the BFE and cannot be located below the structure.

- Be certified by a registered professional engineer or architect that the standards of this subsection are satisfied.

Coastal High-Hazard area (VE Zones) Standards

Within VE Zones, new construction and substantial improvement shall be located 25 feet landward from the Connecticut Coastal Jurisdiction Line. The minimum elevation of the bottom of the lowest horizontal structural member shall be at the BFE plus 1 foot, with free passage of floodwaters underneath.

Building Permanent Flood Protection Walls

Permanent flood protection walls constructed to protect individual structures will provide flood risk reduction; however, these will not achieve compliance with local, State and federal flood regulations.

Deployable Flood Protection Measures

Deployable flood protection measures (e.g., flood gates, temporary flood barriers) used to protect buildings will provide flood risk reduction; however, these will not achieve compliance with local, State and federal flood regulations. (The exception is when used as part of dry flood proofing in compliance with dry flood proofing regulations.)

Alternative 2 – Municipal-Scale Temporary, Deployable Flood Protection

Strategy: Accommodate

Approach: This alternative relies upon the use of I-95 and I-91 as a flood protection embankment/levee[1] and utilizes temporary deployable measures to prevent flooding through the highway underpasses. This alternative also requires construction of permanent earthen berms or flood walls along low-lying areas of I-95.
This alternative also includes installation (where not already present) of backflow preventers for stormwater outfalls located along New Haven Harbor, to prevent flood infiltration via the stormwater infrastructure.
This alternative requires the designation of responsibility (e.g., the City of New Haven) for purchasing, maintaining and implementing the temporary flood protection measures. This alternative also requires a permanent storage facility.

Area Protected: This alternative provides flood protection for Area 3 and I-95. It does not provide flood protection for Areas 1 and 2. This alternative does not provide shoreline protection from erosion and scour.
It does not provide flood protection for roadways or infrastructure located within Areas 1 and 2.

Level of Protection: System dependent. See Attachment 4.

Details: As demonstrated in Sections 3.0 and 4.0, Area 3 floods via the I-95 underpasses located at Canal Dock Road and Long Wharf Drive and the Route 34 underpass at Brewery Street. Floodwaters also propagate: 1) across the central, low-lying portion of I-95: 2) at the I-95 northbound on and off ramps; and 3) at the I-95 northbound lane by the New Haven Sewage Pollution facility.

This alternative involves providing temporary deployable flood protection measures at the underpasses. There are a number of temporary, deployable flood mitigation products that are suitable for this application, in particular aluminum stop logs and inflatable bladders. Details for these products are presented in Attachment 3. Details of the highway underpasses are also presented in Attachment 3.

When floodwaters exceed about 10 feet NAVD88, additional flood protection will be required to protect the central, low-lying portion of I-95 and at I-95 northbound lane on and off ramps. When floodwaters exceed about

[1] While not an accredited levee, the effective FEMA FIRM acknowledges the topography of the I-95 embankment, and assumes that it remains during flooding, in the characterization of the flood hazard zones.

13 to 14 feet NAVD88, additional flood protection will be required at the I-95 northbound lane by the New Haven Sewage Pollution facility. Temporary flood protection measures, such as aluminum stop logs and inflatable bladders are suitable for the I-95 northbound lane on and off ramps; however, these will require closure of the ramps. Permanent flood protection measures (such as an earthen flood berm or flood wall) are recommended at the central, low-lying portion of I-95 and along the I-95 northbound lane by the New Haven Sewage Pollution facility. This alternative does not address management of precipitation or surcharging of the existing stormwater infrastructure, including catch basins along I-95. Additional flood protection measures will be require to address stormwater (from precipitation) and backflow via the stormwater piping (where tide gates or shut-off valves are not already used).

Figure 5-1 illustrates the Alternative 2 concept. Approximate dimensions of the permanent flood protection at these locations include the following:

Central portion of I-95:

- 100-year return period:
  - Length: +/- 400 feet
  - Height: 5 feet (assuming a protection level at Elevation 14 feet NAVD88)
- 500-year return period:
  - Length: +/- 1,100 feet
  - Height: 5.5 to 6.5 feet (assuming a protection level at Elevation 16 feet NAVD88)

Along the I-95 northbound lane by the New Haven Sewage Pollution facility:

- 100-year return period: Not required
- 500-year return period:
  - Length: +/- 400 feet
  - Height: 3 feet (assuming a protection level at Elevation 16 feet NAVD88)

Alternative 3 – Municipal-Scale Permanent, Deployable Flood Protection

Strategy: Protect

Approach: This alternative is similar to Alternative 2 but utilizes permanent deployable flood protection measures at the highway underpasses. Alternative 3 relies upon the use of I-95 and I-91 as a flood protection levee and utilizes temporary deployable measures to prevent flooding through the highway underpasses. This alternative also requires construction of permanent earthen berms or flood walls along low-lying areas of I-95. This alternative also includes installation (where not already present) of backflow preventers for stormwater outfalls located along New Haven Harbor, to prevent flood infiltration via the stormwater infrastructure. This alternative requires the designation of responsibility (e.g., the City of New Haven) for purchasing, maintaining and implementing the temporary flood protection measures.

Area Protected: This alternative provides flood protection for Area 3 and I-95. It does not provide flood protection for Areas 1 and 2. This alternative does not provide shoreline protection from erosion and scour. It does not provide flood protection for roadways or infrastructure located within Areas 1 and 2.

Level of Protection: System dependent. See Attachment 4.

Details: As demonstrated in Sections 3.0 and 4.0, Area 3 floods via the I-95 underpasses located at Canal Dock Road and Long Wharf Drive and the Route 34 underpass at Brewery Street. Floodwaters also propagate: 1) across the central, low-lying portion of I-95: 2) at the I-95 northbound on and off ramps; and 3) at the I-95 northbound lane by the New Haven Sewage Pollution facility.

This alternative involves providing permanent deployable flood protection measures at the underpasses. There are a number of permanent, deployable flood mitigation products that are suitable for this application; however, the purchase, construction and maintenance costs of this alternative are high. Construction will require significant modification of the roadway and highway abutments. Details for these products are presented in Attachment 3. Details of the highway underpasses are also presented in Attachment 3.

When floodwaters exceed about 10 feet NAVD88, additional flood protection will be required to protect the central, low-lying portion of I-95 and at I-95 northbound lane on and off ramps. When floodwaters exceed about 13 to 14 feet NAVD88, additional flood protection will be required at the I-95 northbound lane by the New Haven Sewage Pollution facility. Temporary flood protection measures, such as aluminum stop logs and inflatable bladders are suitable for the I-95 northbound lane on and off ramps; however, these will require closure of the ramps. Permanent flood protection measures (such as an earthen flood berm or flood wall) are recommended at the central, low-lying portion of I-95 and along the I-95 northbound lane by the New Haven Sewage Pollution facility. Figure 5-1 illustrates the Alternative 2 concept. Approximate dimensions of the permanent flood protection at these locations include the following:

Central portion of I-95:

- 100-year return period:
  - Length: +/- 400 feet
  - Height: 5 feet (assuming a protection level at Elevation 14 feet NAVD88)
- 500-year return period:
  - Length: +/- 1,100 feet
  - Height: 5.5 to 6.5 feet (assuming a protection level at Elevation 16 feet NAVD88)

Along the I-95 northbound lane by the New Haven Sewage Pollution facility:

- 100-year return period: Not required
- 500-year return period:
  - Length: +/- 400 feet
  - Height: 3 feet (assuming a protection level at Elevation 16 feet NAVD88)

Alternative 4 – Municipal-Scale Permanent Flood and Shoreline Protection Measures

Strategy: Accommodate and Protect

Approach: This alternative provides a completely different approach than the previous three alternatives. Alternative 4 includes a combination of: 1) a Living Shoreline to enhance both the recreational and environmental values of the Long Wharf shoreline and to support the survivability of the shoreline in response to sea level rise; 2) shoreline protection to prevent erosion and provide protection of existing structures and utilities; 3) a flood wall, located approximately parallel to Long Wharf Drive, to provide flood protection; and 4) ancillary features such as a timber boardwalk. This alternative provides flood protection, shoreline protection and added recreational, environmental and economic benefits.

Area Protected: This alternative can provide flood protection for Areas 1, 2 and 3 and I-95, depending upon the height and extent of the flood wall. Flood protection of Area 3 will also require enhancement of the existing shoreline structures to provide additional flood protection around the perimeter of Area 2, which will connect to the flood wall in Area 1.

Level of Protection: Dependent upon height of floodwall.

Details: Details of Alternative 4 are presented in Section 6.0. Figure 5-2 presents the Alternative 4 concept.

5.2 Comparison of Flood Protection Alternatives

Each of the four alternatives provide a different approach to flood protection and represent different purchase, installation, maintenance and operations costs. Alternatives 1 through 3 provide only flood protection. Alternative 4 provides flood protection, but also provides shore protection and recreational, environmental and economic benefits. The following highlights the differences between the alternatives.

A preliminary "order of "magnitude" cost estimate was performed to compare the alternatives. Table 5-2 presents a summary.

Cost: Alternative 2 will be the lowest cost alternative, by a significant margin. Alternative 1 costs are borne by the property owner. Permanent building modifications are generally absorbed into the cost of construction (for new construction and substantial improvement). Alternative 1 will be the second lowest cost with the exception of the protection of the railyard facilities. One alternative for protecting the railyard facilities is the construction of a +/-5,700 linear foot permanent flood wall of approximately 5.5 feet in height (including modification of stormwater infrastructure). Including the railyard flood protection, costs for Alternative 1 are expected to be similar to Alternatives 3 and 4 (assuming temporary measures are utilized for 56 structures at $200,000 per structure. Alternative 4 presents the highest cost, but also provides the most flood protection.

FEMA Accreditation for Flood Insurance Rate Map (FIRM) Modification: In order to modify the FEMA FIRM, the flood protection would have to be an accredited levee. Alternatives 1 and 2 do not qualify. Alternative 3 has the potential to qualify as an accredited levee. However, certification of the I-95 embankment would be required. Also required is identification of maintenance, management and implementation responsibility. Alternative 4(Low Wall) will not qualify as an accredited levee. The minimum levee height is the FEMA BFE plus 3 feet of freeboard (currently Elevation 16 feet NAVD88). Alternative 4 (High Wall) may qualify as an accredited levee, with a top of wall at Elevation 16 feet NAVD88.

Table 5-2 presents a preliminary estimate of benefit-cost ratios and residual risk for the four alternatives. Alternative 4 (High Wall) has the highest benefit-cost ratio and the lowest amount of residual risk. It also has the added natural resource, recreational and economic benefit that the Alternatives 1, 2 and 3 do not have.

Alternative 2 is estimated to have the next highest benefit-cost ratio but has a significant amount of residual risk as it only protects Area 3.

Alternative 4 (Low Wall) has an acceptable benefit-cost ratio; however, the flood protection value of this alternative diminishes with sea level rise. It also has the added natural resource, recreational and economic benefit that Alternatives 1, 2 and 3 do not have.

5.3 Conclusions

In consideration of cost and complexity, a phased approach to flood protection may be an acceptable approach. Alternative 2 can be readily implemented at the lowest cost of the alternatives. However, this option leaves significant residual risk. Some of the risk can be reduced by constructing the shoreline protection features presented in Alternative 4. Another phasing alternative is construct the Alternative 4 low wall to accommodate raising the wall or construction of additional flood protection in the future dependent upon actual sea level rise.

Figure 5-1: Alternatives 2 and 3 Flood Mitigation Concept

Figure 5-2: Alternative 4 Flood Mitigation Concept

ID	Alternative Description	Property Protected	Construction Items	Unit Cost		# of Units		Cost per Item	Alternative Total Cost	AAL Protected	AAL Reduction Ratio	50-yr Benefit	Residual Risk	B/C Ratio
1	**Property Scale**	Areas 2 & 3	Commercial/Industrial	$500,000	each	46	buildings	$ 23,000,000	$ 35,450,000	$ 1,922,500	80%	$ 97,880,000	$ 24,470,000	**1.6**
			Residential	$150,000	each	7	buildings	$ 1,050,000						
		Railyard PennCtr & ConnDOT	varies	$ 2,000	per LF	5700	feet	$ 11,400,000		$ 524,500	80%			
			stormwater system	$ -	per system	1	--	$ -						
2	**Municipal Scale, Temporary**	Area 3 & I-95	berm at 16'	$ 2,000	per LF	1350	feet	$ 2,700,000	$ 3,966,250	$ 1,931,000	90%	$ 86,895,000	$ 42,850,000	**1.9**
			stormwater	$ -	per outfall	8	outfalls	$ -						
			deployable system purchase	$ 750	per LF	355	feet	$ 266,250						
			temp deployment	$ 10,000	per labor day	30	days over 50-yr period	$ 300,000						
			storage building	$ 200,000	each	1	each	$ 200,000						
			storage & maintanance	$ 10,000	labor cost per year	50	years	$ 500,000						
3	**Municipal Scale, Permanent**	Area 3 & I-95	berm at 16'	$ 2,000	per LF	1350	feet	$ 2,700,000	$ 18,510,000	$ 1,931,000	90%	$ 86,895,000	$ 42,850,000	**1.4**
			stormwater	$ -	per outfall	8	outfalls	$ -						
			permanent system purchase	$ 6,000	per LF	355	feet	$ 2,130,000						
			permanent system installation	$ 1,500	per labor day	120	days	$ 180,000						
			Abutment and Roadway Modification	$ 2,000,000	each	3	each	$ 6,000,000						
			maintanance	$ 150,000	labor cost per year	50	years	$ 7,500,000						
4	**Municipal Scale, Permanent, Shoreline Protection**													
	4a	Areas 1, 2 & 3 and I-95	I-wall at 13'	$ 2,250	per LF	8000	feet	$ 18,000,000	$ 40,625,000	$ 2,788,000	70%	$ 97,580,000	$ 41,820,000	**1.2**
			riprap	$ 3,000	per LF	2500	feet	$ 7,500,000						
		Low wall w No SLR	boardwalk	$ 500	per LF	3450	feet	$ 1,725,000						
			wetland sill	$ 3,000	per LF	3650	feet	$ 10,950,000						
			sand dune	$ 500	per LF	3000	feet	$ 1,500,000						
			wetland restoration	$ 20,000	per acre	10	acres	$ 200,000						
			yearly maintenance	$ 15,000	per year	50	years	$ 750,000						
	4b	Areas 1, 2 & 3 and I-95	I-wall at 13'	$ 2,250	per LF	8000	feet	$ 18,000,000	$ 40,625,000	$ 2,788,000	50%	$ 69,700,000	$ 69,700,000	**0.6**
			riprap	$ 3,000	per LF	2500	feet	$ 7,500,000						
		Low wall w SLR	boardwalk	$ 500	per LF	3450	feet	$ 1,725,000						
			wetland sill	$ 3,000	per LF	3650	feet	$ 10,950,000						
			sand dune	$ 500	per LF	3000	feet	$ 1,500,000						
			wetland restoration	$ 20,000	per acre	10	acres	$ 200,000						
			yearly maintenance	$ 15,000	per year	50	years	$ 750,000						
	4c	Areas 1, 2 & 3 and I-95	I-wall at 16'	$ 3,000	per LF	8000	feet	$ 24,000,000	$ 49,990,000	$ 2,788,000	90%	$ 125,460,000	$ 13,940,000	**2.0**
			riprap	$ 3,750	per LF	2500	feet	$ 9,375,000						
		Tall wall w No SLR	boardwalk	$ 700	per LF	3450	feet	$ 2,415,000						
			wetland sill	$ 3,000	per LF	3650	feet	$ 10,950,000						
			dune	$ 600	per LF	3000	feet	$ 1,800,000						
			wetland restoration	$ 20,000	per acre	10	acres	$ 200,000						
			yearly maintenance	$ 25,000	per year	50	years	$ 1,250,000						
	4d	Areas 1, 2 & 3 and I-95	I-wall at 16'	$ 3,000	per LF	8000	feet	$ 24,000,000	$ 49,990,000	$ 2,788,000	80%	$ 111,520,000	$ 27,880,000	**1.4**
			riprap	$ 3,750	per LF	2500	feet	$ 9,375,000						
		Tall wall w SLR	boardwalk	$ 700	per LF	3450	feet	$ 2,415,000						
			wetland sill	$ 3,000	per LF	3650	feet	$ 10,950,000						
			dune	$ 600	per LF	3000	feet	$ 1,800,000						
			wetland restoration	$ 20,000	per acre	10	acres	$ 200,000						
			yearly maintenance	$ 25,000	per year	50	years	$ 1,250,000						

Section 6.0 Concept Design

New Haven Long Wharf Flood Protection Study

Image from City of New Haven "Request for Proposal for Long Wharf Responsible Growth Plan"

6.0 CONCEPT DESIGN

This section presents concept details for Alternative 4.

6.1 Design Goals, Strategy and Approach

The proposed Alternative 4 design strategy is to: 1) capitalize on proposed improvements to the Long Wharf shoreline as a vehicle for incorporating flood protection; 2) restore and enhance the natural habitats, ecology and the recreational value of the Long Wharf shoreline; and 3) support the Long Wharf shoreline as an attractive destination for the residents and visitors of New Haven.

The Long Wharf Flood Protection Alternative 4 project goals include, first and foremost, flood protection and flood risk reduction. Additional goals include providing shoreline protection and enhancing the recreational and natural resources along the Long Wharf shoreline. The impact of the proposed flood protection project will not be limited to the Long Wharf shoreline. Alternative 4 provides flood protection of Areas 1, 2 and 3 (effectively all of Long Wharf District). The shoreline improvements will also encourage future improvements in access to and use of the waterfront.

The Long Wharf shoreline and nearshore areas, including Long Wharf Pier, Long Wharf Park, the Vietnam Veteran's Memorial Park, the Long Wharf Nature Preserve and the adjacent beach, tidal flats and marsh, serve a critical role to achieving the project goals.

- The natural nearshore features including the tidal flats, marsh and sand beach attenuate wave energy and mitigate wave effects.
- Existing shoreline protection and waterfront structures including the stone revetments and sheetpile and stone bulkheads and paved and grass areas provide some protection from both wave action and flood inundation.
- The proposed seawall along Long Wharf Drive would provide significant additional levels of flood protection, as well as separate the experience of the natural shoreline and nearshore environment from the noise and visual clutter of Interstate 95 and Long Wharf Drive.
- Proposed transportation improvements associated with Alternative 4, although modest in scale and cost, would provide safe and inviting neighborhood connections to New Haven Harbor and make Long Wharf an essential part of a larger regional bike and pedestrian network (both a link and primary destination).

Taken in whole, the project will help make the Long Wharf shoreline a signature citywide open space.

6.2 Flood and Shoreline Protection

The first goal of Alternative 4 is to provide both flood protection and shoreline protection. As described in this report, coastal flooding includes tides, storm surge and waves, and the effect of sea level rise on each of these. Extreme water levels due to storm surge result in flood inundation of the Long Wharf District. Waves occurring coincident with storm surge result in erosion of beach, damage to existing shoreline structures and utilities and worsen flood inundation. Sea level rise will increase the frequency and magnitude of coastal flood events.

The shoreline provides a transition between the natural nearshore environment of Long Wharf and the developed upland areas. However, the existing shoreline protection and waterfront structures have also had a negative impact to the nearshore areas. The stone revetments and bulkheads have contributed to loss of marsh, recession of beach and loss of dune. This can be observed by the significant shoreline transition from marsh and beach (at the south end) to hard structure with no beach or marsh (at the north end).

The existing shoreline protection and waterfront structures provide only minimal flood protection against extreme flood events (e.g., 50-year, 100-year, 500-year recurrence interval floods). Damage has occurred during higher probability floods such as those associated with Hurricane Irene.

The Alternative 4 coastal flood protection measures mitigate the effects of coastal flooding of Areas 1, 2 and 3 by: 1) reducing wave heights and wave energy; 2) protecting against erosion of beach and upland slopes; 3) protecting against flood inundation of upland areas; and 4) mitigating the negative effects of existing hard shoreline features. Each of the project components work together in an integrated way to reduce flood and shoreline erosion. The proposed new project components also build upon, and are consistent with, the existing shoreline features.

6.3 Environmental and Ecological Benefits

Enhancement of the shoreline and nearshore environment is proposed as part of an overall Long Wharf flood protection strategy and to provide natural resource and recreational value. New Haven's Long Wharf area, including the existing shoreline and nearshore environment, was created in 1949 by filling (using spoil from dredging New Haven Harbor) the former shallow estuary to support construction of I-95 and the upland areas located to the west of the highway. The original tidal flats were created from source sediment from the rivers being deposited in the relatively low current velocity estuary. Much of the existing tidal flat is the result of reworked fill placed at the time of the I-95 construction. Over the last 50 years, the shoreline evolved into beach and marsh and small, localized grassland and woodland areas. The tidal wetland and dune area has also changed over the 50 years since I-95 was constructed. River and upland sediment sources have been reduced due to upland development. Hard, shoreline protection (stone revetments and bulkheads) have been constructed along portions of the shoreline. In perspective, the existing shoreline is a man-made creation that has developed (partially) into natural habitats and coastal landforms over the last 50 years. The proposed enhancements are intended to continue and support the dynamic development of natural habitats and coastal landforms and also contribute to flood protection and recreational use.

Alternative 4 enhances the existing tidal wetlands and to add beach and dune.

6.4 Project Components

The Alternative 4 project components include:

1. Submerged bioengineered breakwater (possibly including oyster castles).
2. New tidal marsh with a new wetland sill.
3. Beach nourishment.
4. Buried quarrystone revetment.
5. Flood wall.
6. Ancillary features including timber boardwalk and, potentially, floating wetlands, trickle filters, fish hives and living walls.

Figures 6-1 through 6-3 indicate the locations of the project components. Figures 6-4 through 6-6 present project concept site views. Attachment 5 presents preliminary Concept Plans and Profiles.

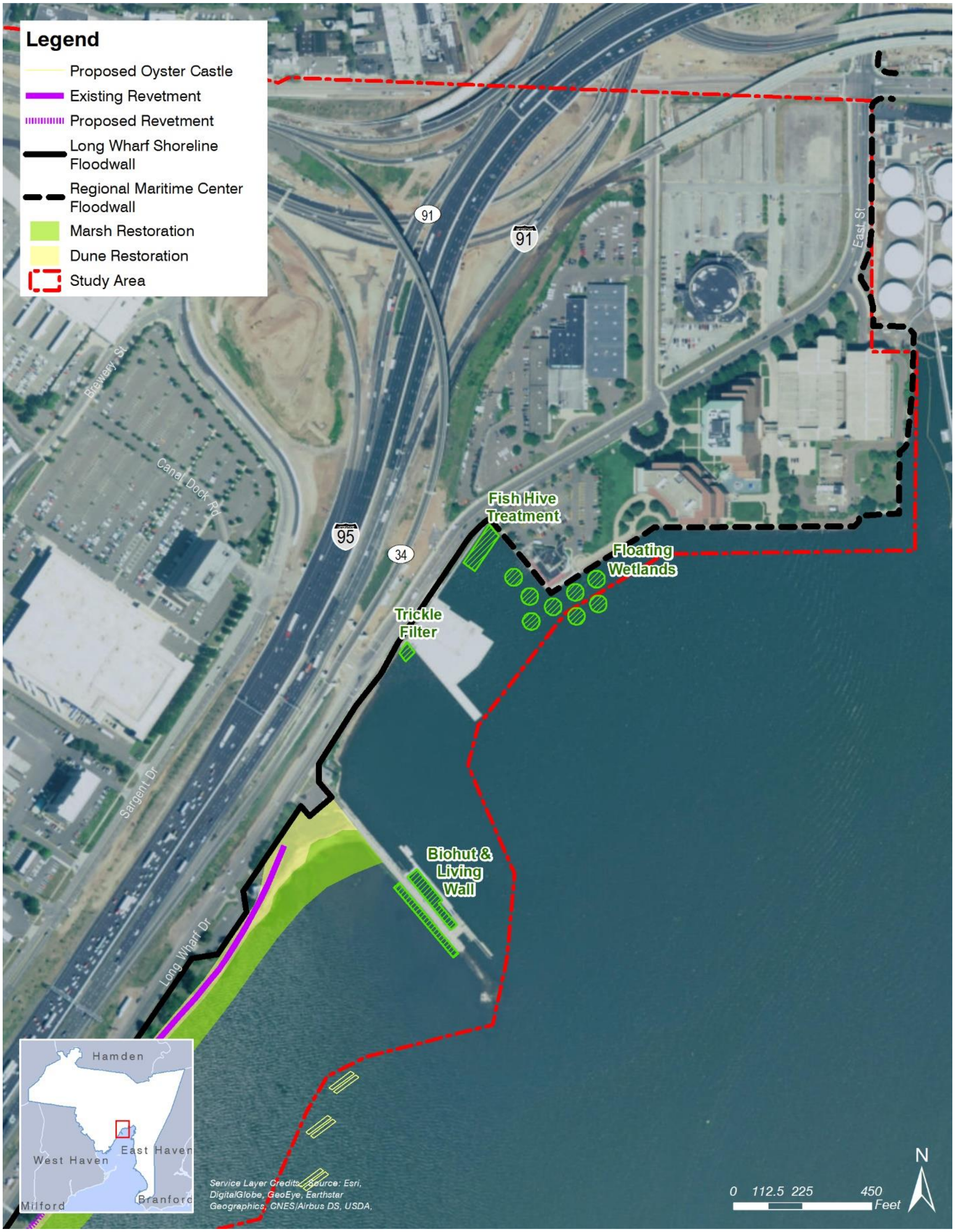


Figure 6-1: Alternative 4 Concept Drawing showing Project Components (North)

Figure 6-2: Alternative 4 Concept Drawing showing Project Components (Middle)

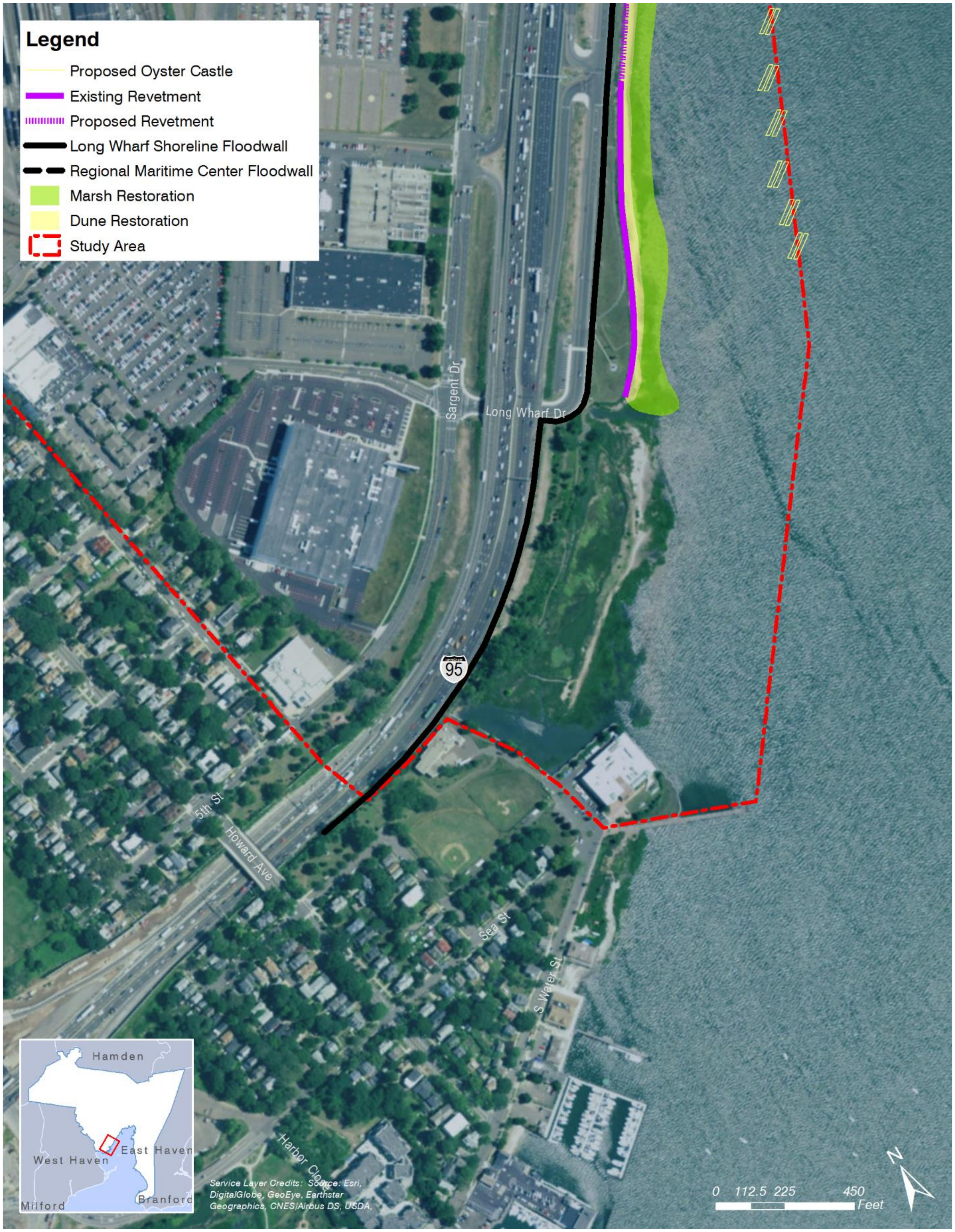


Figure 6-3: Alternative 4 Concept Drawing showing Project Components (Middle)

Figure 6-4: Alternative 4 Concept Drawing showing view from Long Wharf Park looking northeast

Figure 6-5: Alternative 4 Concept Drawing showing view from Long Wharf Drive looking east

Figure 6-6: Alternative 4 Concept Drawing showing view of Veterans Memorial Park

Submerged Bioengineered Breakwater

Submerged bioengineered breakwaters are proposed, located at the edge of the tidal flat and parallel to the shoreline. One option is oyster castles, which are easily-deployed, specialized manufactured concrete units using an environmentally friendly blend of material conducive to attracting and fostering oyster settlement, attachment, and growth. Oyster castles can be placed not only as potential shellfish habitat, but also (when developed) as a submerged offshore breakwater to attenuate wave effects and retain tidal flat sediment.

Oyster castle units are typically manufactured to be 8 inches in height. Castle units interlock when they are stacked, and castles can be formed from layering multiple units to reach a target water elevation for optimum oyster growth. As an example, when stacked three high, the overall oyster castle height would be 20 inches.

Figure 6-7: Installation of Oyster Castles and Reef Balls

Figure 6-8: Installed Oyster Castles (from presentation "Oyster Castles: A New Tool for Site Evaluation and Intertidal Oyster Reef Habitat Restoration and Enhancement in Multiple U.S. States"

Design Criteria:

- Provide adequate wave attenuation to sustain a low-energy nearshore environment to provide ideal environmental conditions for marsh.
- Crest elevation should be high enough to attenuate waves under normal conditions.
- Crest elevation should be low enough for oyster castles to be submerged during low-frequency storm events to minimize storm damage.
- Oyster castle clusters should be placed at a reasonable distance not to impede with horseshoe crab access to the intertidal flats.
- Castles should be placed at the beginning of a calm weather season. This will allow oysters to grow and attach to the castles, increase the stability of the structure and reduce risk of damage during high wave energy season.

Technical Considerations:

The geotechnical characteristics of the sediment will affect the placement, construction and future settlement of the oyster castles. Oyster castles can be placed sub-tidally and are proposed here to be placed 6-inches below MLLW similar to successful placement at other sites (e.g., New York Harbor). Some subsidence of the castles after placement should be anticipated. Castles can be built up if subsidence occur or geotextiles may be used to separate the castles from muddy substrates.

Oyster castle blocks are 12’’ x 12’’ x 8’’ in size and are light enough to be picked up without heavy machinery. The stability of the castles is increased by interlocking between individual blocks and the oyster habitat establishing on the castles. However; there is limited literature on quantifying the added strength and stability by interlocking the oyster habitat. With the lack of available research, anchoring the castles could be an option to increase structure stability. Alternatively, implementing a pilot project to examine the response of the castles in New Haven Harbor would provide beneficial information for designing a sustainable project and determining the longevity of the overall project.

Stability to resist wave forces is a key technical design consideration. Large precast or natural stone wave attenuation systems are available that provide greater stability (for example, see Figure 6-9).

Environmental Considerations:

The mudflats along Long Wharf support important habitat. The oyster castles may have an effect to the benthic environment in which they are placed. For example, the placement of the oyster castles may attract fish and shellfish to an area that currently supports different habitat. Conversely, the oyster castles are proposed to be located at the outer limit of the existing tidal flats and (when developed) will help to attenuate wave action and retain tidal flat sediment. Horseshoe crabs currently use the beaches along Long Wharf. The oyster castle clusters will be placed to not impede their pathways. There are ongoing efforts to define the interactions between horseshoe crabs and oyster reef restoration in southern New Jersey.

Figure 6-9: Large Wave Attenuation Devices

Permitting Considerations:

There are approved and conditionally approved shellfish beds in the New Haven vicinity. There are currently oyster pilot projects located in Stratford, Connecticut and within the closed waters of New York and New Jersey, as well as commercial oyster operations in Connecticut. However, shell fishing appears to be discouraged within New Haven Harbor. A pre-application meeting to understand any agency concerns would be important early on so that the final design can be developed considering any potential permitting issues.

Tidal Marsh and Dune Restoration

Establishment of a wider zone of native vegetation will provide habitat for wildlife, stormwater infiltration and absorption, flood/storm surge protection and aesthetic enhancement. The focus is on creating a diverse mix of coastal scrub/shrub vegetation along the upper shoreline edges and a transition to tidal marsh on a wave-protected shelf. This native vegetated edge provides increased biodiversity and a variety of habitat types for native wildlife. Creation of additional marsh, beach and dune will also create more land and wetlands habitat in areas where water currently encroaches on existing revetments and bulkheads during mid-and high tides.

Figure 6-10: Restored Tidal Marsh

Creating the dune and/or marsh will require importing sand material and grading to create landforms at the proper elevations. Creating the salt marsh will also require designing drainage paths for water to drain properly during ebb tide to avoid salt pannes to form. *Spartina alterniflora* would be planted in the marsh zones, while a mix of dune grasses and shrubs would be planted within the dune areas.

Design Criteria:

- Contribution to Long Wharf flood protection by providing wave attenuation and erosion protection of dunes and upland areas, particularly during higher probability flood events such as the 1-year to 10-year recurrence interval floods.
- Support existing habitat and ecology.
- The restoration of dune and marshes would enhance protection of existing roadways, infrastructure and other proposed flood protection measures.

Figure 6-11: Newly Planted Dune

Design Approach:

- Add complexity to the edge through the development of a tiered vegetated edge that includes native coastal scrub/shrub vegetation and tidal wetlands along an armored/cobble shelf.
- Consider fetch when determining placement of the proposed intertidal zone, specifically depth and distance offshore based on wave energy. Examine water depth to bottom within approximately 30 feet of existing and proposed revetment riprap edges to determine width of shoreline expansion.
- Consider protecting the edges of marsh restoration from toe scour by utilizing coir logs or placing a toe sill.
- Create a maintenance plan to maintain vegetative habitat and clear any large woody debris or floatable trash deposition that could impede survival of the marsh and/or dune grass.

Technical Considerations:

The marsh and dune system can be placed either within limited, specific areas or along the entire length of the beach and path. Construction requirements include a sand source, creation of a staging area, and covering existing habitats, paths and, potentially, infrastructure. Also, marsh and dune habitats by nature are not static environments. Natural systems migrate, adjusting themselves according to the environment and changing climate. Because the area where these features can migrate is bounded by man-made structures (e.g., Long Wharf Drive), they may require periodic maintenance and may need to be replanted and/or renourished at times. Dependent upon the rate of sea level rise versus natural deposition, marsh filling and re-designing drainage paths may be required.

Environmental Considerations:

Impacts associated with the creation of new marsh within subaqueous areas include replacement of some tidal flat habitat with marsh habitat. Other impacts include creating a visual and physical barrier between upland areas and the tidal flats. Dune restoration will occur in areas currently dominated by mowed grass or revetments placed to stabilize the shoreline. Also, marsh restoration would typically occur in recently eroded habitat, providing additional benefits due to creation of a stabilized shoreline. Healthy marshes improve water quality with the help of rich diversity of plants and animals contained in the system. These habitats act as filtering systems by removing nutrients, pollutants and sediment from water.

Permitting Considerations:

The proposed work includes sand fill placement and vegetation planting. Some of the work (revetment, dune creation) will be above the Coastal Jurisdiction Line. The remainder of the work (marsh creation) will be below the Coastal Jurisdiction Line and include fill placement within the waters of the U.S. The proposed work will require permits from the USACE and the State. A pre-application meeting to understand any agency concerns would be important early on so that the final design can be developed considering any potential permitting issues.

Existing Revetments

The existing revetments were constructed to prevent shoreline erosion and protect areas located upland of the revetments. As part of the proposed enhancements, the existing and new revetments would continue to serve that purpose. It is proposed to bury the revetments beneath a planted dune feature that will become part of an integrated system of dunes, marsh and beach. Their primary purpose is to provide erosion protection (of upland areas including Long Wharf Drive, existing utilities, etc.) and wave attenuation during extreme flood events. The proposed new revetment would be constructed above the MHHW elevation. Locating the revetments above MHHW and incorporating beach and marsh seaward of the revetment will allow normal coastal processes to occur without negative impacts (e.g., wave reflection, scour). This approach will require expanding (and creating) the width of marsh, dune and beach in front of the revetments. Figure 6-12 shows a typical buried revetment and vegetated dune.

Design Criteria:

- Contribution to Long Wharf flood protection by providing wave attenuation and erosion protection of adjacent upland areas including Long Wharf Drive and existing utilities.
- Perform during the 100-year recurrence interval storm.
- Support the growth of vegetated dunes over the revetment.
- Do not restrict future access to existing buried utilities.
- Do not restrict shoreline access.
- Do not affect existing marine habitat or ecology.

Figure 6-12: Image from Scottish Natural Heritage; Guide to Managing Coastal Erosion in Beach/Dune Systems

Design Approach:

- Provide flood protection during extreme flood events, without impacting normal shoreline coastal processes (specifically, to avoid future loss of beach source sediment, passive erosion of dry beach and inter-tidal flats in front of revetment due to sea level rise).
- Make the revetment an integrated component of the shoreline and nearshore system of dune, marsh and beach.

Technical Considerations:

- The revetment dimensions and stone size should support the 100-year recurrence interval design wave.
- The crest elevation of new revetments should be (minimum) at about elevation 10 feet NAVD88.
- Revetment settlement should be anticipated due to the presence of compressible organic materials.
- To avoid passive erosion of areas seaward of the revetment due to sea level rise, on-going, long term beach nourishment may be required.

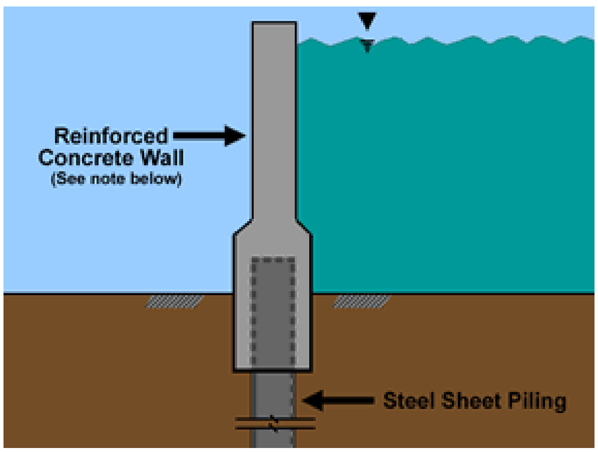
Environmental Considerations:

- The location of the proposed new and improved revetments should not result in impacts to existing habitat and ecology.
- The dimensions and depth of the proposed new revetments will support dune placement and vegetation planting over the revetment.

Long Wharf Floodwall

The natural shoreline features (existing and proposed) provide some level of wave attenuation reducing the wave effects of erosion and scour. The buried quarrystone revetment provides both flood protection (up to the revetment crest elevation) and shoreline protection from erosion during storm events. These features will be inundated with floodwaters during the 100-year return period (1% annual chance) and lower probability flood events. The floodwall is intended to provide flood mitigation and protection of upland areas (inland of the flood wall) during these flood events. The floodwall also provides an aesthetic divide between the natural environment and the built environment (i.e., Long Wharf Drive).

The floodwall is a structural wall designed to resist flood loads but also meet aesthetic goals. Figure 6-13 presents typical floodwall structures types:



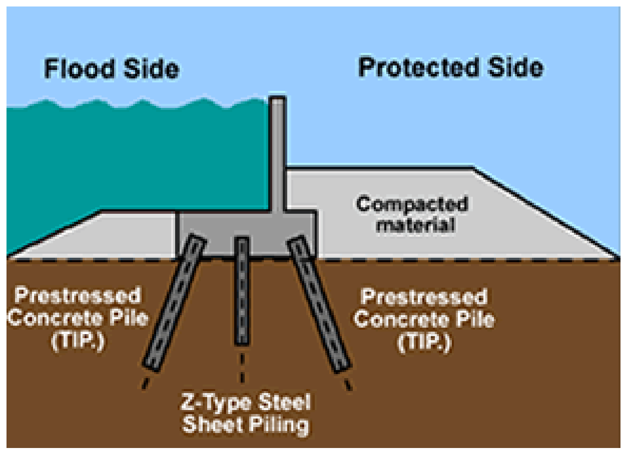


Figure 6-13: Floodwall Alternative Structure Types (I-walls and T-walls) (ref. USACE)

I-walls act as cantilevered structures and are limited in unreinforced wall height. T-walls are constructed typically when higher walls are required.

The proposed Long Wharf floodwall length, height and type will conform to the existing site conditions and level of desired flood protection and, generally will have three segments:

- The main (central) segment (see Figures 6-1 through 6-3) will extend parallel to Long Wharf Drive from the Long Wharf Drive underpass to the south to the intersection with the east-west bulkhead at 501 Long Wharf Drive (approximately 4,700 linear feet). The area of this segment of the Long Wharf floodwall consists principally of grass and pavement and is accessible for new construction (except existing utilities). The existing grades range from about Elevation 8 to 12 feet NAVD88 and are generally around 8 to 9 feet NAVD88. There are, currently, no flood protection structures within this area.
- The second (south) wall segment is located to the south of the main segment and would extend parallel to the Long Wharf Nature Preserve and in front (toward I-95) of the New Haven Sewage Treatment Facility. The ground surface along I-95 within this segment is much higher (about Elevations 12 to 20 feet NAVD88). The existing ground surface within this area is already high enough to provide flood protection of inland (Area 3) areas during the current 100-year return period (1% annual chance) flood event and is, therefore, less critical than the main floodwall segment. However, this segment would be important for higher, less probable, coastal floods. Due to the very high ground surface elevations west of the Nature Preserve (Elevations 19 to 20 feet), this wall segment does not need to be contiguous with the main floodwall segment. The estimated segment length is about 400 linear feet.

- The third (north) wall segment, represented by dashed lines on Figure 6-1, surrounds Area 2. As described in Section 2.0, the shoreline along Area 2 is already improved with a range of shoreline structures, many with parapet walls that are elevated above land grade. These structures provide some level of flood protection; however, they are not contiguous and, therefore, limited relative to flood protection. The third Long Wharf floodwall segment would be to adapt, infill and (possibly) raise the wall height of the existing shore protection structures to provide contiguous flood protection. As shown of Figure 6-1, this wall segment extends past the bulk storage terminal to Water Street to prevent floodwater inundation from the backside of Area 3. This segment could also be extended to prevent floodwater propagation along Water Street. The estimated segment length is about 3,000 linear feet.

Design Criteria:

- The Long Wharf floodwall needs to be contiguous (central and north segments) in order to be effective.
- The top of floodwall elevation is selected to achieve a specific flood protection goal, including resisting both storm surge stillwater elevation and wave runup and overtopping. The height of the wall also needs to support project aesthetic and practical design considerations. Final wall design will be a balance of cost, benefits (in terms of reduced flood loss) and the aesthetic design goals. In general, however, a higher wall will provide a greater amount of flood protection. Section 5.0 evaluates two potential flood wall elevations relative to prevented loss:
  - Top of wall at about Elevation 12 to 13 feet NAVD88. Over the central segment, the height of the wall would range from 1 to 2 feet to about 5 feet (although site grading could reduce the height to achieve an overall "waist-high" wall).
  - Top of wall at about Elevation 15 to 16 feet NAVD88. Over the central segment, the height of the wall would range from 1 to 2 feet to about 4 to 8 feet (typically around 6 feet).
- Additional options relative to floodwall height, assuming initial construction to the lower wall include:
  - Design the wall to use temporary, deployable measures (such as aluminum stop logs) installed on the top of the permanent wall to achieve additional protection as-needed.
  - Design the wall to support construction of an additional vertical wall section in the future.

Technical Considerations:

- During the design of the flood wall, one of the most significant challenges is going to be working around existing utilities, in particular the sewer main. The sewer main is a 36-inch ductile iron pipe that is located seaward of Long Wharf Drive. The distance between the wall and the pipe should allow enough space for utility maintenance and repair access and avoid construction-related damage. Based on preliminary discussions with the Greater New Haven Water Pollution Control Authority, a minimum distance of 10 feet is reflected in the plans at the conceptual design stage.
- The subsurface geologic conditions include compressible organic materials, which will require that the floodwall be constructed with deep foundation support (sheetpile, piles or ground inclusions).
- The floodwall will have openings at strategic locations to allow pedestrian access to the shoreline area. These openings will use deployable flood barriers.

Figures 6-14 and 6-15 shows examples of permanent floodwalls. Figure 6-14 shows the Stratford, Connecticut sea wall under normal conditions and being overtopped by waves during Hurricane Sandy. Stratford, Connecticut has a relatively similar coastal flood risk as New Haven. For comparison, the top of the Stratford sea wall is at about Elevation 10 feet NAVD88.

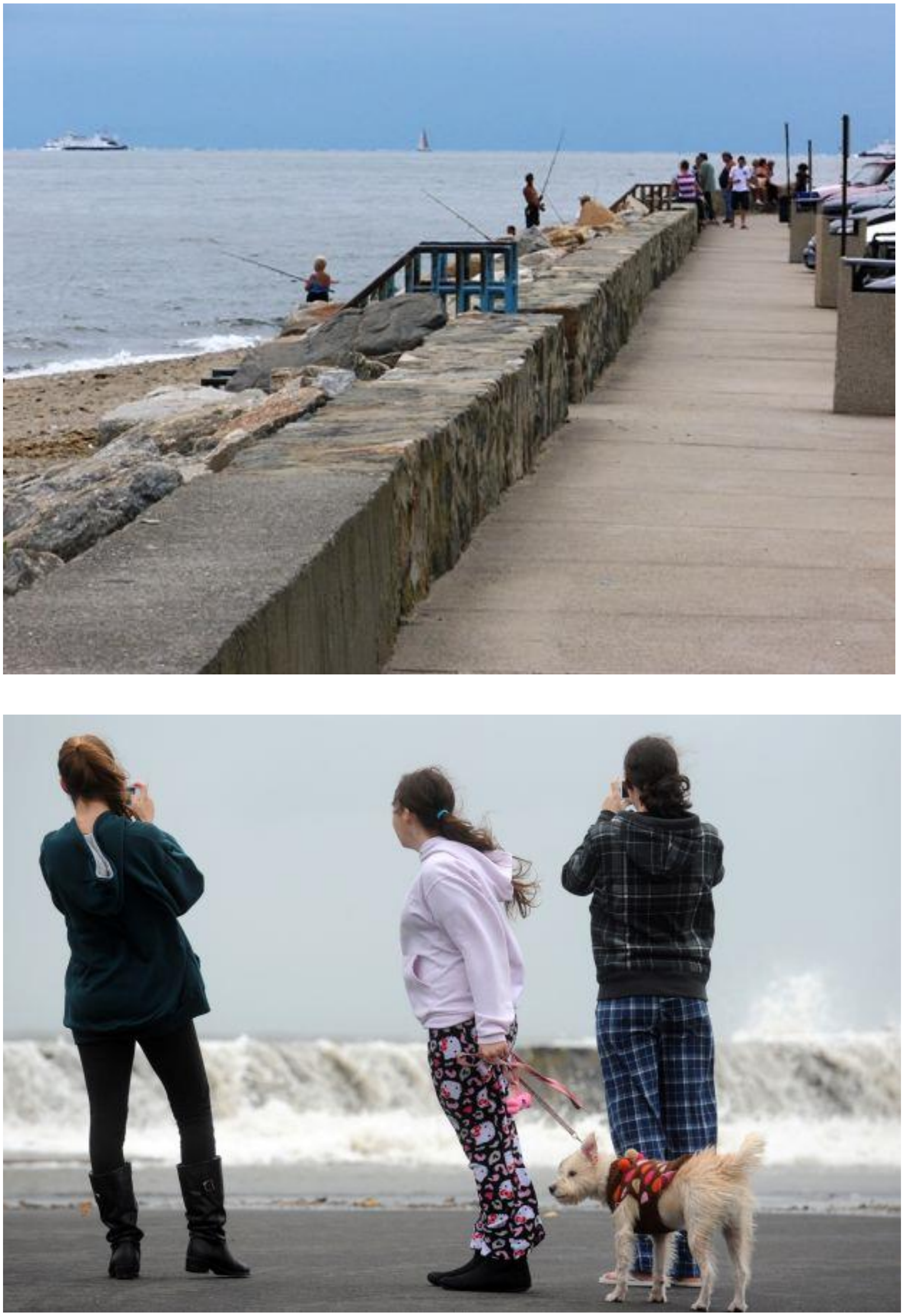


Figure 6-14: Stratford, Connecticut Stone Masonry Sea Wall with Revetment

Figure 6-15 shows a different type of flood wall, using a concrete (brick-faced) lower wall with a structure glass top that is capable of resisting flood loads but maintaining the view.

Figure 6-15: Example of alternative flood wall design, with glass upper wall.

Additional Project Components: Timber Boardwalk, Living Walls, Biohuts®, Floating Wetlands

A timber boardwalk is included in Alternative 4 and will provide access to wetlands and beach as well as provide pedestrian connectivity between the different Long Wharf shoreline areas. Possible additional project components include living walls, Biohuts® and floating wetlands. Portions of the Long Wharf shoreline consist of marine bulkheads and a pier. These types of structures general do not support native habitat. Measures are proposed to enhance the shoreline complexity and epifaunal substrate. Starting at the upper shoreline edge, the introduction of a mechanical tidal wetland along the top of the bulkhead allows for water filtration benefits. A textured façade along the bulkhead would attract colonization by crustaceans and mollusks. Biohuts® or other green bulkhead designs provide important shelter for smaller fish from predators along the bulkhead. Designing the textured bulkhead and the Biohuts® in close proximity to one another supports further biodiversity and the creation of an aquatic community. Floating wetlands in the water along the bulkhead increase water nutrient absorption, while providing important shelter as well as a food source for a variety of organisms.

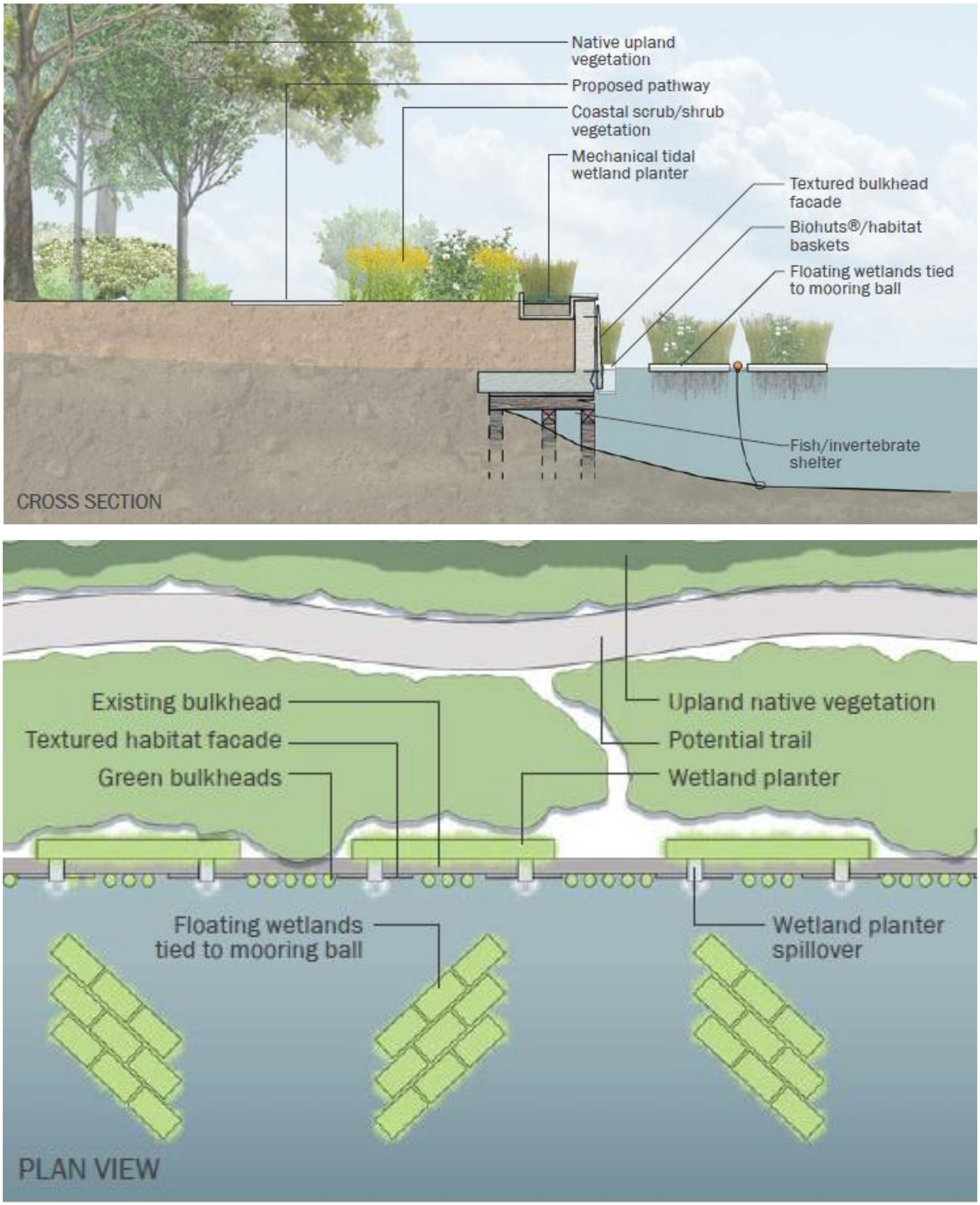


Figure 6-16: Conceptual Representation of Biohuts® and Floating Wetlands (Plan and Section)

Design Approach:

- A textured bulkhead treatment, bolted directly to the facade, adds increased surface roughness along the water's edge to create new substrate for aquatic species.
- Biohuts® or other habitat baskets are fastened to the bulkhead, with the cage/basket fully submerged in the water on front of the bulkhead. Substrate can include oyster shells, organic materials like woody debris or coconut fiber. Plants may be added to the top surface or within the basket.
- Floating wetlands are anchored with a mooring ball and moored with enough length to adjust with tidal fluctuations and weather events. The wetlands are planted with a variety of native marsh species.
- A mechanical tidal wetland planter is integrated along the top edge of the bulkhead, designed either to filter water from the harbor or stormwater runoff.
- An increased width of native vegetation along the shoreline uses a diverse array of native riparian scrub/shrub species.

Technical Considerations:

The proposed measures will require retrofits to the built structures.

Environmental Considerations:

Because these retrofits would occur in built environments, the assumption is that no negative effects to the environment would occur. However, because these treatments are not well known in the regulatory or environmental community, there may be some concern about introducing new structures into the ecological community.

Permitting Issues:

Because these retrofits would occur on built environments, the assumption is that no negative effects to the environment would occur. However, because these treatments are not well known in the regulatory or environmental community, there may be some concern about introducing new structures into the ecological community.

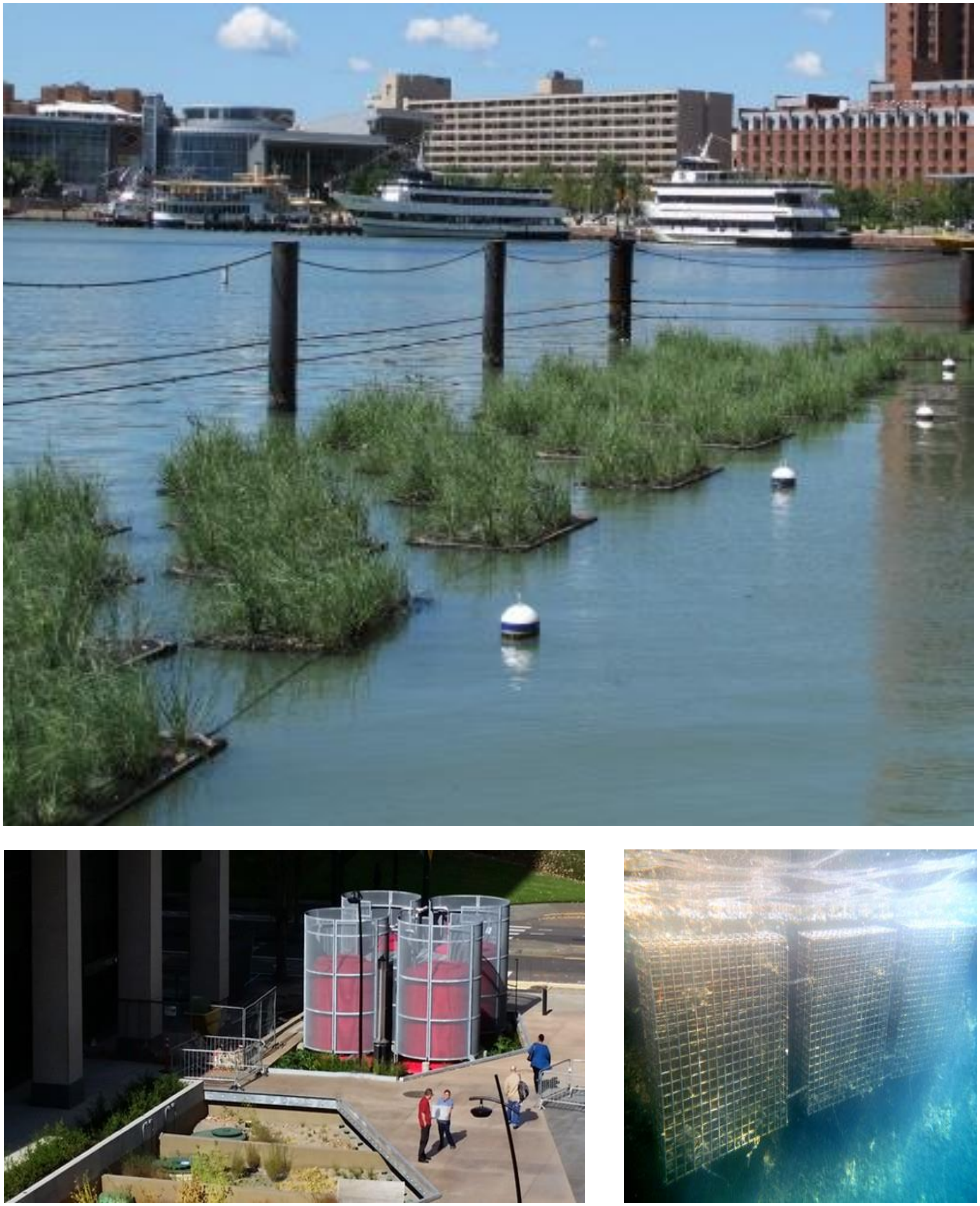


Figure 6-17: Examples of Floating Wetlands, Baltimore, Maryland (top), Trickle Filter and Living Wall

Attachment 1: Limitations

USE OF REPORT

1. GeoEnvironmental, Inc. (GZA) prepared this report on behalf of, and for the exclusive use of the Client for the stated purpose(s) and location(s) identified in the Report. Use of this Report, in whole or in part, at other locations, or for other purposes, may lead to inappropriate conclusions and we do not accept any responsibility for the consequences of such use(s). Further, reliance by any party not identified in the agreement, for any use, without our prior written permission, shall be at that party's sole risk, and without any liability to GZA.

STANDARD OF CARE

2. Our findings and conclusions are based on the work conducted as part of the Scope of Services set forth in the Report and/or proposal, and reflect our professional judgment. These findings and conclusions must be considered not as scientific or engineering certainties, but rather as our professional opinions concerning the limited data gathered during the course of our work. Conditions other than described in this report may be found at the subject location(s).

3. The interpretations and conclusions presented in the Report were based solely upon the services described therein, and not on scientific tasks or procedures beyond the scope of the described services. The work described in this report was carried out in accordance with the agreed upon Terms and Conditions of Engagement.

4. GZA prepared an existing condition topographic map of the study area based on available topographic and bathymetric data. The data sources are presented in Attachment 2. The topographic data was also converted into a Digital Elevation Model (DEM) for use in numerical flood modeling. It is noted that extensive re-grading was being performed during the course of the study related to reconstruction of I-95. The final, proposed re-construction grades are not reflected in GZA's existing condition topographic maps, DEM or numerical flood modeling. Therefore, certain aspects of the flood model results may incorrectly represent the flood conditions once the I-95 and vicinity construction is complete.

5. GZA flood evaluation was performed in accordance with generally accepted practices of qualified professionals performing the same type of services at the same time, under similar conditions, at the same or a similar property. No warranty, expressed or implied, is made. The findings of the risk characterization are dependent on numerous assumptions and uncertainties inherent in the risk assessment process. The findings of the flood evaluation are not an absolute characterization of actual flood hazard, but rather serve to highlight potential sources of flood risk at the site(s).

6. GZA's flood evaluation included hydrodynamic computer flood models that are limited to determining coastal flooding risk. Computer models do not include the influence of rainfall, river flooding and drainage structures on flood inundation.

7. GZA performed a limited, approximate estimate of building flood losses (Loss Estimation Calculations). The purpose of this estimate was for planning and decision making. Due to its approximate nature and need for making broad assumptions about certain properties and conditions, the absolute loss values presented here should not be relied upon. See report text for additional limitations and assumptions.

8. GZA did not perform detailed purchase, installation or construction cost estimates as part of the study. General ranges of flood alternative costs are presented for the purpose of relative comparison. They are highly approximate and should not be relied upon for project cost estimating.

RELIANCE ON INFORMATION FROM OTHERS

9. In conducting our work, GZA has relied upon certain information made available by public agencies, Client and/or others. GZA did not attempt to independently verify the accuracy or completeness of that information. Any inconsistencies in this information which we have noted are discussed in the Report.

10. GZA evaluated multiple sources of metocean and publicly-available flood data. GZA's numerical flood models reflect the coastal flood levels developed by the U.S. Army Corps of Engineers North Atlantic Coast Comprehensive Study (NACCS) for the Long Wharf area. GZA did not independently confirm the flood levels developed by the NACCS.

11. City of New Haven's Assessor's Data was used for determining structure and content values for Loss Estimation Calculations. The Assessor's Data may have inconsistencies specifically at parcels owned by agencies exempt from City of New Haven Taxes. GZA did not attempt to independently verify the accuracy or completeness of the structural and content values because it was beyond the scope of the study.

COMPLIANCE WITH CODES AND REGULATIONS

12. GZA did not perform an audit of flood regulations as part of the study. However, certain flood regulations are discussed and presented in Section 5.0. We used reasonable care in identifying and interpreting applicable codes and regulations necessary to execute our scope of work. These codes and regulations are subject to various, and possibly contradictory, interpretations. Interpretations with codes and regulations by other parties are beyond our control.

Attachment 2 – Terrain Metadata

CT New Haven Terrain Dataset

Thumbnail Not Available

Tags

terrain, elevation, contours, DEM

Summary

This terrain dataset was created to combine LiDAR, USACE Soundings and digitized coastal chart depth points into a single comprehensive elevation dataset for both topography and bathymetry.

Description

This terrain dataset was built using ArcGIS 10.2.2 from which topographic and bathymetric contours were developed and combines elevation data from several sources:

LiDAR from:

2012 USACE Post-Sandy Lidar: Coastal CT

https://coast.noaa.gov/dataservices/Metadata/TransformMetadata?u=https://coast.noaa.gov/data/Documents/Metadata/Lidar/harvest/2012_USACE_PostSandy_Connecticut_m1434_metadata.xml&f=html

2011 FEMA Lidar: Quinnipiac River Watershed (CT)

https://coast.noaa.gov/dataservices/Metadata/TransformMetadata?u=https://coast.noaa.gov/data/Documents/Metadata/Lidar/harvest/ct2011_fema_quinnipiacriver_m1472_metadata.xml&f=html

2006 FEMA Lidar: Connecticut Coastal

https://coast.noaa.gov/dataservices/Metadata/TransformMetadata?u=https://coast.noaa.gov/data/Documents/Metadata/Lidar/harvest/ct2006_fema_coastal_m1468_metadata.xml&f=html

Bathymetric information from:

USACE Connecticut Navigation Projects, New England Division Soundings for New Haven Harbor

http://www.nae.usace.army.mil/Portals/74/docs/Navigation/CT/NHH/NHH924.txt

NOAA Office of Coast Survey

Digitized coastal chart depth points.

Credits

There are no credits for this item.

Use limitations

This dataset is for the City of New Haven, CT, and the Long Wharf Project team use only.

Extent

West -73.002083 **East** -72.817551
North 41.376840 **South** 41.217392

Scale Range

Maximum (zoomed in) 1:5,000
Minimum (zoomed out) 1:50,000

ArcGIS Metadata ►

Topics and Keywords ►

Hide Topics and Keywords ▲

Citation ►

TITLE CT New Haven Terrain Dataset
CREATION DATE 2016-02-01 00:00:00
PUBLICATION DATE 2016-02-01 00:00:00
REVISION DATE 2016-02-01 00:00:00

PRESENTATION FORMATS * digital map
FGDC GEOSPATIAL PRESENTATION FORMAT vector digital data

Hide Citation ▲

Citation Contacts ►

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ORGANIZATION'S NAME GZA GeoEnvironmental, Inc.
CONTACT'S POSITION Geospatial Systems Manager
CONTACT'S ROLE point of contact

RESPONSIBLE PARTY
INDIVIDUAL'S NAME Daniel J. Boudreau, Jr., GISP
ORGANIZATION'S NAME GZA GeoEnvironmental, Inc.
CONTACT'S POSITION Geospatial Systems Manager
CONTACT'S ROLE originator

Hide Citation Contacts ▲

Resource Details ►

DATASET LANGUAGES * English (UNITED STATES)
DATASET CHARACTER SET utf8 - 8 bit UCS Transfer Format

STATUS completed
SPATIAL REPRESENTATION TYPE * vector

* PROCESSING ENVIRONMENT Microsoft Windows 7 Version 6.1 (Build 7601) Service Pack 1; Esri ArcGIS 10.2.2.3552

ARCGIS ITEM PROPERTIES
* NAME Terrain_Terrain
* LOCATION file://\\GZADCAPP\ags_Share\WebApp\CT_Long_Wharf\Data\Terrain.gdb
  * ACCESS PROTOCOL Local Area Network

Hide Resource Details ▲

Extents ►

EXTENT
DESCRIPTION
New Haven and New Haven Harbor

VERTICAL EXTENT
* MINIMUM VALUE -56.317053
* MAXIMUM VALUE 175.552994

EXTENT
DESCRIPTION
Current as of data creation date.

EXTENT
GEOGRAPHIC EXTENT
BOUNDING RECTANGLE
EXTENT TYPE Extent used for searching
* WEST LONGITUDE -73.002083
* EAST LONGITUDE -72.817551
* NORTH LATITUDE 41.376840
* SOUTH LATITUDE 41.217392

EXTENT CONTAINS THE RESOURCE Yes

EXTENT IN THE ITEM'S COORDINATE SYSTEM
* WEST LONGITUDE 930815.308357
* EAST LONGITUDE 981415.265228
* SOUTH LATITUDE 640036.009934
* NORTH LATITUDE 698040.130146
* EXTENT CONTAINS THE RESOURCE Yes

Hide Extents ▲

Resource Maintenance ►

RESOURCE MAINTENANCE
UPDATE FREQUENCY as needed

Hide Resource Maintenance ▲

Resource Constraints ►

CONSTRAINTS
LIMITATIONS OF USE
This dataset is for the City of New Haven, CT, and the Long Wharf Project team use only.

Hide Resource Constraints ▲

Spatial Reference ►

ArcGIS coordinate system
* Type   Projected
* Geographic coordinate reference   GCS_North_American_1983
* Projection   NAD_1983_StatePlane_Connecticut_FIPS_0600_Feet
* Coordinate reference details
  Projected coordinate system
    Well-known identifier   102656
    X origin   -119756300
    Y origin   -96342500
    XY scale   3048.0060960121928
    Z origin   -100000
    Z scale   10000
    M origin   -100000
    M scale   10000
    XY tolerance   0.0032808333333333331
    Z tolerance   0.001
    M tolerance   0.001
    High precision   true
    Latest well-known identifier   2234
    VCSWKID   5703
    LatestVCSWKID   5703
    Well-known text   PROJCS["NAD_1983_StatePlane_Connecticut_FIPS_0600_Feet",GEOGCS["GCS_North_American_1983",DATUM["D_North_American_1983",SPHEROID["GRS_1980",6378137.0,298.257222101]],PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],PROJECTION["Lambert_Conformal_Conic"],PARAMETER["False_Easting",999999.999996],PARAMETER["False_Northing",499999.999998],PARAMETER["Central_Meridian",-72.75],PARAMETER["Standard_Parallel_1",41.2],PARAMETER["Standard_Parallel_2",41.86666666666667],PARAMETER["Latitude_Of_Origin",40.83333333333334],UNIT["Foot_US",0.3048006096012192],AUTHORITY["EPSG",2234]],VERTCS["NAVD_1988",VDATUM["North_American_Vertical_Datum_1988"],PARAMETER["Vertical_Shift",0.0],PARAMETER["Direction",1.0],UNIT["Meter",1.0],AUTHORITY["EPSG",5703]]

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* Codespace   EPSG
* Version   8.2.6

Hide Spatial Reference ▲

Spatial Data Properties ►

Vector ►
* Level of topology for this dataset   geometry only

  Geometric objects
    Feature class name   Digitized_Chart_Points_1
    * Object type   point
    * Object count   785

GEOMETRIC OBJECTS
FEATURE CLASS NAME USACE_NH_Nav_Soundings_1
* OBJECT TYPE point
* OBJECT COUNT 26791

GEOMETRIC OBJECTS
FEATURE CLASS NAME LAS_Multipoint
* OBJECT TYPE complex
* OBJECT COUNT 7614997

Hide Vector ▲

ARCGIS FEATURE CLASS PROPERTIES ►
FEATURE CLASS NAME Digitized_Chart_Points_1
* FEATURE TYPE Simple
* GEOMETRY TYPE Point
* HAS TOPOLOGY FALSE
* FEATURE COUNT 785
* SPATIAL INDEX TRUE
* LINEAR REFERENCING FALSE

FEATURE CLASS NAME USACE_NH_Nav_Soundings_1
* FEATURE TYPE Simple
* GEOMETRY TYPE Point
* HAS TOPOLOGY FALSE
* FEATURE COUNT 26791
* SPATIAL INDEX TRUE
* LINEAR REFERENCING FALSE

FEATURE CLASS NAME LAS_Multipoint
* FEATURE TYPE Simple
* GEOMETRY TYPE Multipoint
* HAS TOPOLOGY FALSE
* FEATURE COUNT 7614997
* SPATIAL INDEX TRUE
* LINEAR REFERENCING FALSE

Hide ArcGIS Feature Class Properties ▲

ARCGIS TERRAIN PROPERTIES ►
* TOTAL NUMBER OF POINTS 328947742

Hide ArcGIS Terrain Properties ▲

Hide Spatial Data Properties ▲

Data Quality ►

SCOPE OF QUALITY INFORMATION ►
RESOURCE LEVEL attribute

Hide Scope of quality information ▲

Hide Data Quality ▲

Lineage ►

LINEAGE STATEMENT

USACE New England Division New Haven Harbor Soundings
http://www.nae.usace.army.mil/Missions/Navigation/ConnecticutProjects.aspx
http://www.nae.usace.army.mil/Portals/74/docs/Navigation/CT/NHH/NHH924.txt

NOAA Office of Coast Survey
http://www.charts.noaa.gov/OnLineViewer/12371.shtml

SOURCE DATA ►

DESCRIPTION

Originator: U.S. Army Corps of Engineers, New England District(ed.)
Publication_Date: 20140522
Title: New Haven Harbor, New Haven, CT After-Dredge / Condition Survey
Edition: Survey No. 14-1262
Geospatial_Data_Presentation_Form: Chart
Series_Information:
Series_Name: N/A
Issue_Identification: N/A
Publication_Information:
Publication_Place: Concord, Massachusetts
Publisher: Navigation, Project Management Section, New England
District

SOURCE MEDIUM NAME online link

Hide Source data ▲

Hide Lineage ▲

Metadata Details ►

* METADATA LANGUAGE English (UNITED STATES)
* METADATA CHARACTER SET utf8 - 8 bit UCS Transfer Format

SCOPE OF THE DATA DESCRIBED BY THE METADATA dataset

LAST UPDATE 2016-02-01

ARCGIS METADATA PROPERTIES

METADATA FORMAT ArcGIS 1.0
STANDARD OR PROFILE USED TO EDIT METADATA FGDC

CREATED IN ARCGIS FOR THE ITEM 2016-02-24 14:44:39
LAST MODIFIED IN ARCGIS FOR THE ITEM 2016-02-24 16:38:47

AUTOMATIC UPDATES

HAVE BEEN PERFORMED Yes
LAST UPDATE 2016-02-24 16:27:30

Hide Metadata Details ▲

Metadata Contacts ►

METADATA CONTACT
INDIVIDUAL'S NAME Daniel J. Boudreau, Jr, GISP
ORGANIZATION'S NAME GZA GeoEnvironmental, Inc.
CONTACT'S POSITION Geospatial Systems Manager
CONTACT'S ROLE point of contact

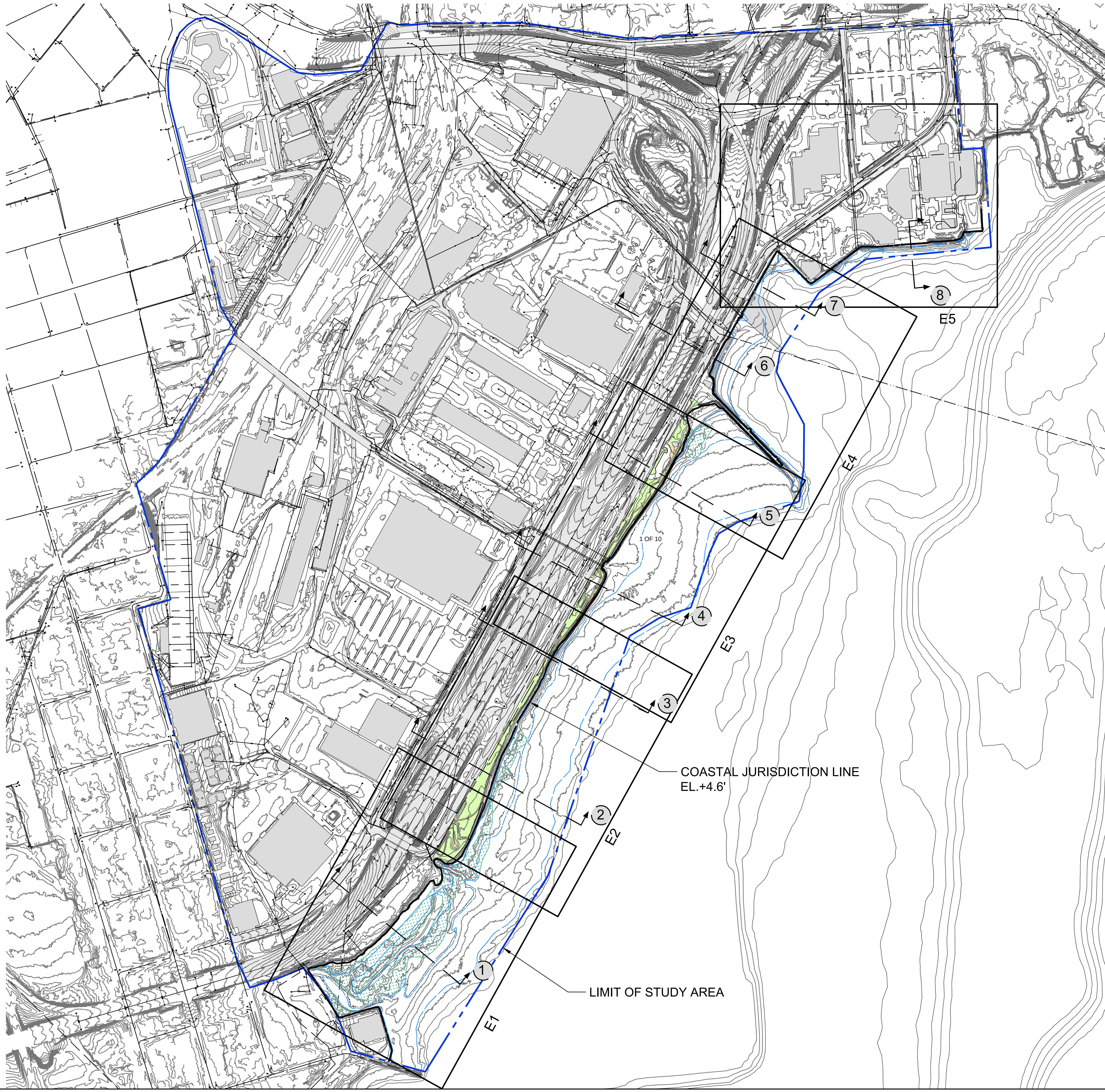
Hide Metadata Contacts ▲

Metadata Maintenance ►

MAINTENANCE
UPDATE FREQUENCY as needed

Hide Metadata Maintenance ▲

Attachment 3 – Existing Conditions Plan and Profiles



LEGEND

- STUDY AREA LIMITS
- TOPOGRAPHIC SURFACE CONTOUR MINOR (1' INTERVAL)
- 5 — TOPOGRAPHIC SURFACE CONTOUR MAJOR (5' INTERVAL)
- CROSS SECTION LINE
- 3 CROSS SECTION NUMBER

N

0 160 320 640 960
SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

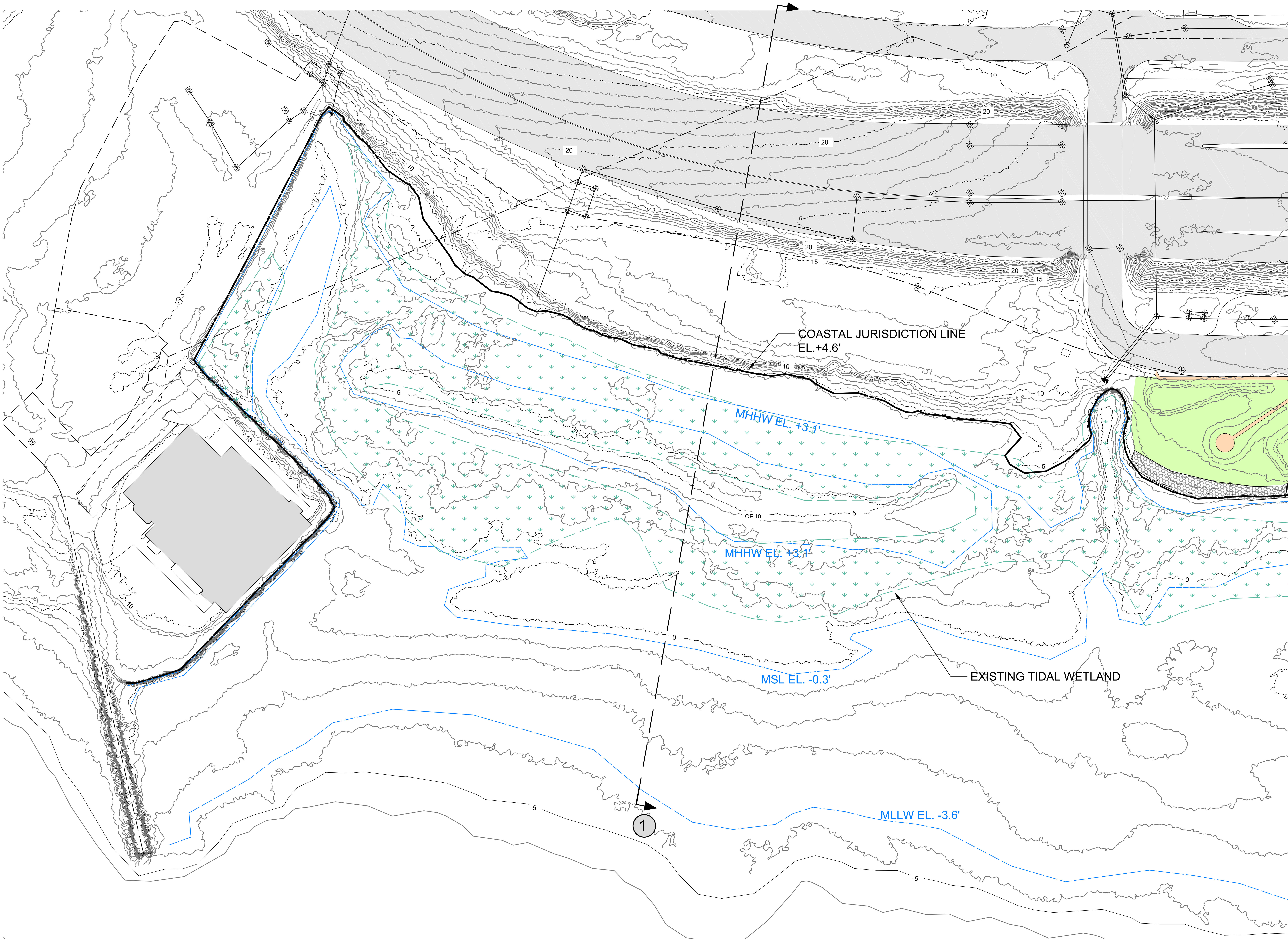
NEW HAVEN, CONNECTICUT

STUDY AREA - SITE PLAN OVERVIEW

PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	INDEX
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 1 OF 10



LEGEND

- PROPOSED CATCH BASIN
- ACTIVE CATCH BASIN
- ABANDONED CATCH BASIN (NOT SHOWN FOR CLARITY)
- DRAINAGE FEATURE
- PROPOSED MANHOLE
- ACTIVE MANHOLE
- ABANDONED MANHOLE (NOT SHOWN FOR CLARITY)
- PROPOSED OUTFALL
- ACTIVE OUTFALL
- ABANDONED OUTFALL (NOT SHOWN FOR CLARITY)
- ACTIVE SEWER CONNECTION
- ABANDONED SEWER CONNECTION (NOT SHOWN FOR CLARITY)
- STUDY AREA LIMITS
- ACTIVE DRAIN LATERAL
- ABANDONED DRAIN LATERAL (NOT SHOWN FOR CLARITY)
- PROPOSED DRAIN LINE
- ACTIVE DRAIN LINE
- ABANDONED DRAIN LINE (NOT SHOWN FOR CLARITY)
- ACTIVE FIBER OPTIC LINE
- ACTIVE SEWER MAIN
- BUILDING LOCATION
- ACTIVE RAILROAD CENTERLINE
- EDGE OF PAVED ROADWAY
- EDGE OF PAVED PARKING
- COASTAL JURISDICTION LINE (EL.+4.6' NEW HAVEN, CT)
- TOPOGRAPHIC SURFACE CONTOUR MINOR (1' INTERVAL)
- 5 — TOPOGRAPHIC SURFACE CONTOUR MAJOR (5' INTERVAL)
- TIDAL WETLAND
- EXISTING RIPRAP
- EXISTING SOIL BACKFILL
- EXISTING GRASS AREA
- EXISTING PAVED PATH
- CROSS SECTION LINE
- 3 — CROSS SECTION NUMBER

NOTES:

1. THE BASE MAP WAS DEVELOPED FROM ELECTRONIC FILES PROVIDED BY CTGIS ENTITLED "2012 USACE POST-SANDY LIDAR" DATED: 2012 AND ENTITLED "TRANSPORTATION ARCHIVE GDB" DATED: 2010 FILE NAME: "TRANSPORTATION_ARCHIVE.GDB" AND ENTITLED "150814 STORMWATER GDB" DATED: 2016 FILE NAME: "150814 STORMWATER.GDB"
2. SOME PLANIMETRIC DATA INCLUDING: RAILROADS, ROADWAYS, BUILDING FOOTPRINTS AND PAVED PARKING WERE UPDATED FROM AERIAL IMAGERY PROVIDED BY MICROSOFT IN 2016.
3. ELEVATION CONTOURS BELOW -5 FEET (NAVD88) GENERATED BASED ON BATHYMETRIC DATA.
4. COASTAL SWAMP DELINEATION BASED ON A GIS LAYER NAMED "HYDROLOGYAREA2007".

N

0 30 60 120 180

SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

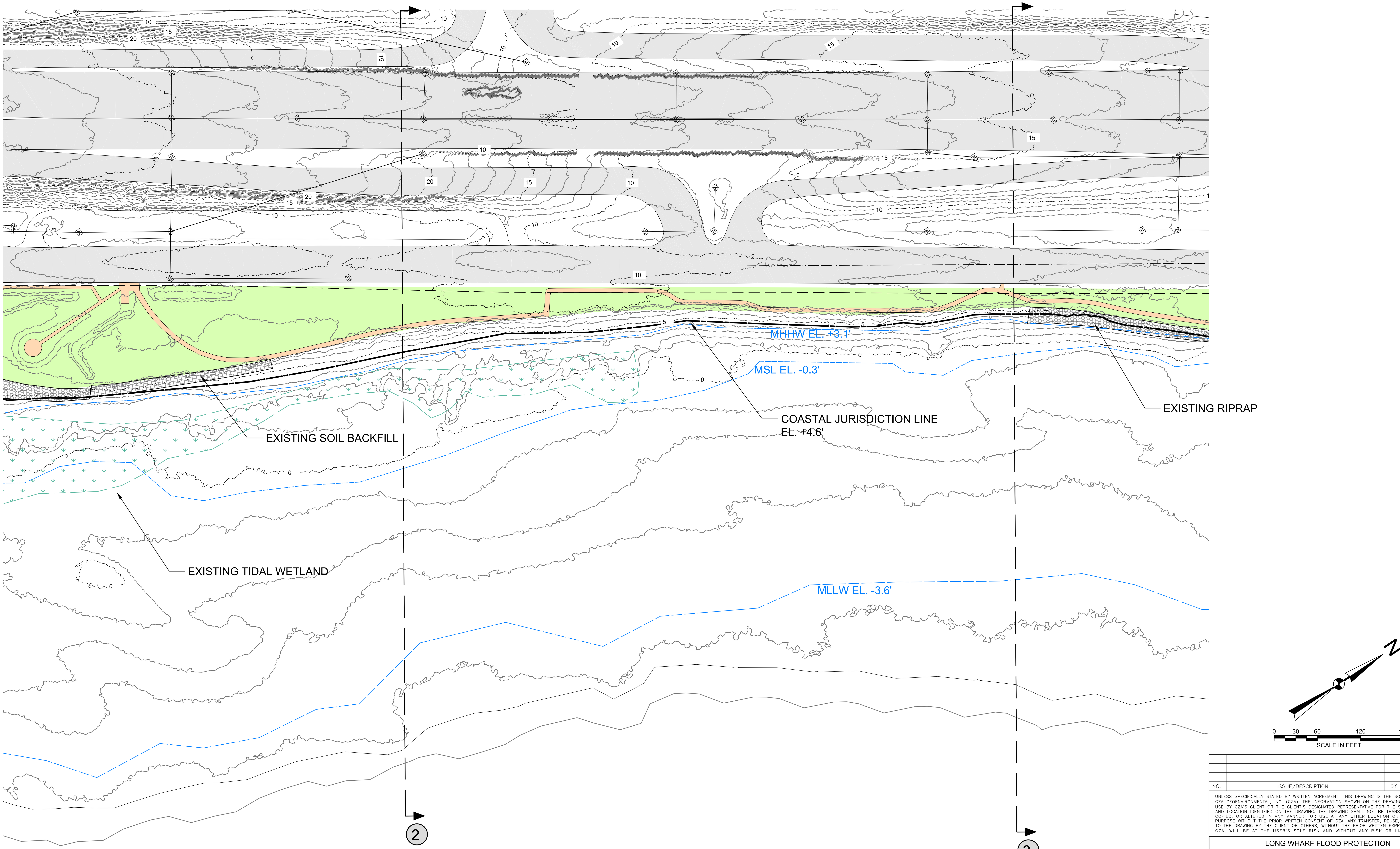
NEW HAVEN, CONNECTICUT

EXISTING CONDITIONS PLAN

PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE E1
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 2 OF 10



NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

EXISTING CONDITIONS PLAN

PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	E2
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 3 OF 10

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

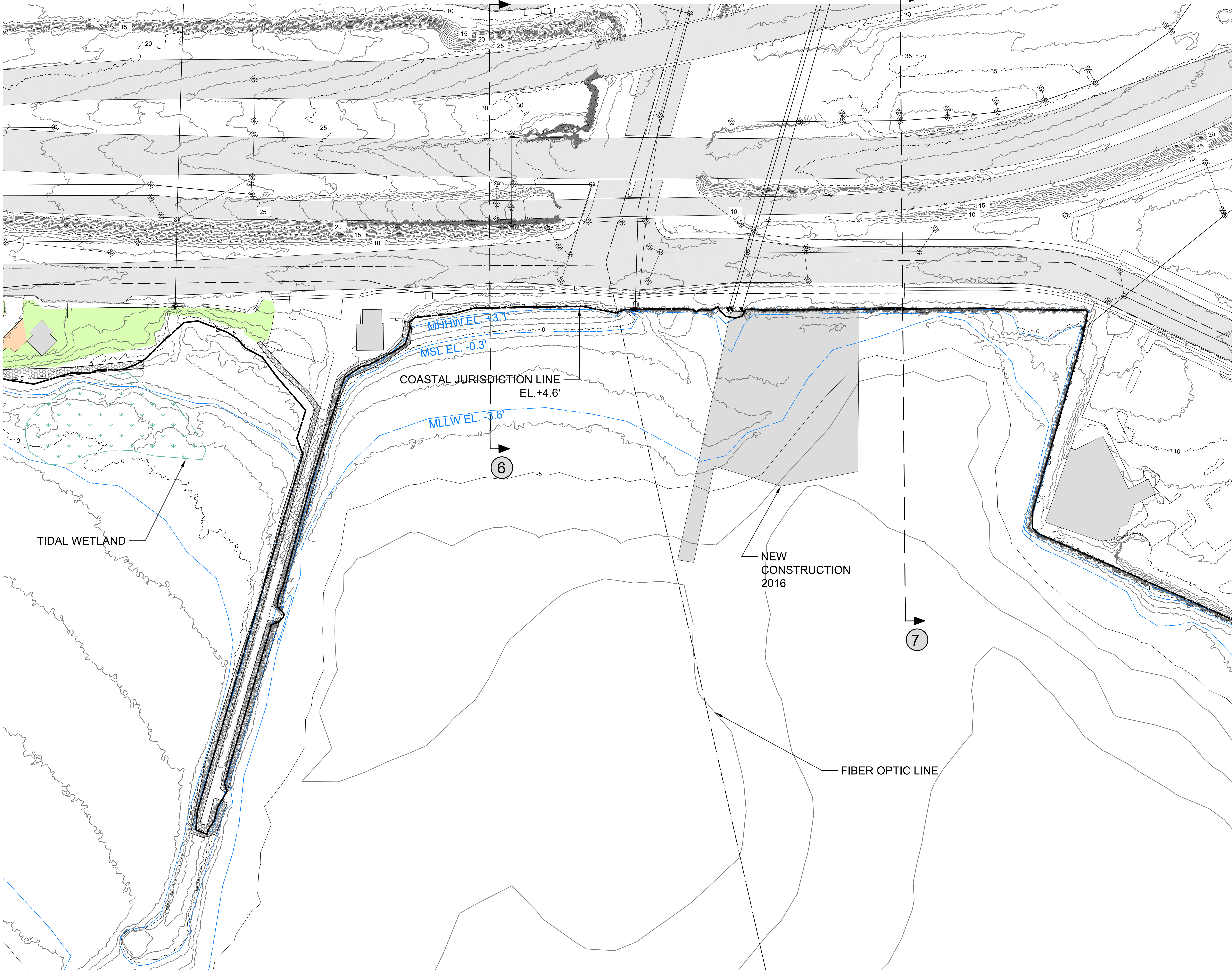
NEW HAVEN, CONNECTICUT

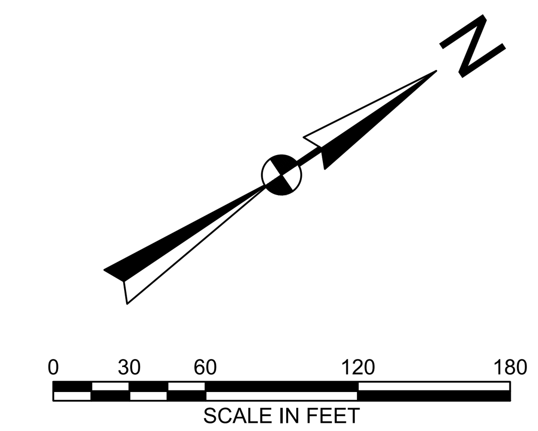
EXISTING CONDITIONS PLAN

PREPARED BY: GZA GeoEnvironmental, Inc. Engineers and Scientists www.gza.com

PREPARED FOR: CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE E3
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 4 OF 10





NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

EXISTING CONDITIONS PLAN

PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	E4
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 5 OF 10

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

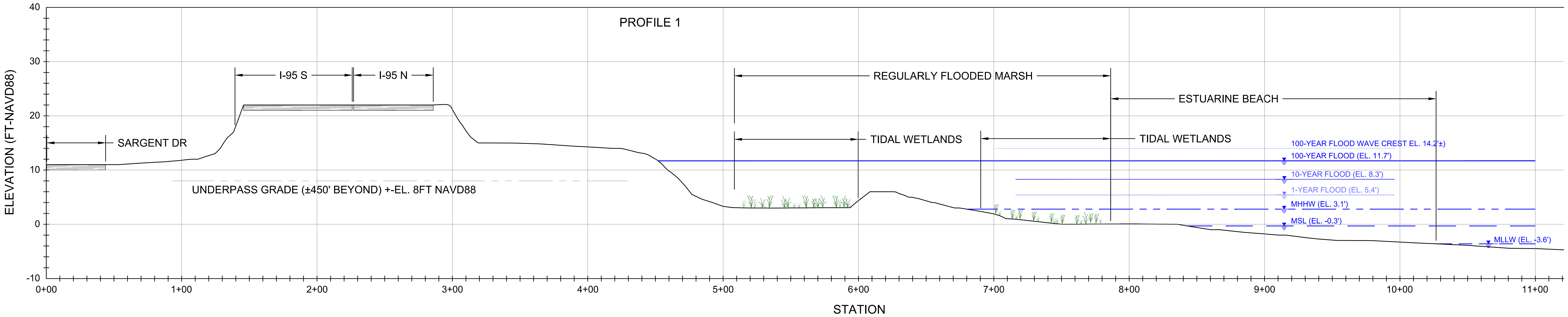
NEW HAVEN, CONNECTICUT

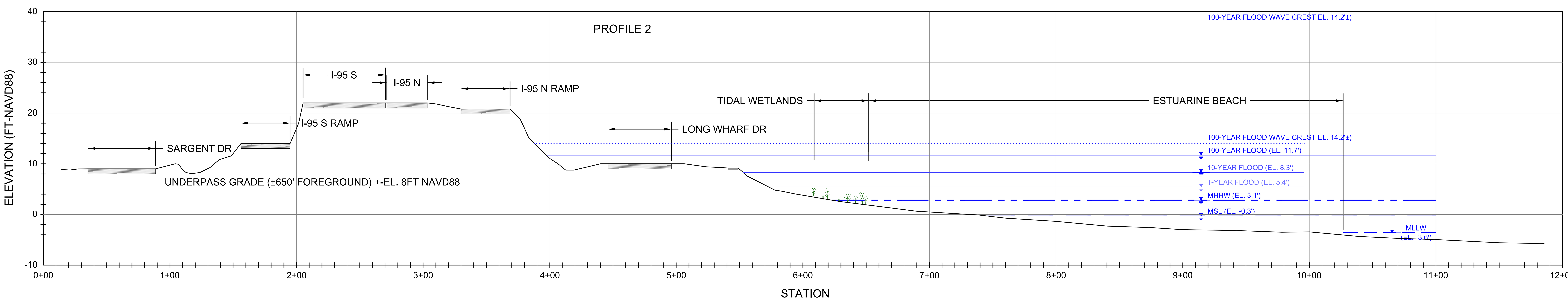
EXISTING CONDITIONS PLAN

PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE E5
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 6 OF 10





LEGEND

- GROUND SURFACE
- 100-YEAR FLOOD WATER TABLE ELEVATION
- MEAN HIGHER HIGH WATER WATER TABLE ELEVATION
- MEAN SEA LEVEL WATER TABLE ELEVATION
- MEAN LOWER LOW WATER TABLE ELEVATION

NOTES:

1. THE PROPOSED FLOOD WALL HAS A WALL THICKNESS OF 2', TOP OF WALL ELEVATION 14' NAVD88 AND DEPTH BELOW GROUND SURFACE OF 4'.

VERTICAL SCALE IN FEET (4x EXAGGERATION) 0 5 10 20 30
0 20 40 80 120
HORIZONTAL SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

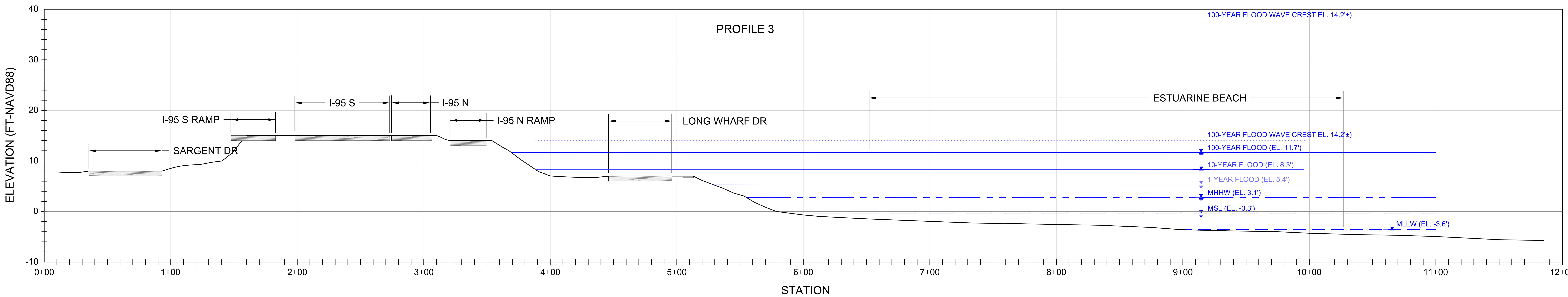
NEW HAVEN, CONNECTICUT

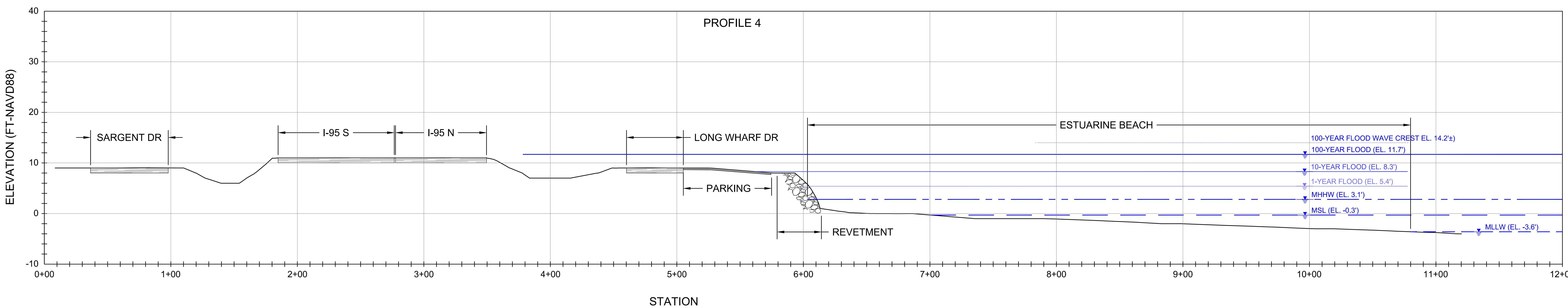
EXISTING PROFILES

PREPARED BY: GZA GeoEnvironmental, Inc. Engineers and Scientists www.gza.com

PREPARED FOR: CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	E6
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 7 OF 10





VERTICAL SCALE IN FEET (4x EXAGGERATION)
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0 20 40 80 120
HORIZONTAL SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

EXISTING PROFILES

PREPARED BY: GZA GeoEnvironmental, Inc. Engineers and Scientists www.gza.com

PREPARED FOR: CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
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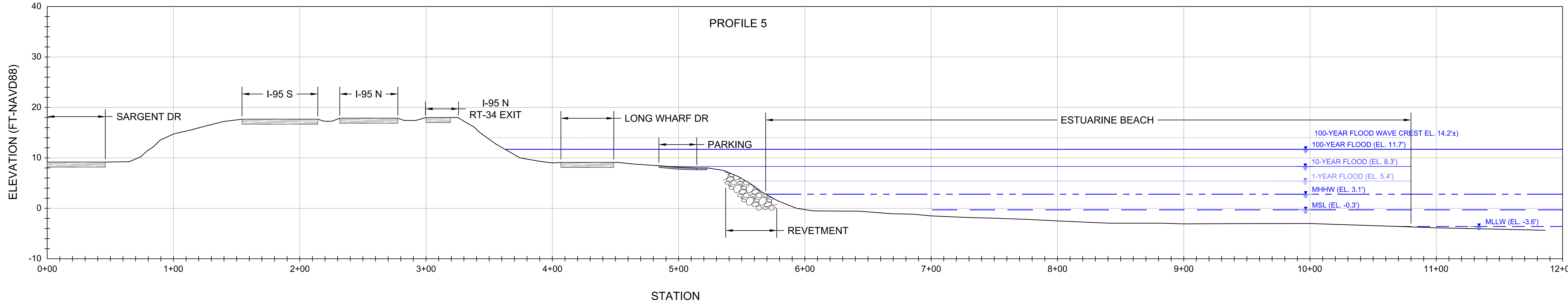
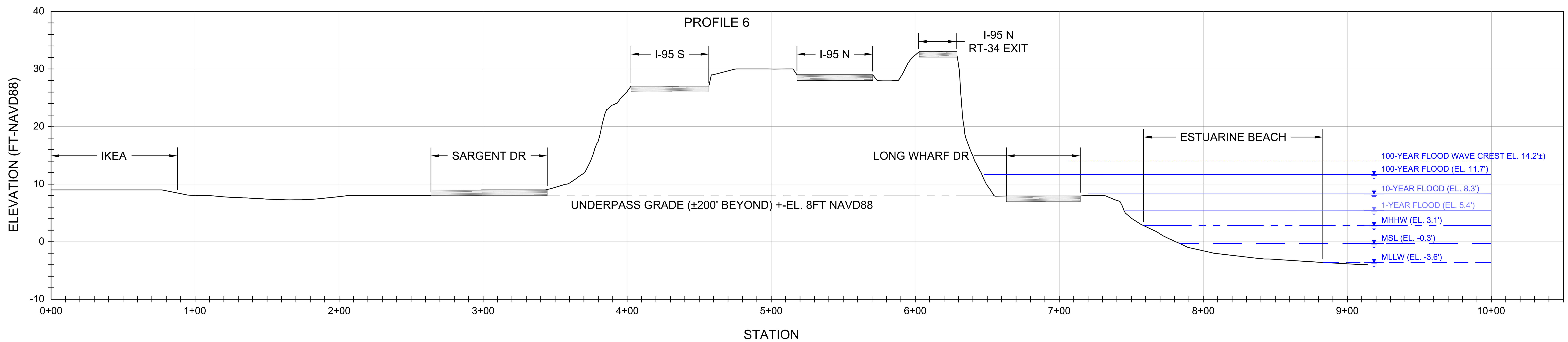
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 8 OF 10





VERTICAL SCALE IN FEET (4x EXAGGERATION)
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0 20 40 80 120
HORIZONTAL SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

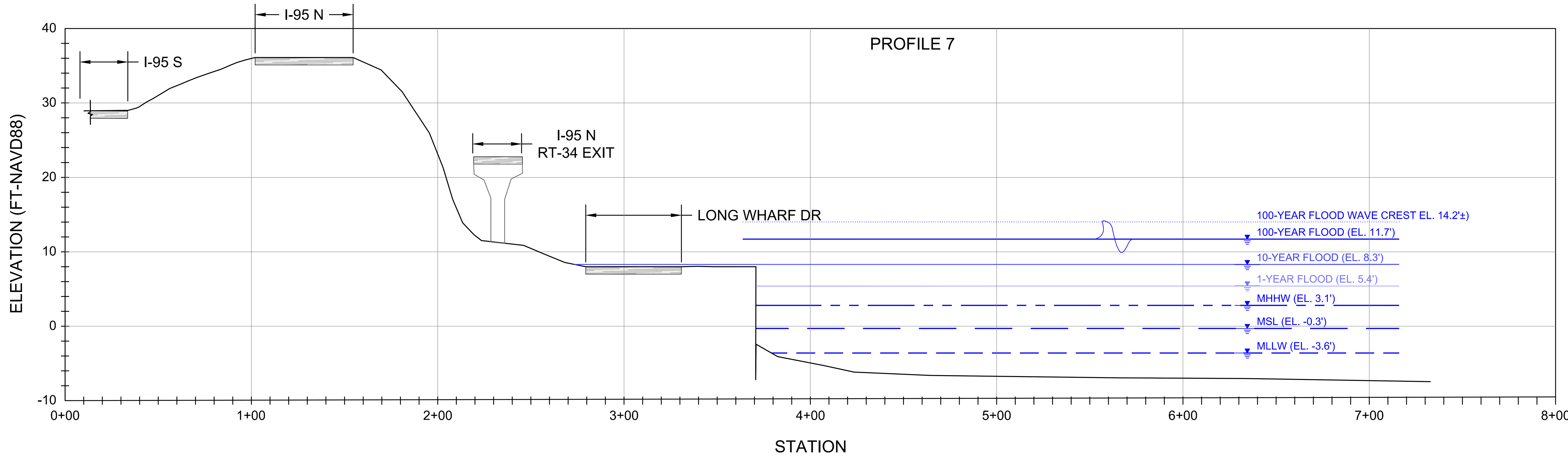
NEW HAVEN, CONNECTICUT

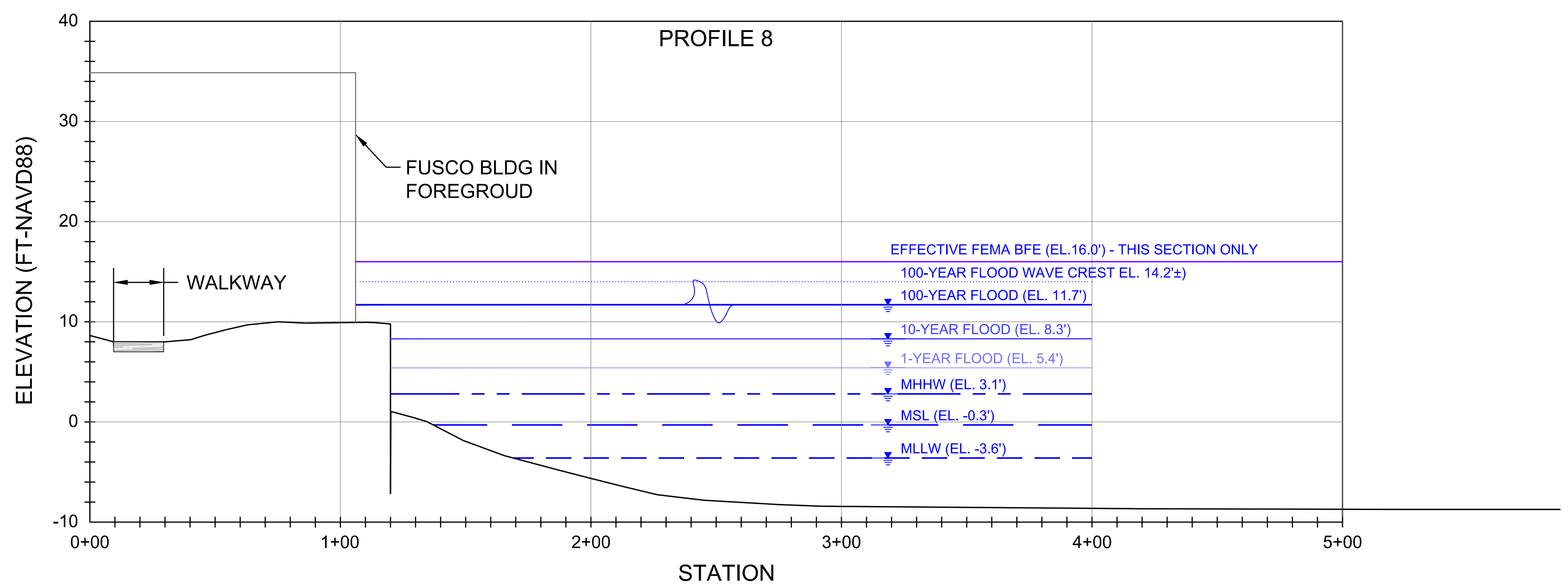
EXISTING PROFILES

PREPARED BY:
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	E8
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 9 OF 10





VERTICAL SCALE IN FEET (4x EXAGGERATION)
0 5 10 20 30
0 20 40 80 120
HORIZONTAL SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

EXISTING PROFILES

PREPARED BY:	PREPARED FOR:
GZA GeoEnvironmental, Inc. Engineers and Scientists www.gza.com	CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	E9
DATE: SEPTEMBER, 2016	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 10 OF 10

Attachment 4: Evaluation of Deployable Flood Protection Barriers

Introduction

Attachment 4 presents the results of GZA's evaluation of deployable flood barrier systems for use at roadway underpasses. See Figure 1 for location of flood barriers.
Coastal flooding of Project Study Area 3 occurs via flood propogation through existing highway underpasses including:

1. Canal Dock Road Underpass beneath I-95;
2. Long Wharf Drive Underpass beneath I-95; and
3. Brewery Street Underpass (closest to Water Street) beneath Rt. 34.

Flood protection Alternatives 2 and 3 utilize deployable flood barriers at the highway underpasses. GZA evaluated several temporary and permanent deployable flood barrier alternatives, including: 1) Permanent Systems; 2) Deployable/Permanent Systems; and 3) Temporary Deployable Systems (e.g. bladder dams, stop logs, etc.).

The suitability of alternative flood protection barriers to this project was evaluated relative to the following criteria, specifically:

- Flood resistance capacity including flood depth and hydrostatic, hydrodynamic and debris load resistance;
- Width of underpasses;
- Existing underpass structure (e.g., curbs, abutments, sidewalks, roadway crown, etc.);
- Installation and construction requirements (i.e., site modifications, surface preparation, etc.);
- Operational requirements including but not limited to:

a. How many people are needed to deploy the flood protection

b. How long does it take and what kind of equipment is needed for installation

c. What are the storage requirements for each alternative;

- Traffic Impacts;
- Storage requirements for each alternative; and
- Cost.

As discussed below, three flood barrier system categories were considered: 1) Permanent Systems, 2) Deployable/Permanent Systems and 3) Fully Deployable Systems.
The following presents flood risk and site details. Flood barrier alternatives are then discussed.

Figure 1: Location of Proposed Deployable Flood Barriers (FEMA Flood Hazard area shown)

Flood Risk and Site Details

Location 1: Canal Dock Road Underpass

Flood Protection Strategy: Deployable Permanent or Temporary Flood Barrier

Objective: The objective of this alternative is to provide deployable flood protection that prevents coastal floodwaters from passing through the Canal Dock Road underpass beneath I-95.

Ground Surface Elevation: Approximately Elevation 7 to 8 feet NAVD88

Flood Hazard Details: The flood hazard that is applicable to this location is summarized below:

- Effective FEMA Base Flood Elevation: Elevation 11 feet NAVD88
- Effective FEMA Stillwater Elevations:
  - 10% Annual Chance: Elevation 6.8 feet NAVD88
  - 2% Annual Chance: Elevation 8.3 feet NAVD88
  - 1% Annual Chance: 8.9 feet NAVD88
  - 0.2% Annual Chance: 10.5 feet NAVD88
  - 1% Wave Height: 1.5 feet or less
- GZA Flood Hazard Study (for the year 2016):
  - 1% Annual Chance: 12.4 feet NAVD88
  - 0.2% Annual Chance: 15.6 feet NAVD88
  - 1% Wave Height: 2.5 feet or less

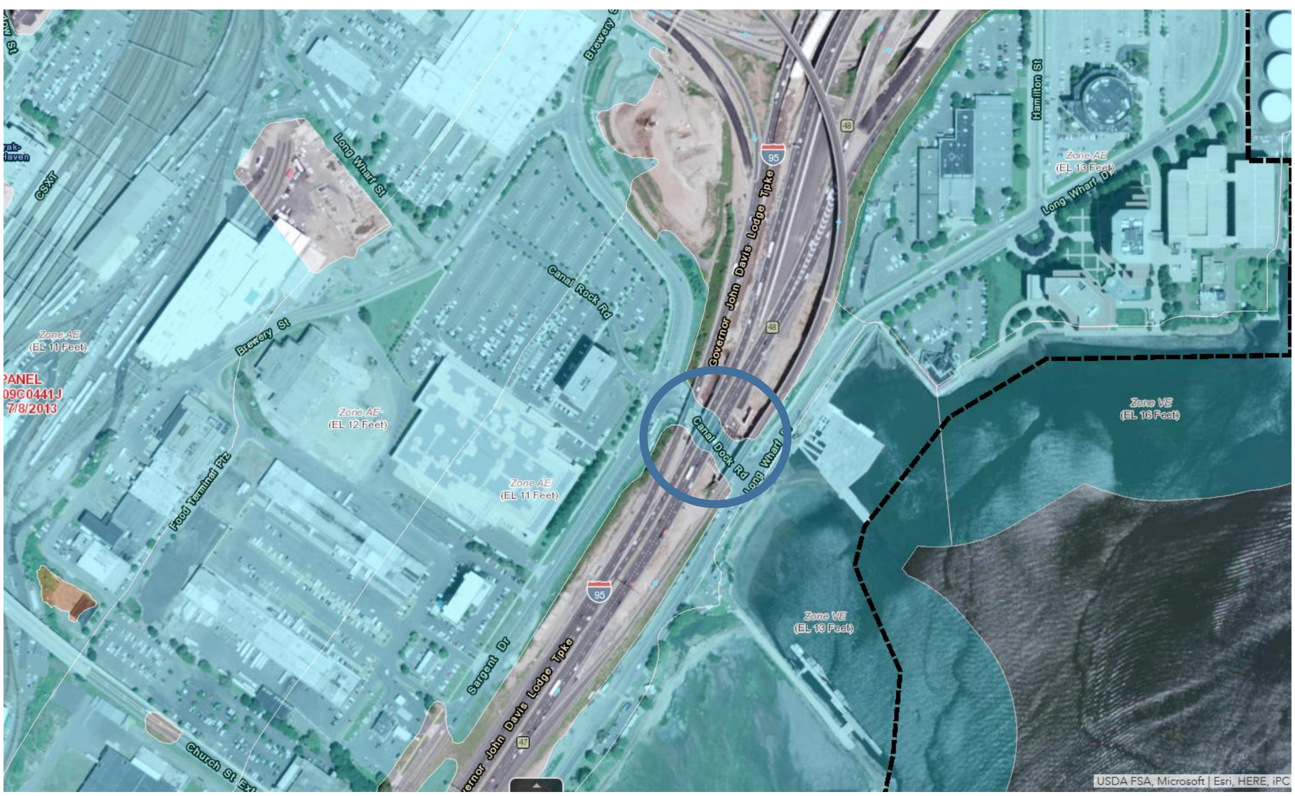
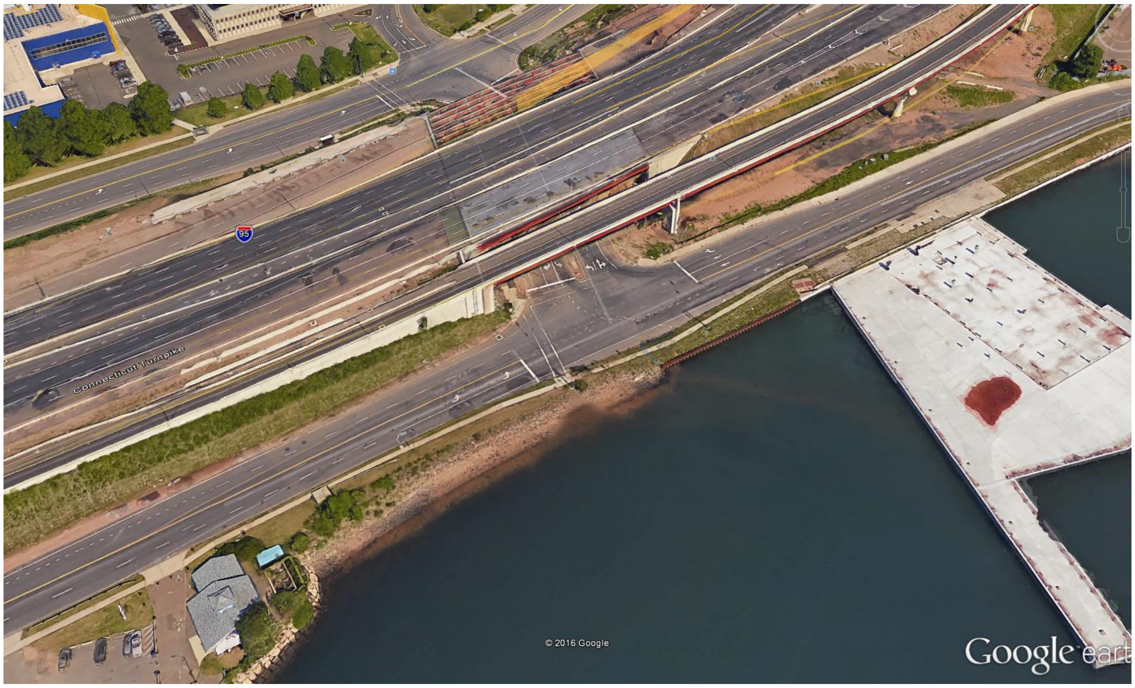


Figure 2: Canal Dock Road Underpass beneath I-95

Site Details: Three road section overpass Canal Dock Road. The middle overpass (I-95 Northbound) includes an earth embankment and would be the preferred location of the flood barrier. The third overpass (I-95 Southbound) is also an alternative. The width of the underpass is approximately 200 feet. There are raised sidewalks on both sides and a slight roadway crown with a raised medium strip.

Canal Dock Road Underpass Photographs:

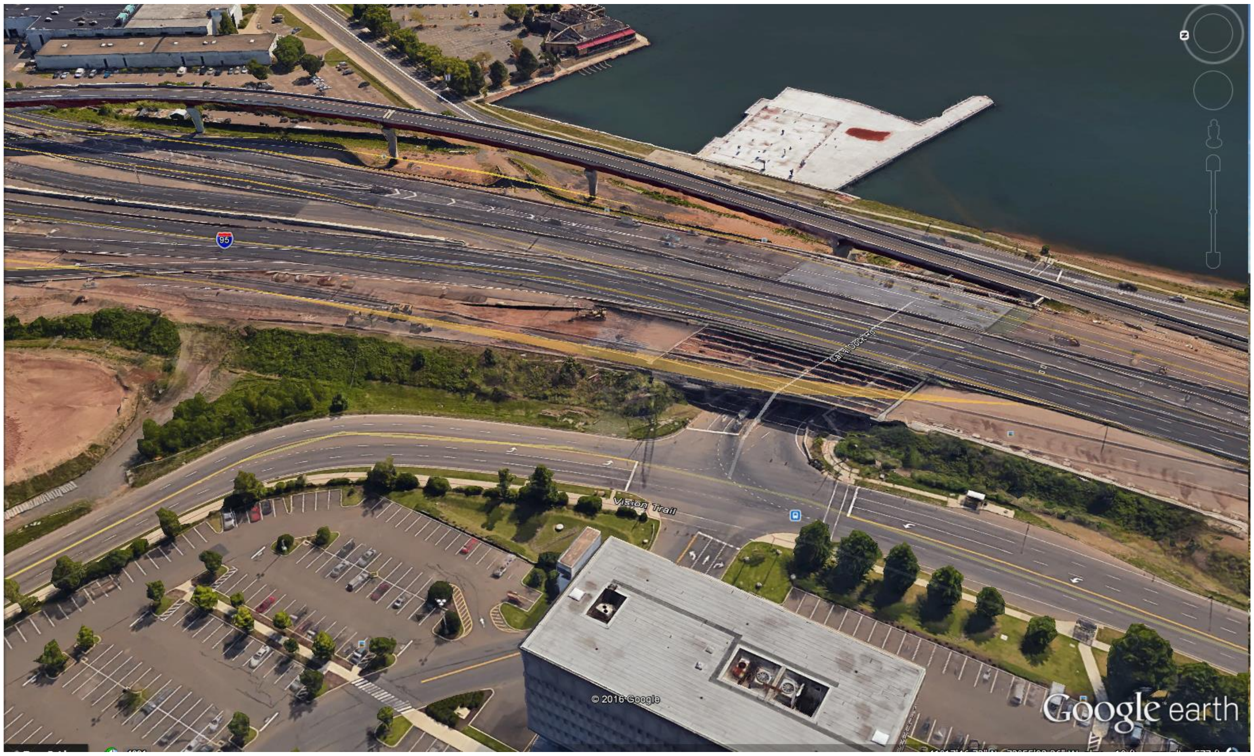



Long Wharf Dr
Exit Street View
© 2016 Google
© 2016 Google
Google earth


Long Wharf Dr
Exit Street View
©2016 Google
©2016 Google
Google earth


Canal Dock Rd
Exit Street View
©2016 Google
© 2016 Google
© 2016 Google
Google earth
Report a problem


Canal Dock Rd
Exit Street View
©2016 Google
© 2016 Google
© 2016 Google
Google earth
Report a problem
Tour Guide
Imagery Date: 1/2016 41°17'45.17" N 72°55'01.52" W elev 7 ft eye alt 15 ft


Vision Trail
© 2016 Google
Google earth


Sargent Dr
Exit Street View
© 2016 Google
Google earth
Report a problem

Location 2: Long Wharf Drive Underpass

Flood Protection Strategy: Deployable Permanent or Temporary Flood Barrier

Objective: The objective of this alternative is to provide deployable flood protection that prevents coastal floodwaters from passing through the Long Whar Drive underpass beneath I-95.

Ground Surface Elevation: Approximately Elevation 7.5 to 8.5 feet NAVD88

Flood Hazard Details: The flood hazard that is applicable to this location is summarized below:

- Effective FEMA Base Flood Elevation: Elevation 11 feet NAVD88
- Effective FEMA Stillwater Elevations:
  - 10% Annual Chance: Elevation 6.8 feet NAVD88
  - 2% Annual Chance: Elevation 8.3 feet NAVD88
  - 1% Annual Chance: 8.9 feet NAVD88
  - 0.2% Annual Chance: 10.5 feet NAVD88
  - 1% Wave Height: 1.5 feet or less
- GZA Flood Hazard Study (for the year 2016):
  - 1% Annual Chance: 12.4 feet NAVD88
  - 0.2% Annual Chance: 15.6 feet NAVD88
  - 1% Wave Height: <1 foot

Figure 3: Long Wharf Drive Underpass

Site Details: Two road section overpass Long Wharf Drive. Either overpass is an appropriate alternative for placement of the flood barrier. The width of the underpass is approximately 55 feet. There are raised sidewalks on both sides.

Long Wharf Drive Underpass Photographs:


Long Wharf Dr
Exit Street View
© 2016 Google
© 2016 Google
Google earth


Long Wharf Dr
Exit Street View
ONLY
Sargent Dr
© 2016 Google
© 2016 Google
Google earth

Location 3: Brewery Street Underpass

Flood Protection Strategy: Deployable Permanent or Temporary Flood Barrier

Objective: The objective of this alternative is to provide deployable flood protection that prevents coastal floodwaters from passing from the north through the Brewery underpass beneath Route 34 to project study Area 3. Note that the FEMA FIRM (shown below) does not show this flood hazard. GZA's modeling (which reflects higher flood levels) show flooding from Water Street through the underpass.

Ground Surface Elevation: Approximately Elevation 12 feet NAVD88

Flood Hazard Details: The flood hazard that is applicable to this location is summarized below:

- Effective FEMA Base Flood Elevation: Elevation 12 feet NAVD88
- Effective FEMA Stillwater Elevations (inferred by GZA):
  - 10% Annual Chance: Elevation 6.8 feet NAVD88
  - 2% Annual Chance: Elevation 8.3 feet NAVD88
  - 1% Annual Chance: 8.9 feet NAVD88
  - 0.2% Annual Chance: 10.5 feet NAVD88
  - 1% Wave Height: 1.5 feet or less
- GZA Flood Hazard Study (for the year 2016):
  - 1% Annual Chance: 12.4 feet NAVD88
  - 0.2% Annual Chance: 15.6 feet NAVD88
  - 1% Wave Height: <1 foot

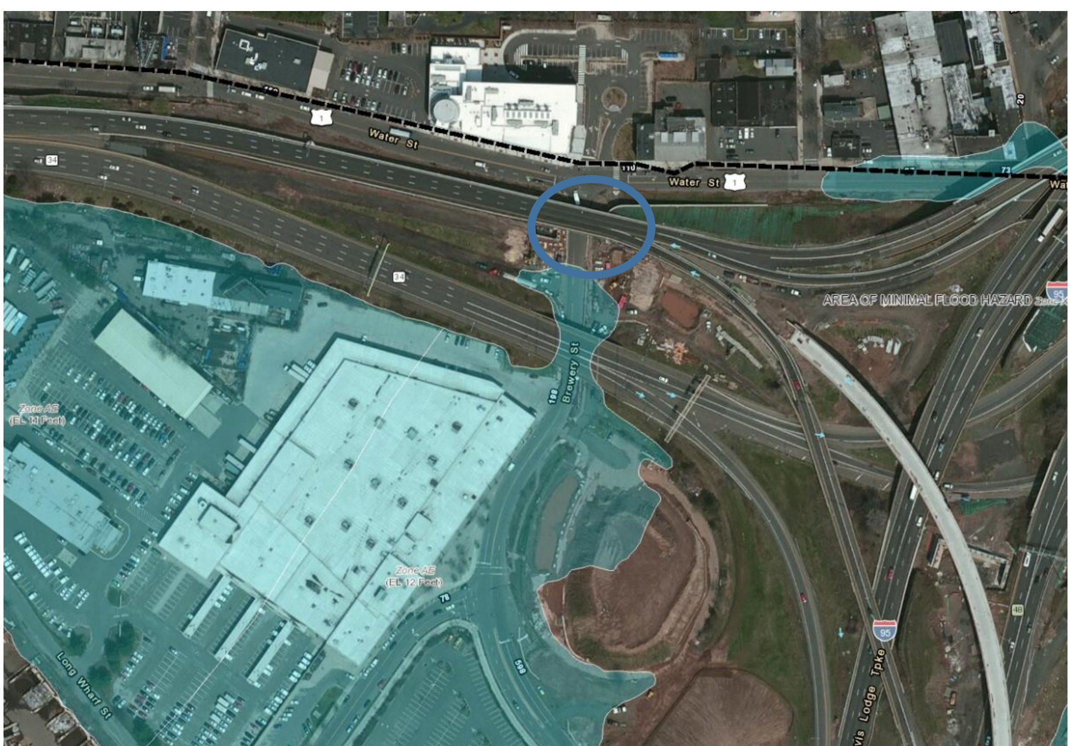


Figure 4: Brewery Street Underpass

Site Details: Two road section overpass Brewery Street including the Oak Street Connector to I-95 and Route 34. The Oak Street Connector overpass includes an earth embankment and vertical abutment walls and would be the preferred location of the flood barrier. The width of the underpass is approximately 100 feet. There are raised sidewalks on both sides and a slight roadway crown.

Brewery Street Underpass Photographs:

Flood Barrier Alternatives

GZA's evaluated about twenty delpoyable flood protection solutions. In consideration of the site conditions, criteria and flood protection objectives, eight deployable flood barrier sytems alternatives were identified as appropriate for the Canal Dock, Long Wharf Drive and Brewery

Street underpasses. The eight alternatives are organized into three system categories, including: 1) Permanent Systems, 2) Deployable/Permanent Systems and 3) Fully Deployable Systems.

PERMANENT SYSTEMS

- Hinged/Sliding Large Flood Barriers
- Self-Rising Flood Barriers

PERMANENT/PARTIALLY DEPLOYABLE SYSTEMS

- Stop Log Systems

FULLY DEPLOYABLE SYSTEMS

- Bladder Dams
- Rapid Deployable Earthen Flood Walls (Hesco)
- PortaDam
- AquaFence
- Portable Cylinder Barriers (Big Bags or Super Sack)

GZA contacted several flood barrier vendors to gather information on each alternative's construction and operational requirements. The list of the vendors are provided below:

- PortaDam
- AquaFence
- Presray – Self-Rising Flood Barrier
- Walz & Krenzer – Hinged Large Flood Barriers and Stop Log Systems
- FloodBreak

Permanent Flood Barrier Systems

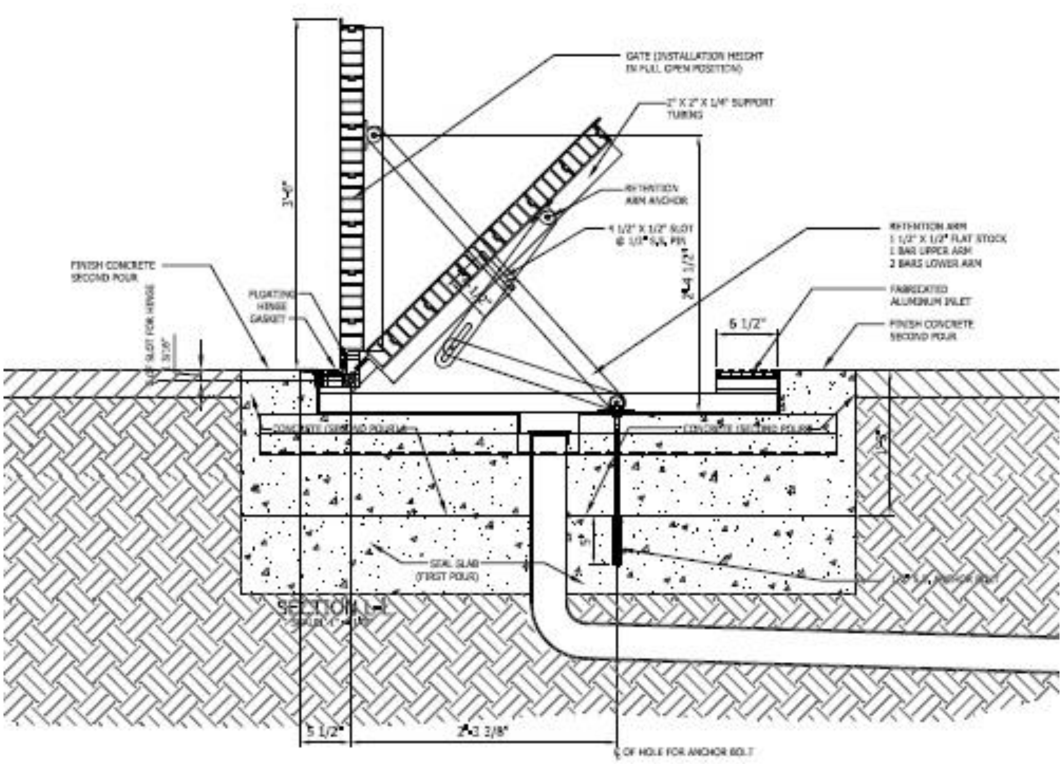
Permanent flood barrier systems are permanently installed and deployed on demand. The advantage of permanent, in-situ flood barrier systems is that they are already in place and do not need to be installed in advance of the flood. Some systems self-deploy automatically. Others require active intervention to deploy. Permanent systems are generally retractable (hinged or retractable).

I. Hinged Large Flood Barriers

Hinged barriers can either swing horizontally of vertically. Examples are shown below:

Examples of Horizontal Side Hinged Flood Barriers

Vertical Hinged Flood Barriers (examples shown are by FloodBreak)



Hinged Barrier Construction Requirements:

- ✓ Requires extensive site modification to install
- ✓ Requires level grade (e.g., pavement)

- ✓ Large hinge loads (side hinges mounted to abutments)
- ✓ Large post loads (if posts are used)
- ✓ Major Construction Project;
- ✓ High construction cost;
- ✓ Reuires retrofit of existing bridge structures

Hinged Barrier Operational Requirements:

- ✓ Approximately 4-6 people needed for side hinged barriers 40 to 50 feet wide by 8 to 11 feet high.
- ✓ During high winds it's recommended the barrier be supported with power equipment (forklift)
- ✓ Minimal deployment time
- ✓ Heavy gates will require power equipment to deploy (side hinged)
- ✓ Training required
- ✓ Need space to accommodate doors when open (side hinged)

II. Self-Rising Flood Barriers

Self-rising, retractable flood barriers utilize hydrostatic pressure from rising floodwaters to cause flood barriers to rise from a recessed location until the barrier is fully upright and automatically saeled. GZA could not identify a use of this system (at the required size and scale required for this project) in the U.S.

Self-Rising Barrier Construction Requirements:

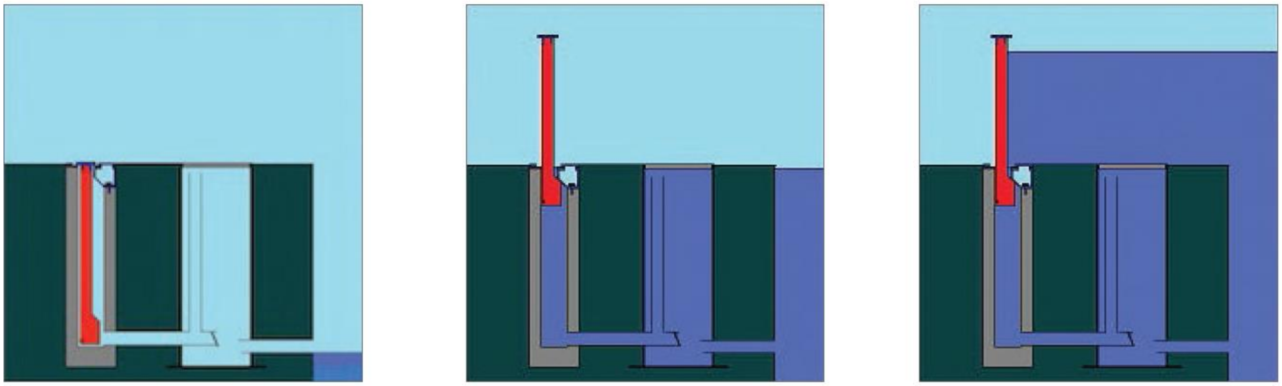
- ✓ All frames and sills need to be surface mounted to existing wall/slab
- ✓ Major Construction Project
- ✓ High construction cost
- ✓ Reuires retrofit of existing bridge structures
- ✓ Deep construction for self-rising system

Self-Rising Barrier Operational Requirements:

- ✓ No storage
- ✓ Minimal size crew required (depends on the size of the gate)
- ✓ Minimal deployment time
- ✓ Significant Maintenance
- ✓ Reliability Concerns

Examples of Self-Rising Flood Barrier

Advantages of Permanent Flood Barrier Systems



- ✓ Barrier is always there and ready for deployment
- ✓ No storage
- ✓ Minimal size crew required (depends on the size of the gate)
- ✓ Minimal deployment time

Disadvantages of Permanent Flood Barrier Systems

- ✓ Major Construction Project
- ✓ High construction cost
- ✓ Retrofit of existing bridge structures required
- ✓ Large width of underpasses at the limits of system technology

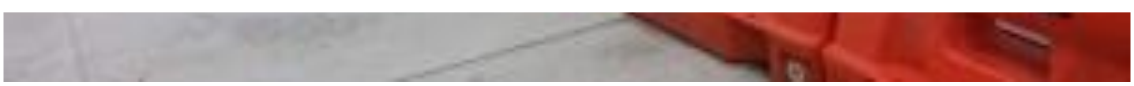
Partially Deployable/Permanent Flood Barrier Systems

Partially deployable/permanent flood barriers require permanent installation of certain system components like brackets and supports, with the flood barrier components installed on a temporary basis. Stop log systems are an effective alternative for this type of systems due to their flexibility, durability and cost effectiveness. Significant manpower is required to install. Component storage is also required. Typically, aluminum plank stop logs are used.

Stop Log Flood Barrier Systems

Stop Log Barrier Construction Requirements:

Examples of Aluminum Stop Log Flood Barrier



- ✓ Permanent anchoring mounts required
- ✓ Reinforced concrete foundation with embedded base plates, parting posts required
- ✓ Aluminum planks stored and temporarily installed

Stop Log Barrier Operational Requirements:

- ✓ Requires large team to deploy (example: to complete installation a 550 linear foot, approximately 10 foot high barrier required about 25 people to install within 4 hours).

- ✓ As an alternate system, if power equipment is available, a system with fewer parts could be deployed faster (say instead of 100 pound weight limit of each log, the limit is 1000 pounds)
- ✓ Training required
- ✓ Recommend color coding the bottom logs to facilitate the installation process
- ✓ Need storage that is accessible during the flood event
- ✓ Matching the road slope may be challenging as specific logs need to be placed in a specific order

Advantages of Partially Deployable/Permanent Flood Barrier Systems

- ✓ Low cost (relative to permanent flood barriers)
- ✓ Flexible (relative to flood protection barrier elevation and length)
- ✓ Modular system
- ✓ Simple and easy installation

Disadvantages of Partially Deployable/Permanent Flood Barrier Systems

- ✓ Some permanent components
- ✓ Longer deployment installation time (relative to permanent flood barriers)
- ✓ Large deployment team needed
- ✓ On-going training required
- ✓ Storage Required

Fully Deployable Flood Barrier Systems

Fully deployable flood barrier systems are fully deployed on a temporary basis, with no permanent installation required. There are several fully deployable flood barrier systems that are available. Systems range from inflatable bladders, to earthen fill to mecahnical structures.

I. Bladder Dams

Bladder dams are portable, water-inflated, temporary, reusable elongated flood barriers. The bladder tubes can be stacked in a pyramid structure and interlocked to increase flood protection height. The tubes are filled with water (from a hydrant or portable water pump). Bladder dam considerations:

- ✓ Requires surface clearing and subgrade preparation prior to placement (e.g. bladder dams);
- ✓ Inflated by pumping water inside the rubber body until the design height or pressure is reached.
- ✓ Deflated by allowing the air or water inside the rubber body to escape.
- ✓ Storage Required
- ✓ Clean operation; no hydraulic oil required; light structure
- ✓ Susceptible to vandalism

II.

Example of Inflatable Bladder Dam (example shown is the Tiger Dam system)

Deployable Earthen Fill Flood Barriers

Deployable earthen fill systems consist of rigid/shaped/flexible, earth filled geosynthetic or wire mesh containers and are a more efficient alternative to sand bags. These containers require mechanical equipment (e.g., front end loader) and significant manpower and deployment time to fill the containers. Annual training and assembly is required. On-site storage is required; in particular an on-site or nerby source of earth materials is required. Significant system takedown time and effort is also required. Earth-filled flood barrier system considerations:

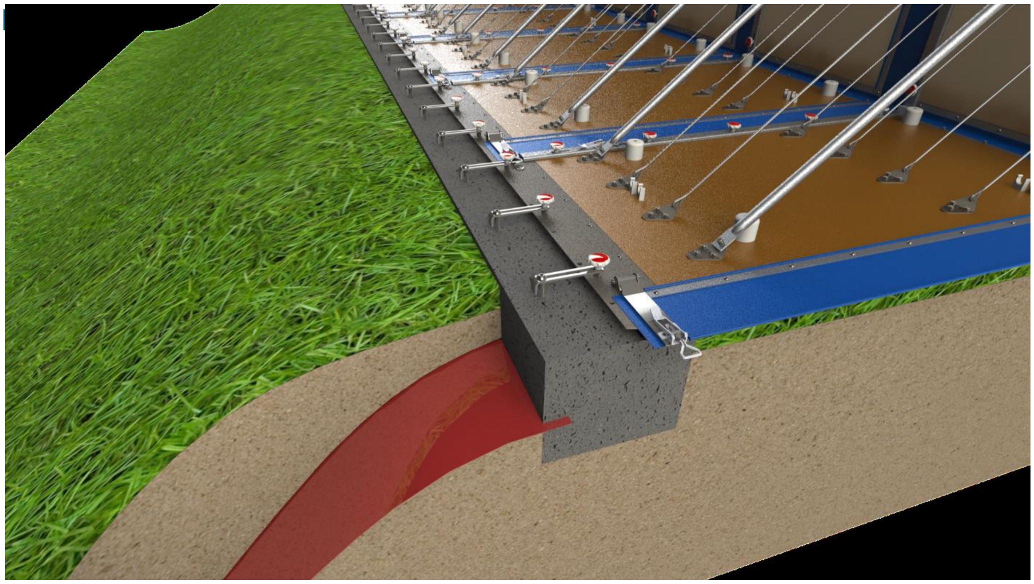
- ✓ Heavy equipment that is normally used to fill the bags are: Front End Loaders, Skid Steers, Backhoes, Side Dump Trucks, Cement Trucks (with a slurry of sand and water) and Concrete Conveyor belt Trucks.
- ✓ Time-consuming and labor intensive to deploy;
- ✓ May require a contractor to deploy;
- ✓ Requires storing sediment and materials off-site;
- ✓ Difficult training opportunities
- ✓ Storage requirements

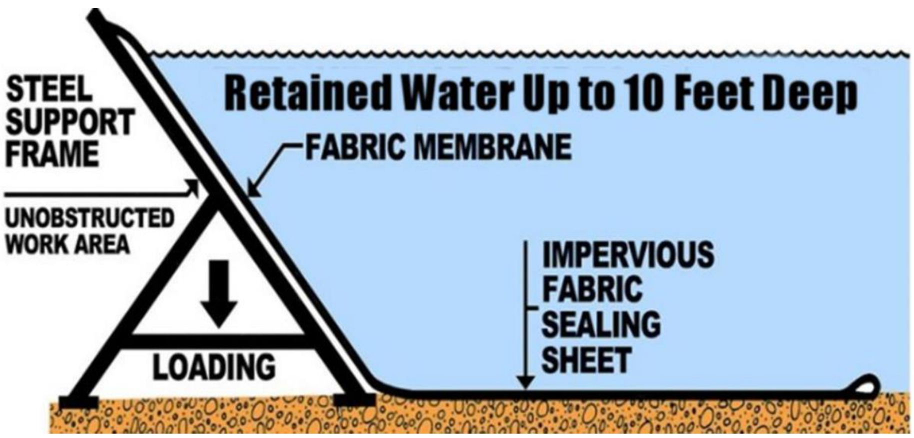
Examples of Earthen Fill Flood Barriers

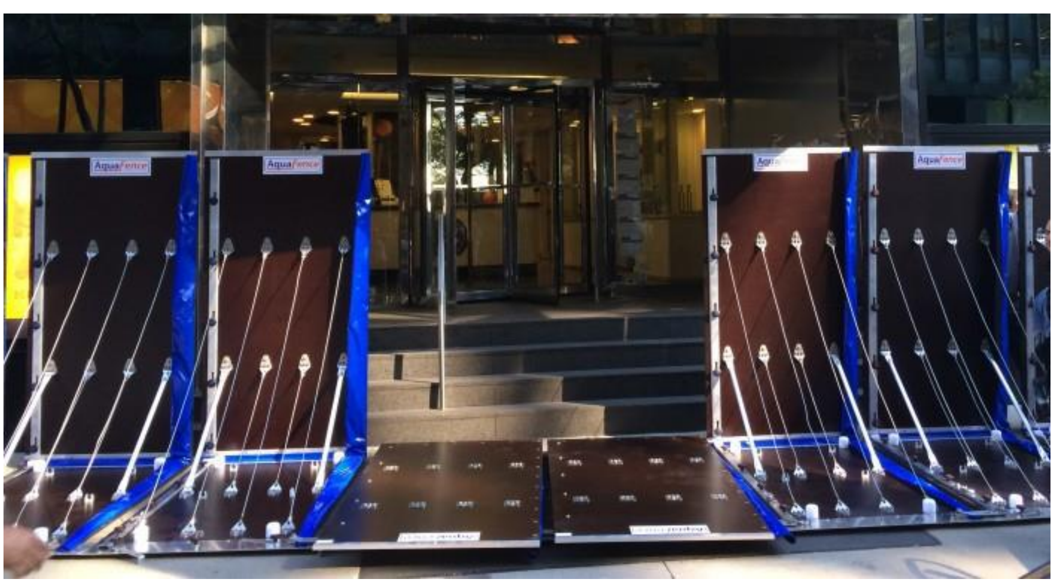
III. Panel Flood Barriers

Panel flood barriers (e.g., PortaDams, AquaDams, AquaFence) use flood mechanical flood panels as a temporary flood barrier/cofferdam. They typically require ground anchoring. The panels require lifting equipment and significant manpower to install. Annual training and material storage is also required. An example of installation time: a team of 10 assembled 328 feet in 1 hour. (ref. FM Global). Eight to 10 people can assemble 250 linear feet of 4-foot high panels in less than 2 hours. Panel flood barrier considerations include:

- ✓ Low cost relative to permanent systems
- ✓ Relatively simple system
- ✓ System requires require surfical clearing and subgrade preparation prior to placement;
- ✓ Frames will need to be anchored (drilled and pinned) to prevent sliding
- ✓ Storage Required
- ✓ Significant installation effort
- ✓ Requires large team to deploy
- ✓ Training required
- ✓ Long spans up to 100m
- ✓ Require Large Team to Deploy
- ✓ Susceptible to vandalism




STEEL SUPPORT FRAME
Retained Water Up to 10 Feet Deep
FABRIC MEMBRANE
UNOBSTRUCTED WORK AREA
IMPERVIOUS FABRIC SEALING SHEET
LOADING



Summary

Attachment 4 Table 1 presents a comparison of the deployable flood protection barriers.

Comparison Overview:

1. Permanent deployable flood barrier systems have the benefit of deploying readily when needed without significant warning and installation time and without siginificant manpower to deploy. However, there are significant issues associated with permanent flood barrier systems:

    a. Extensive modificaton of the existing bridge structures (e.g., abutments) and underpass roadways will be required. These structures were just recently constructed and retrofitting them at this time will be have very high capital costs and results in signficant traffic disruption during construction.

    b. Permanent deployable flood barriers will also have significant and regular maintenance requirements and costs.

    c. The physical layout of the underpasses does not support horizontal hinged or sliding permanent barriers.

2. In consideration of the above-noted limitation and ease of construction, it appears that the preferred permanent system would be vertical hinged barrier system. The flood protection capability of this system is on the order of 3 feet.

3. A permanent/partially deployable stop log flood barrier has the benefit of lower capital cost (relative to permanent systems). The system (using aluminum stop logs) are lightweight, durable and flexible. The system can also be installed to provide relatively high levels of flood protection (with lateral bracing). Some permanent installation (anchors, brackets, level concrete pad, etc.) is required. Additional, supplemental protection may also be advisable to resist debris loads an protect against vehicles. Additional requirements include:

    a. Storage facility;
    b. Emergency flood response plan;
    c. Periodic training (assume annually);
    d. Flood warning and installation time; and
    e. Installation manpower.

4. Fully deployable flood barriers have the lowest capital costs. They do not have permanent installation requirements. However, construction of a level concrete pad is desireable; alternatively temporary measures will be required to seal the contact between the system and the pavement and side wall contacts. Additional, supplemental protection may also be advisable to resist debris loads an protect against vehicles. Additional requirements include:

    a. Storage facility;

b. Emergency flood response plan;
c. Periodic training (assume annually);
d. Flood warning and installation time; and
e. Installation manpower.

5. Fully deployable earth filled systems are not expected to be practical for the proposed application in consideration of: a) need to have large quantity fill on-site or nearby; b) need for heavy equipment; c) long installation time; and d) long breakdown time.

6. Aluminum stop logs systems are th most durable of the partially and fully deployable options. Materal degradation and replacement should be expected for the other alternatives.

7. Level of Flood Protection: The level of flood protection available is dependent, in part, upon the flood barrier system capabilities. A reasonable flood protection goal is Elevation 15 feet NAVD88, which is equivelanet to the effective FEMA Base Flood Elevation plus 3 feet of freeboard.

Table Legend:

- Flood Retention and Adequate Loads: Yes = Y, No = N
- All other Criteria: High =H, Moderate=M, Low=L

CRITERIA	PERMANENT SYSTEMS		PERMANENT/PARTIALLY DEPLOYABLE SYSTEMS		FULLY DEPLOYABLE SYSTEMS			
	Hinged Large Flood Barriers	Self-Rising Flood Barriers	Stop Log Systems	Bladder Dams	Rapid Deployable Earthen Flood Walls (Hesco)	PortaDam	AquaFence	Portable Cylinder Barriers (Super Sack or Big Bags)
Flood Retention Water Height	8 to 12 feet[1]	8 feet	10 to 12 feet[1]	8 feet	No Limit[4]	5, 7 and 10 feet[5]	8 feet (barriers are up to 7 feet with a 1 foot extension)	10 feet[4]
Purchase Costs	H $6,100 linear foot[1]	H $5,300/ linear foot[2]	M $1,200/linear ft[1]	L $150/linear ft[3]	L $40/linear ft[4]	M $550/linear ft[5]	M $1000/linear ft[6]	L $5 linear ft[4]
Construction Costs	H	H	L to M	L	M	M	M	H
Operational/Installation Information and Issues	To complete installation for a 50ft W X 11ft H gate required a crew of 4-6 people. Power equipment (fork lift) may be required for deployment especially during high winds.		To complete installation within 4 hours for a 550ft W x 10ft H system, a crew of approximately 20-30 people were used as long as all of the parts were delivered in proper sequence.		• Will likely require contract with Hesco for deployment. • Large amounts of fill material will be needed for installation that will require the use of heavy equipment.	All frames on asphalt or concrete will need to be pinned to anchors to prevent sliding.	• A crew of 10 people will need 1 hour to deploy 100' of fence. • Equipment needed will be a forklift or van to get panels to site.	Large amounts of fill material will be needed for installation that will require the use of heavy equipment.
Operational Costs	None	None	M	L	H	H	M	H
Maintenance Costs	M	H	M	L	L	L	M	L
Storage Costs	None	None	M	L	L[7]	M	M	L[7]

Notes:

1. Based on quote provided to GZA by Walz & Krenzer, INC. on 09/14/2016. Purchase and installation costs included together as the overall cost estimate. Cost is for 8 feet water retention height for Hinged Large Barriers and 10 feet high Stop Log System.
2. Based on a quote provided to GZA by Presray on 09/14/2016 (Separate cost estimates for construction and purchase costs were included in the estimates provided by vendor)
3. Based on a quote provided to the City of New Haven on 08/23/2016 (Only purchase costs were included in estimate provided by vendor)
4. Costs provided by vendor for example application for similar project. Purchase cost is based on 4 feet high containers for Rapid Deployable Earthen Flood Walls and is based on a 72" bag with a 35 x 35" base for Portable Cylinder Barriers.
5. Based on quote provided by PortaDam on 09/06/2016. Estimate only included purchase costs. Purchase cost is based on 10 feet high PortaDam.
6. Based on quote provided by Aquafence on 09/01/2016. This quote includes cost for connection pieces to the wall ($2500 each) and connections over the six (6) curbs (at $4000 each) and debris shields ($80/linear foot). Estimate only included purchase costs.
7. This cost does not include the cost of storing the earthen material required to adequately deploy these measures

Cost Legend:

Construction costs refer to the cost for permanent modification of roadway and abutment as required to install the flood protection barrier.

Purchase:

- **Low** < $250 per linear foot; **Moderate** $250 to $1,500 per linear foot; **High** > $1,500 per linear foot

Construction (per abutment):

- **Low** < $500,000; **Moderate** $500,000 to $2,000,000; **High** > $2,000,000

Operations:

- **Low** < $20,000; **Moderate** $20,000 to $100,000; **High** > $100,000

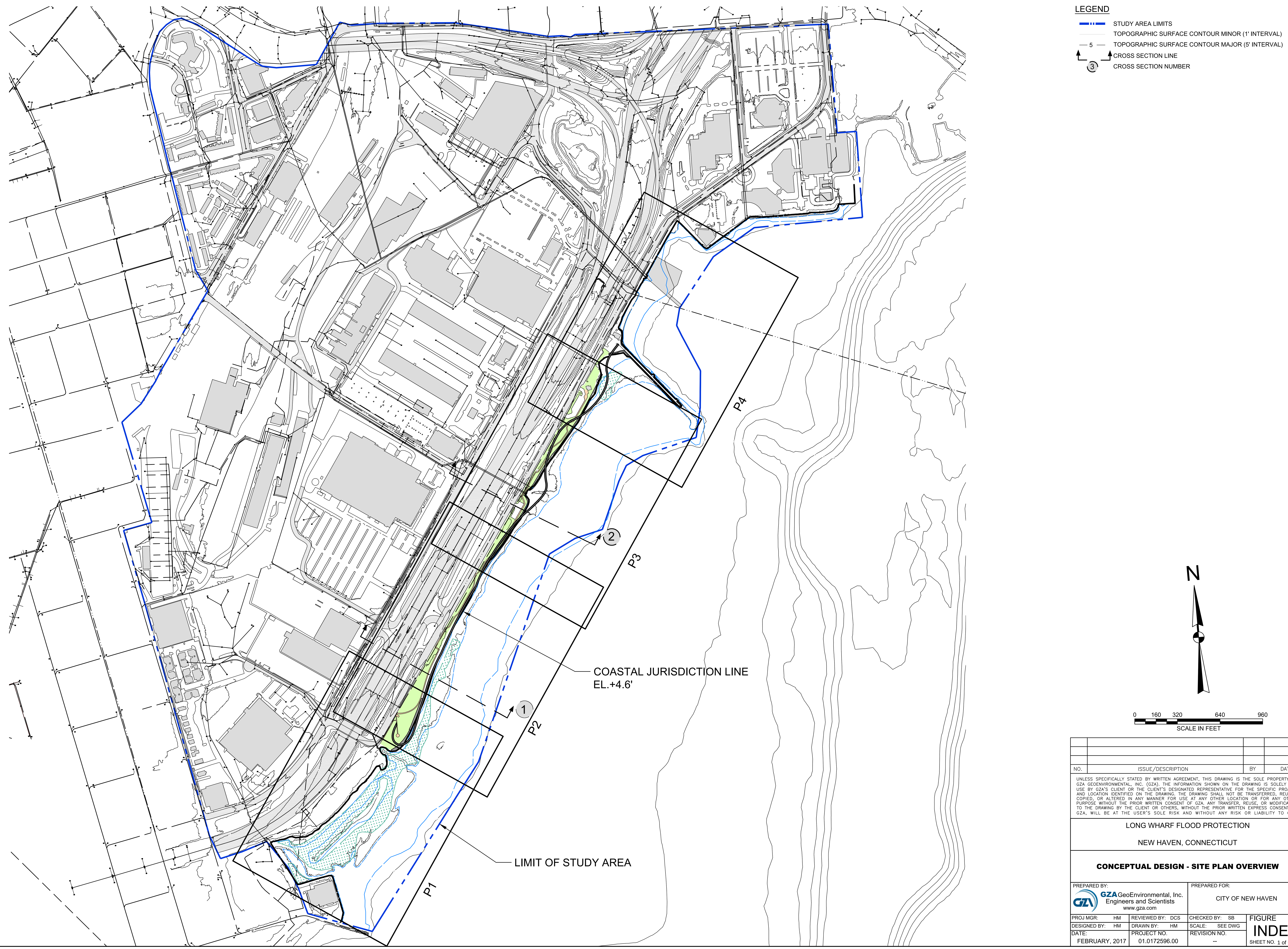
Maintenance:

- **Low** < $10,000; **Moderate** $10,000 to $50,000; **High** > $50,000

Storage:

- **Low** < $30,000; **Moderate** $30,000 to $100,000; **High** > $100,000

Attachment 5 – Alternative 4 Plan and Profiles



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LONG WHARF FLOOD PROTECTION

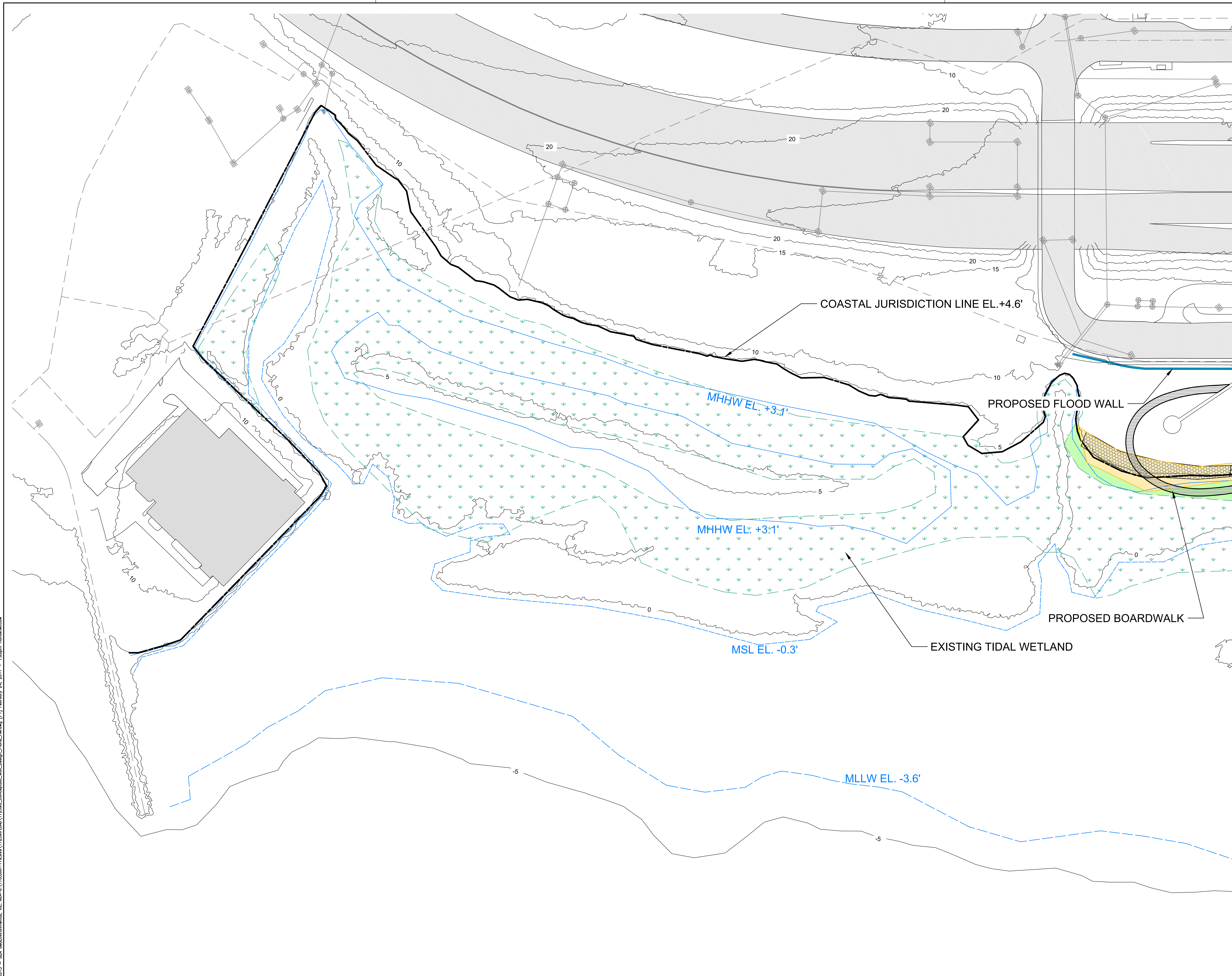
NEW HAVEN, CONNECTICUT

CONCEPTUAL DESIGN - SITE PLAN OVERVIEW

PREPARED BY: GZA GeoEnvironmental, Inc. Engineers and Scientists www.gza.com

PREPARED FOR: CITY OF NEW HAVEN

PROJ MGR: HM	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: HM	DRAWN BY: HM	SCALE: SEE DWG	INDEX
DATE: FEBRUARY, 2017	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 1 of 6



LEGEND

- PROPOSED CATCH BASIN
- ACTIVE CATCH BASIN
- ABANDONED CATCH BASIN (NOT SHOWN FOR CLARITY)
- DRAINAGE FEATURE
- PROPOSED MANHOLE
- ACTIVE MANHOLE
- ABANDONED MANHOLE (NOT SHOWN FOR CLARITY)
- PROPOSED OUTFALL
- ACTIVE OUTFALL
- ABANDONED OUTFALL (NOT SHOWN FOR CLARITY)
- ACTIVE SEWER CONNECTION
- ABANDONED SEWER CONNECTION (NOT SHOWN FOR CLARITY)
- STUDY AREA LIMITS
- ACTIVE DRAIN LATERAL
- ABANDONED DRAIN LATERAL (NOT SHOWN FOR CLARITY)
- PROPOSED DRAIN LINE
- ACTIVE DRAIN LINE
- ABANDONED DRAIN LINE (NOT SHOWN FOR CLARITY)
- ACTIVE FIBER OPTIC LINE
- ACTIVE SEWER MAIN
- BUILDING LOCATION
- ACTIVE RAILROAD CENTERLINE
- EDGE OF PAVED ROADWAY
- EDGE OF PAVED PARKING
- COASTAL JURISDICTION LINE (EL.+4.6' NEW HAVEN, CT)
- TOPOGRAPHIC SURFACE CONTOUR MINOR (1' INTERVAL)
- 5 TOPOGRAPHIC SURFACE CONTOUR MAJOR (5' INTERVAL)
- TIDAL WETLAND
- EXISTING RIPRAP
- EXISTING SOIL BACKFILL
- PROPOSED TIDAL WETLAND
- PROPOSED DUNE
- PROPOSED REVETMENT
- PROPOSED RIPRAP SILL
- PROPOSED BOARDWALK
- PROPOSED FLOOD WALL
- PROPOSED COIR LOG

NOTES:

1. THE BASE MAP WAS DEVELOPED FROM ELECTRONIC FILES PROVIDED BY CTGIS ENTITLED "2012 USACE POST-SANDY LIDAR" DATED: 2012 AND ENTITLED "TRANSPORTATION ARCHIVE GDB" DATED: 2010 FILE NAME: "TRANSPORTATION_ARCHIVE.GDB" AND ENTITLED "150814 STORMWATER GDB" DATED: 2016 FILE NAME: "150814 STORMWATER.GDB"
2. SOME PLANIMETRIC DATA INCLUDING: RAILROADS, ROADWAYS, BUILDING FOOTPRINTS AND PAVED PARKING WERE UPDATED FROM AERIAL IMAGERY PROVIDED BY MICROSOFT IN 2016.
3. ELEVATION CONTOURS BELOW -5 FEET (NAVD88) GENERATED BASED ON BATHYMETRIC DATA.
4. COASTAL SWAMP DELINEATION BASED ON A GIS LAYER NAMED "HYDROLOGYAREA2007".

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LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

PROPOSED CONDITIONS

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Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

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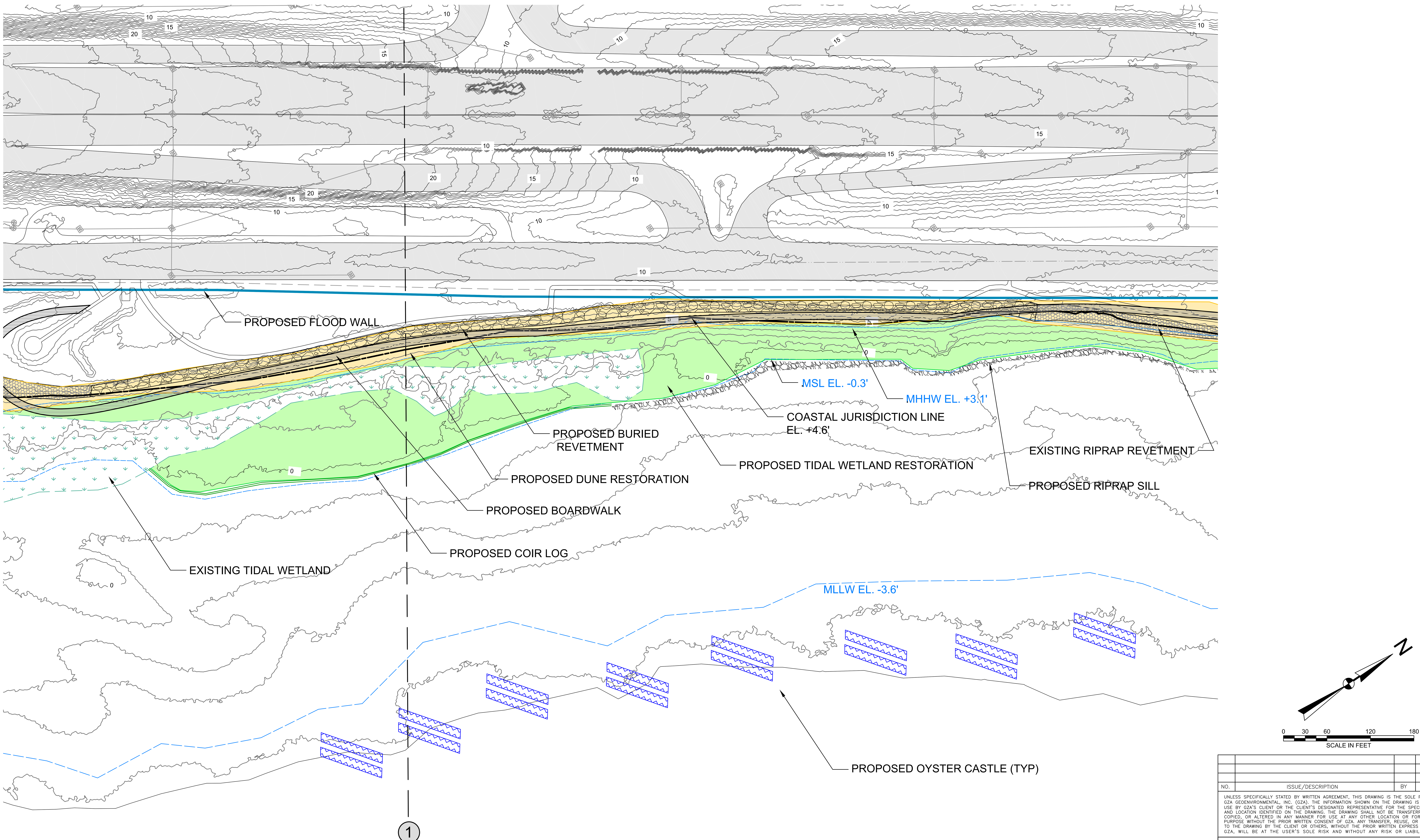

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LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

PROPOSED CONDITIONS

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PREPARED FOR: CITY OF NEW HAVEN

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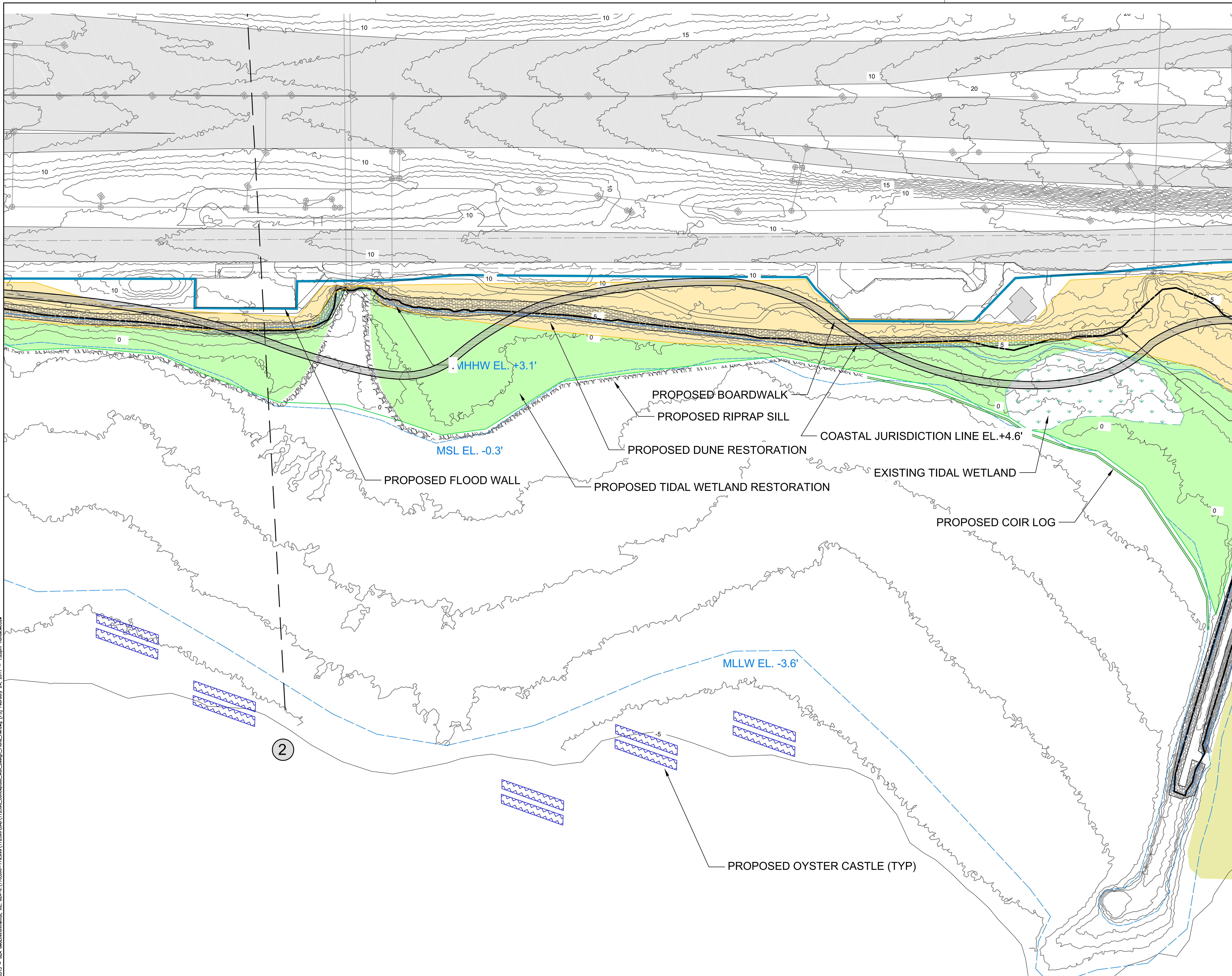

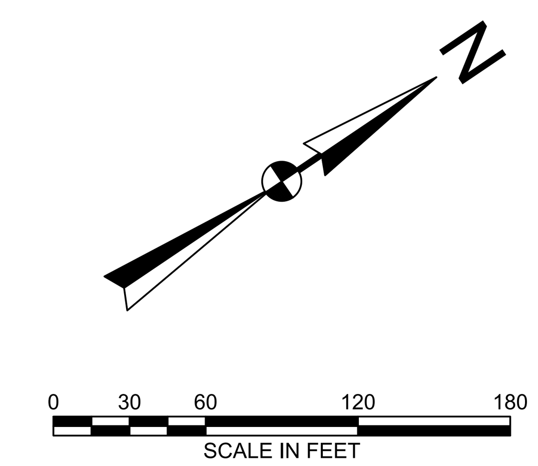

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LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

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LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

PROPOSED CONDITIONS PLAN

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Engineers and Scientists
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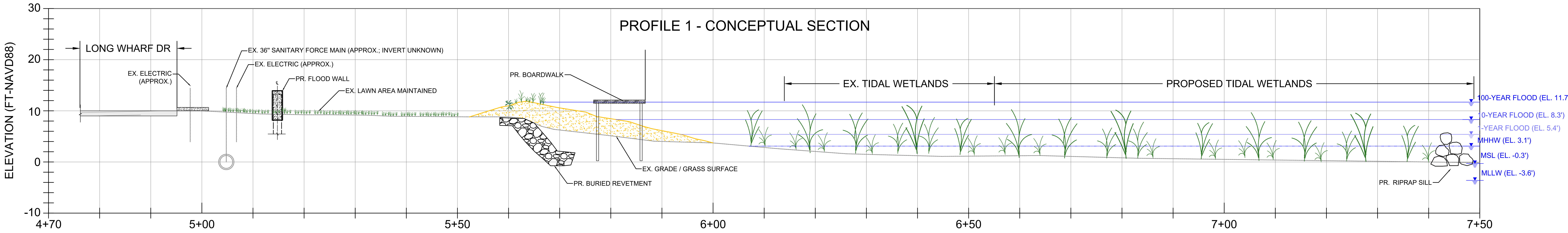
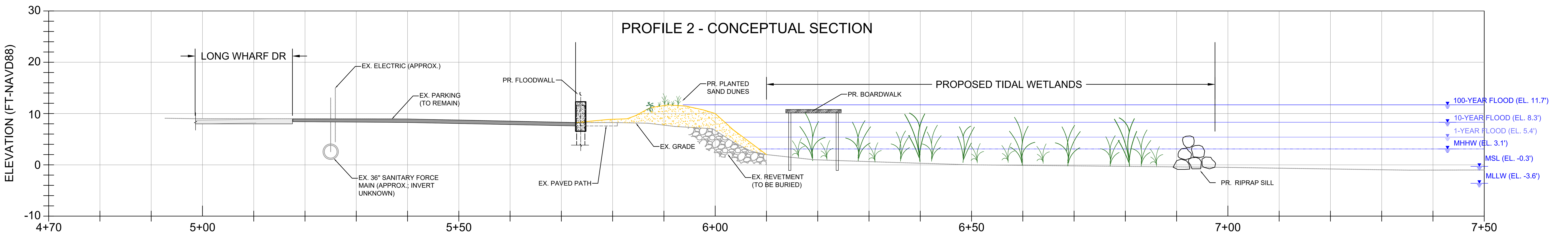
PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: HM	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE P4
DESIGNED BY: HM	DRAWN BY: HM	SCALE: SEE DWG	
DATE: FEBRUARY, 2017	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 5 of 6





VERTICAL SCALE IN FEET
0 5 10 20 30
0 5 10 20 30
HORIZONTAL SCALE IN FEET

NO.	ISSUE/DESCRIPTION	BY	DATE

LONG WHARF FLOOD PROTECTION

NEW HAVEN, CONNECTICUT

PROPOSED PROFILES - SECTIONS

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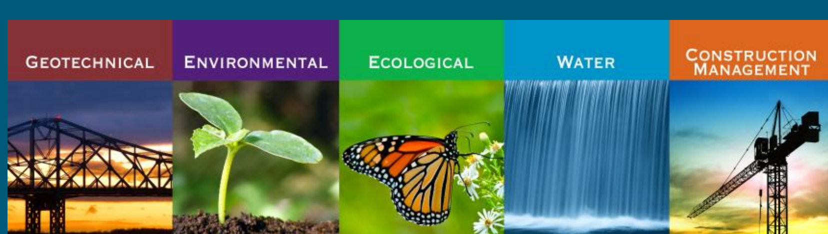
GZA GeoEnvironmental, Inc.
Engineers and Scientists
www.gza.com

PREPARED FOR:
CITY OF NEW HAVEN

PROJ MGR: SB	REVIEWED BY: DCS	CHECKED BY: SB	FIGURE
DESIGNED BY: BW	DRAWN BY: BW	SCALE: SEE DWG	P101
DATE: FEBRUARY, 2017	PROJECT NO. 01.0172596.00	REVISION NO. --	SHEET NO. 6 of 6



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