# NEW HAVEN HARBOR
# CONNECTICUT
# NAVIGATION IMPROVEMENT PROJECT

# DRAFT INTEGRATED FEASIBILITY REPORT AND ENVIRONMENTAL IMPACT STATEMENT

## APPENDIX E
## COASTAL ENGINEERING

# NEW HAVEN HARBOR, CT
# NAVIGATION IMPROVEMENT STUDY
# FEASIBILITY STUDY

# APPENDIX E
## COASTAL ENGINEERING

August 2018

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# 1.0 Study Overview

The New Haven Harbor Navigation Improvement Study investigated the feasibility of improving the New Haven Harbor, Connecticut Federal Navigation Project to decrease inefficiencies caused by tidal delays while promoting safe navigation for deep draft vessels servicing the Port of New Haven. The location of the study area can be seen in Figure 1-1. Within the study area are the cities of New Haven and West Haven, both of which are within southern New Haven County along the north shore of Long Island Sound.

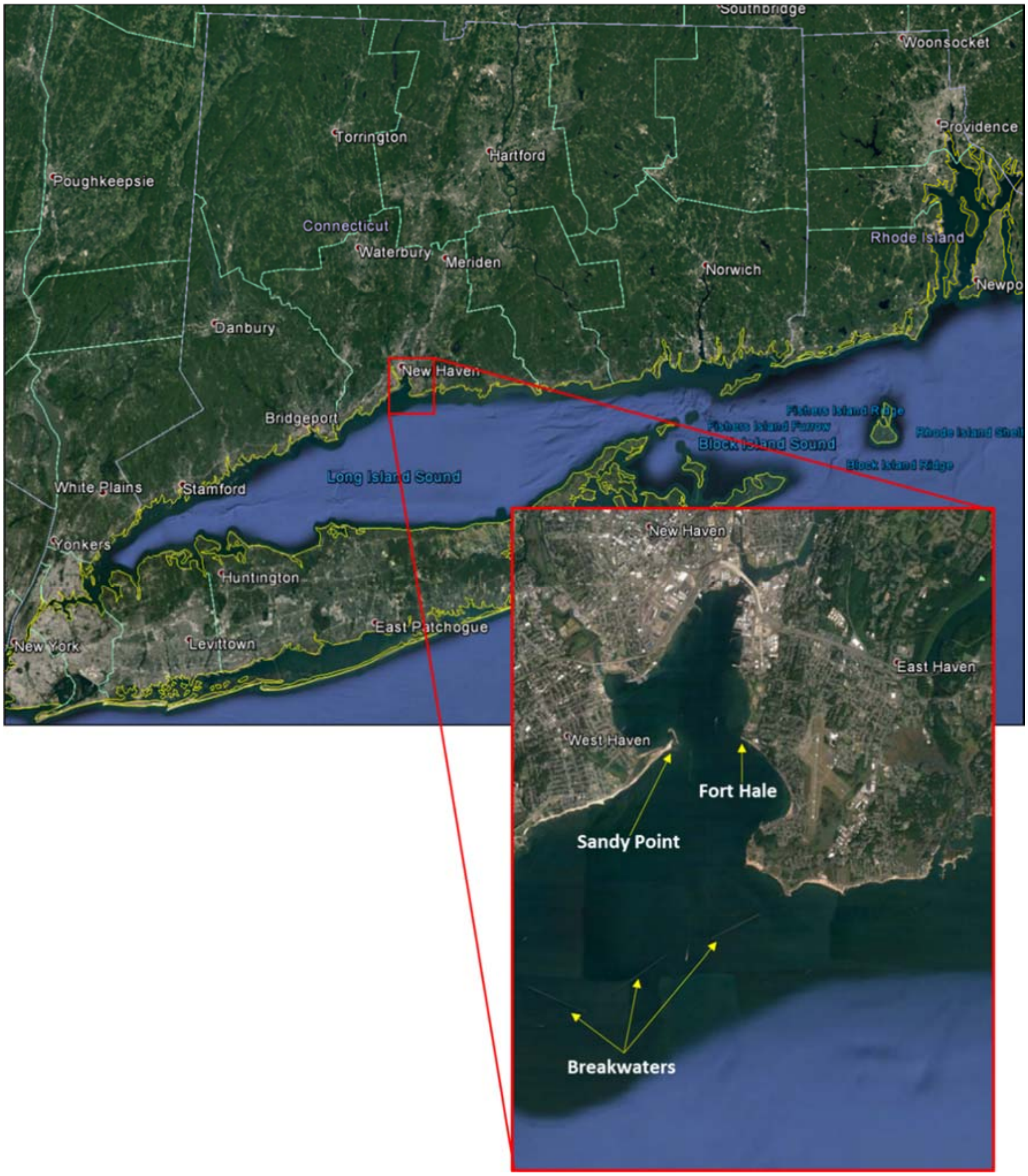

**Figure 1-1. Study Location Map**

To improve the Port's economic efficiency and the channel's navigability, the study considered structural improvements to the channel such as deepening, widening, and realignment, and placement options for dredged material. The study also evaluated the resilience of the Port of New Haven and existing and proposed features of the Federal Navigation Project to sea level change. The study relied upon existing available information and did not require the collection of additional data.

## 1.1 Study Area

New Haven Harbor, a bay on the northern side of Long Island Sound, is located 75 miles northeast of metropolitan New York City. Three detached breakwaters protect the entrance to New Haven Harbor from Long Island Sound. The deepwater entrance of the main ship channel to the harbor lies between the Luddington Rock (Central) Breakwater and the East Breakwater. The ship channel extends approximately 5.7 miles from deepwater in the Sound to the head of the harbor. The harbor terminals are situated in the inner portion of New Haven Harbor, north of Sandy Point on the west and Fort Hale on the east, below the head of the harbor. The Mill and Quinnipiac Rivers empty into the head of the harbor through a common mouth at Tomlinson Bridge (Route 1) while the West River enters the west side of the harbor about 1 mile below its head. All said, New Haven Harbor is approximately 4.5 miles long and varies from 1 to 4 miles in width.

Within the study area there are several fairly defined areas that can be considered separately. Brief descriptions of each area and its exposure to coastal forcings is provided below.

### 1.1.1 Port of New Haven

The Port of New Haven resides at the north end of the study area just south of the head of the harbor. The Port is comprised of a group of privately owned facilities, collectively administered by the New Haven Port Authority, primarily situated on the east side of the harbor south of the Interstate 95 highway corridor. The Port of New Haven and the harbor terminals included in the study area are shown in Figure 1-2. New Haven Harbor is the largest port in Connecticut and the second largest in New England, behind Boston, based on commercial tonnage. Petroleum products account for the majority of the tonnage, with the remainder consisting of scrap metal, steel, and minerals. The New Haven fuel facilities are part of the U.S. Government's Strategic Petroleum Reserve. Pipeline connections from the port handle jet fuel for Bradley International Airport and for the Massachusetts Air National Guard Base in Westover, Massachusetts. The port also benefits from its proximity to the interstate highway and rail freight networks. At the head of the harbor, the port is sheltered from strong winds and waves approaching from most directions, but does experience daily tidal water level fluctuations and, less frequently, storm surge generated by tropical and extratropical storms.

**Figure 1-2. Port of New Haven Terminals**

### 1.1.2 Main Ship Channel and Turning Basin

The main ship channel extends from deepwater in Long Island Sound through the harbor breakwaters to the head of New Haven Harbor. The federal navigation channel has been improved numerous times as the port has grown with increased demands of commerce and to accommodate longer, deeper draft vessels. However, with the exception of maintenance dredging, there has been no modification to the navigation channel at New Haven Harbor since 1950 when dredging of the existing 35 foot main channel, shown in Figure 1-3, was completed. The entrance channel width in Long Island Sound is 500 feet and widens to 560 feet at the bend between the breakwaters. The channel width is 400 feet from the bend north past Fort Hale and Sandy Point, where it widens again to 500 feet. In the vicinity of the Port of New Haven, the channel and maneuvering area are 800 feet wide. The project also includes a 35 foot deep, trapezoidal-shaped turning basin west of the main channel across from New Haven Terminal.

Vessels transporting commodities to and from the port experience navigation difficulties due primarily to the limitation imposed by the existing 35 foot channel depth. Inbound ships are disproportionately affected as they enter New Haven Harbor fully-loaded, drawing more water. The presence of a rock bottom in part of the channel makes a 4 foot clearance mandatory for visiting ships. Therefore, with the existing channel depth at 35 feet, a ship must either come into port with a draft of 31 feet or less, or wait for proper tidal conditions before entering the harbor. Using the full 6 foot tide range, ships drawing up to 37 feet can transit the channel at high tide. In addition to tidal delays, ships drafting over 37 feet must first lighter in Long Island Sound to offload cargo to meet the depth restriction.

Other navigation difficulties include channel width and alignment problems associated with safely maneuvering today’s larger ships within the confines of the existing channel, most notably at the channel’s bend between the breakwaters (Figure 1-4). With the existing approach, inbound vessels favor the starboard side of the channel, lining up nearest the red buoys, in anticipation that they will be set by the east to west flood current and experience bank suction at the bend which pulls their stern to port. In order to make this turn and straighten up to make the next set of navigation buoys, ships have to make full use of their rudder and engine, leaving little room for adjustment or error.

Figure 1-3. New Haven Channel, NOAA Chart 12371

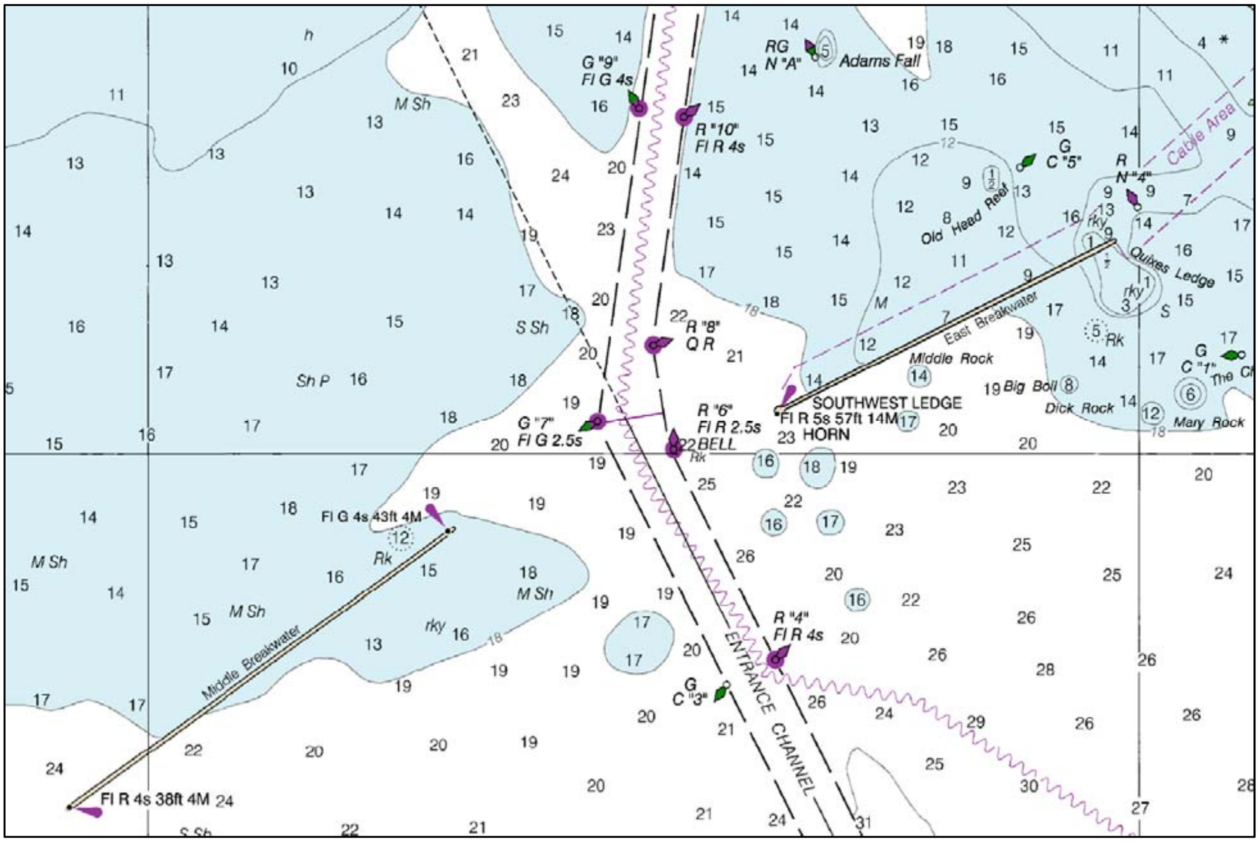

**Figure 1-4. Channel Bend at Breakwaters**

### 1.1.3 Offshore Breakwaters

The Federal Navigation Project also includes three armor stone breakwaters at the southern entrance to New Haven Harbor. These structures were constructed for making a harbor of refuge and authorized by the River and Harbor Acts of 3 March 1879 and 19 September 1890. Construction of the East Breakwater was started in 1880 and was completed to a length of 3,450 feet in 1890. The Middle or Luddington Rock Breakwater was started in 1891 and was completed to a length of 4,500 feet in 1896. Construction of the West Breakwater began in 1896 and was completed to a length of 4,200 feet in 1915. The breakwaters have a uniform cross section design with a crest elevation at 12.25 feet above MLLW. These structures provide a harbor of refuge at the mouth of the harbor and afford protection to the harbor from all but southwestern storms. The breakwaters also afford West Haven protection from southern and southeastern storms, thereby reducing storm damage to this area.

### 1.1.4 Sandy Point Dike

Sandy Point Dike is a training dike located on the west side of New Haven Harbor opposite Fort Hale. It was constructed as a federal project authorized by the River and Harbor Act of August 2, 1882 after attempts to keep the channel open by dredging alone were unsuccessful. The dike consists of a 2,140 foot shore arm extending easterly from a long sand spit known as Sandy Point and a 2,089 foot channel arm running north and south approximately parallel to the main harbor channel. The shore arm and one-half of the channel arm were built in 1888 and the structure was completed in 1890. The inner 1,294 feet of the shore arm consists of riprap while the outer 846 feet of the shore arm and the northern 254 feet of the channel arm consists of two rows of piling filled with stone. The remaining 1,835 feet of the channel arm are built of rip rap, with a 20 foot ice breaker of heavy riprap at the north end of the channel arm.

Drawings indicate that the entire shore arm of the structure was built to or slightly above MHW. A small portion of the northernmost end of the channel arm was built to 1 foot above MHW and the remaining portion built to 2 feet above MHW. Records indicate that shortly after the structure was completed, it settled 1-2 feet in places. Today, the shore arm is almost entirely below Mean Sea Level, whereas the channel arm crest varies from Mean Sea Level where it meets the shore arm to slightly above MHW at its southern tip. Although the structure has settled in places it appears to be functioning properly relative to its authorized purpose to decrease the width of the waterway between Sandy Point and Fort Hale to lessen sediment deposition. Secondarily, the dike serves to arrest northeastern sand movement from West Haven.

### 1.2 Coastal Engineering Scope of Work

Supporting the study, coastal analysis and engineering work was completed and provided to the Project Delivery Team (PDT). The coastal engineering tasks included evaluation of existing conditions, future without project conditions, design of improvement alternatives, and assessments to determine the influence of the proposed modification on harbor hydrodynamics, sedimentation, and navigability. The information within this appendix describes this work and the information provided. As part of the Corps' SMART Planning process, earlier alternative screening was completed which limited and focused the level of analysis associated with the project. As part of the reduced level of analysis, an effort was made to use existing information where it remained applicable. This work focused on providing representative conditions for navigation in New Haven Harbor and Long Island Sound and assessing the projected impacts of climate change and sea level rise on the tentatively selected project. These analyses are detailed in this report.

## 2.0 Coastal Climatology and Setting

Due to its proximity to the coast, the south central Connecticut region generally has a warm summer cooled by coastal breezes and a vigorous winter moderated by the warming effects of the Atlantic Ocean currents and Long Island Sound. The harbor at New Haven, being tidal water, is essentially ice-free. The area is subject to occasional hurricanes and nor'easters. It is not uncommon for fog to set in over the harbor.

### 2.1 Tidal Regime and Water Levels

New Haven Harbor experiences semi-diurnal tides (two low and two high tides per day) with one high and low tide typically of greater magnitude than the other due to a slight diurnal shift. NOAA installed a tide gage (Station 8465705) in August of 1999. The mean tide range in the Harbor is 6.14 feet and the diurnal range is 6.7 feet. The tides, which are created by the gravitational pull of the moon, the sun, and the earth's rotations are responsible for most of the water levels observed. Occasionally, abnormally high or low water levels occur as a result of changes in atmospheric pressure, storm surge, the magnitude and direction of wind and/or waves, and other meteorological anomalies. Table 2-1 provides the tidal datums for New Haven at Station 8465705. In New Haven the highest water level observed was 12.23 feet MLLW, which was during Hurricane Sandy on October 30, 2012. The lowest observed water level was -3.09 feet MLLW on December 12, 2000.

**Table 2-1. New Haven Harbor Tide Range – NOAA Station 8465705**

| **Condition** | **Elevation (feet, MLLW)** | **Elevation (feet, NAVD88*)** |
|---|---|---|
| Mean Spring High Water (MSHW) | 7.22 | 3.60 |
| Mean Higher High Water (MHHW) | 6.71 | 3.09 |
| Mean High Water (MHW) | 6.39 | 2.77 |
| NAVD88 | 3.62 | 0.00 |
| Mean Sea Level (MSL) | 3.32 | -0.30 |
| Mean Tide Level (MTL) | 3.32 | -0.30 |
| Mean Low Water (MLW) | 0.24 | -3.38 |
| Mean Lower Low Water | 0.00 | -3.62 |

***North American Vertical Datum of 1988**

In addition to the daily tidal conditions at Station 8465705, extreme water levels are provided for New Haven Harbor at select output points from the North Atlantic Coast Comprehensive Study (NACCS). Table 2-2 contains statistical annual exceedance probability water levels at the NACCS save points shown in Figure 2-1.

**Table 2-2. Annual Exceedance Probability Water Levels from NACCS Study**

| **NACCS Save Point** | | **Annual Recurrence Interval Water Level (feet, NAVD88)** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Location** | **Number** | 1 | 2 | 5 | 10 | 20 | 50 | 100 |
| **New Haven Harbor** | 271 | 5.30 | 6.22 | 7.40 | 8.29 | 9.14 | 10.39 | 11.57 |
| **East Breakwater** | 276 | 5.21 | 6.12 | 7.27 | 8.06 | 8.81 | 9.80 | 10.78 |
| **Central (Luddington) Breakwater** | 277 | 5.25 | 6.17 | 7.31 | 8.10 | 8.86 | 9.84 | 10.79 |
| **West Breakwater** | 278 | 5.29 | 6.21 | 7.36 | 8.15 | 8.90 | 9.89 | 10.84 |

**Figure 2-1. NACCS save point locations**

## 2.2 Currents

Current data was measured by NOAA over 6 weeks as part of the Long Island Sound 2010 Current Survey at 3 locations in New Haven: the Tanker Terminal (LIS1022), Harbor Entrance (LIS1023), and Gateway Terminal (LIS1024) (Figure 2-2). At each location, currents were recorded at 6 minute intervals at 7, 9, and 8 foot depths respectively, and averaged. The depth-averaged average velocities are 0.19 knots at the Tanker Terminal, 0.38 knots in the entrance channel, and 0.26 at the Gateway Terminal. A critical location for maximum currents and navigability however is where the channel passes between the two breakwaters.

The 1988 New Haven Harbor Numerical Model Study conducted by the USACE Waterways Experiment Station Hydraulics Laboratory observed a substantial Long Island Sound current is produced as tide levels rise (flood) and fall (ebb). This current flows parallel to the harbor breakwaters and is greatest midway between tidal extremes (high and low tides).. Currents through the openings in the breakwaters show a significant increase in speed and change in direction with a substantial gradient in velocity field across the opening in the breakwaters that is reversed between flood and ebb. Once the flows pass through the opening, they leave the navigation channel and proceed over the shallower areas behind each breakwater, producing large eddies that move throughout the tidal cycle. This study's numerical model demonstrated that the currents are strongest between the breakwaters at peak ebb tide flow, approximately 2-3 hours after high tide (Richards, 1988). Model results at peak ebb and peak flood conditions are shown in Figure 2-3 and Figure 2-4, respectively. A hydrographic survey performed by Alyn Crandall Duxbury from Yale University found that the peak ebb tide currents through the breakwaters averaged 1.3 knots. Peak flood currents through the breakwaters averaged 0.9 knots approximately 2-3 hours after low tide (Duxbury) (Richards, 1988).

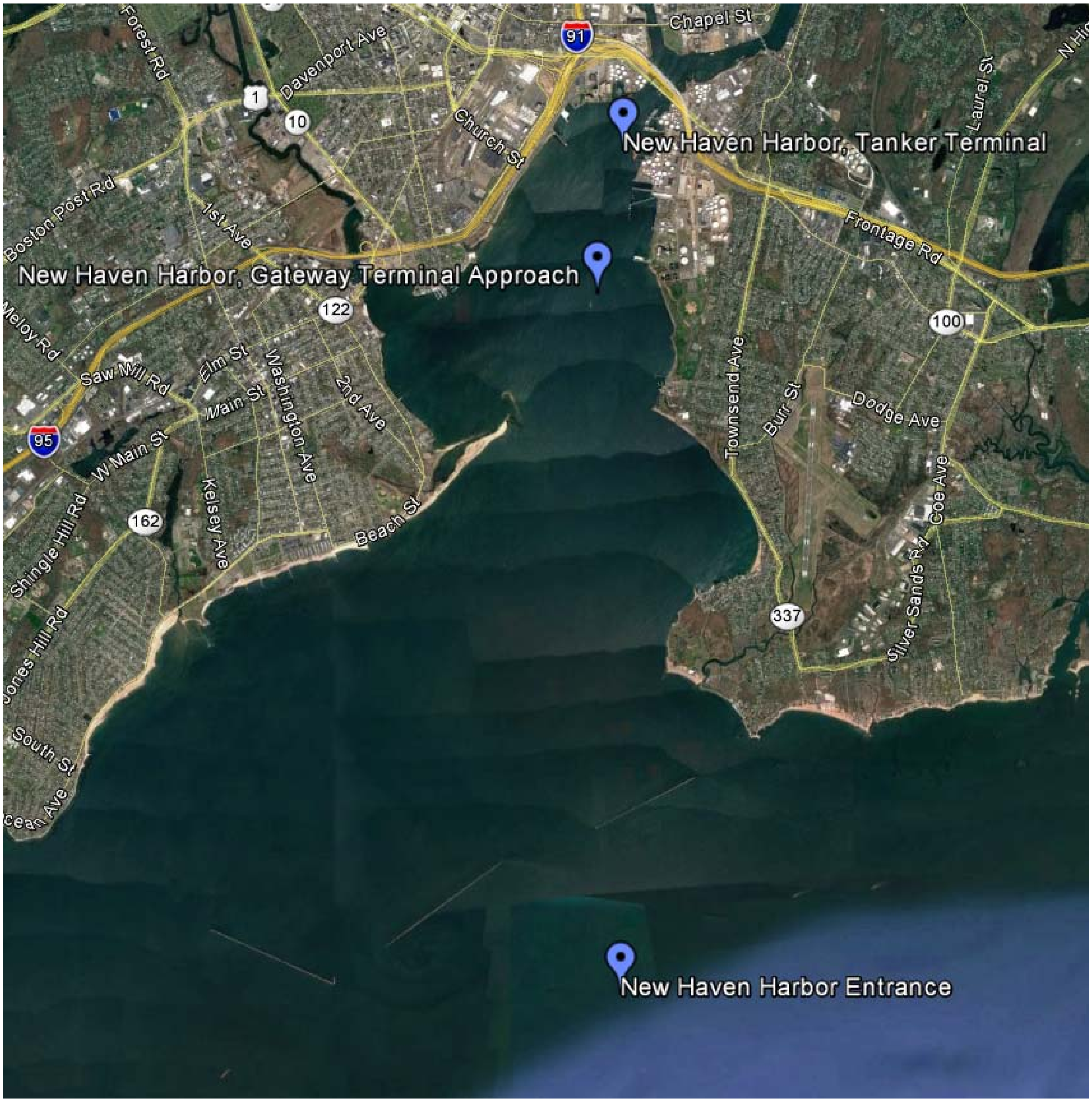

Figure 2-2. Current Station Map

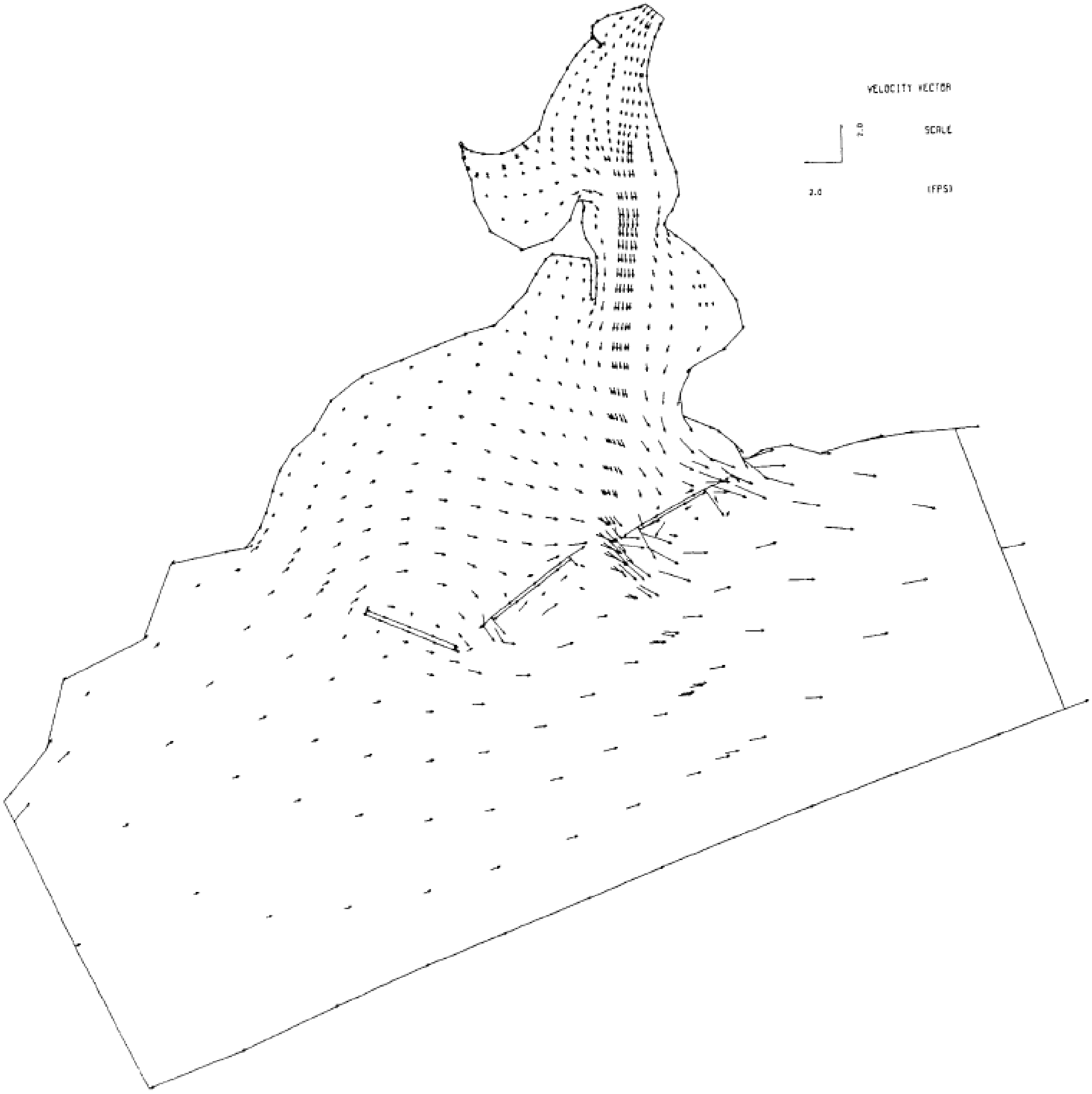

**Figure 2-3. 1988 numerical model study results, maximum ebb condition**

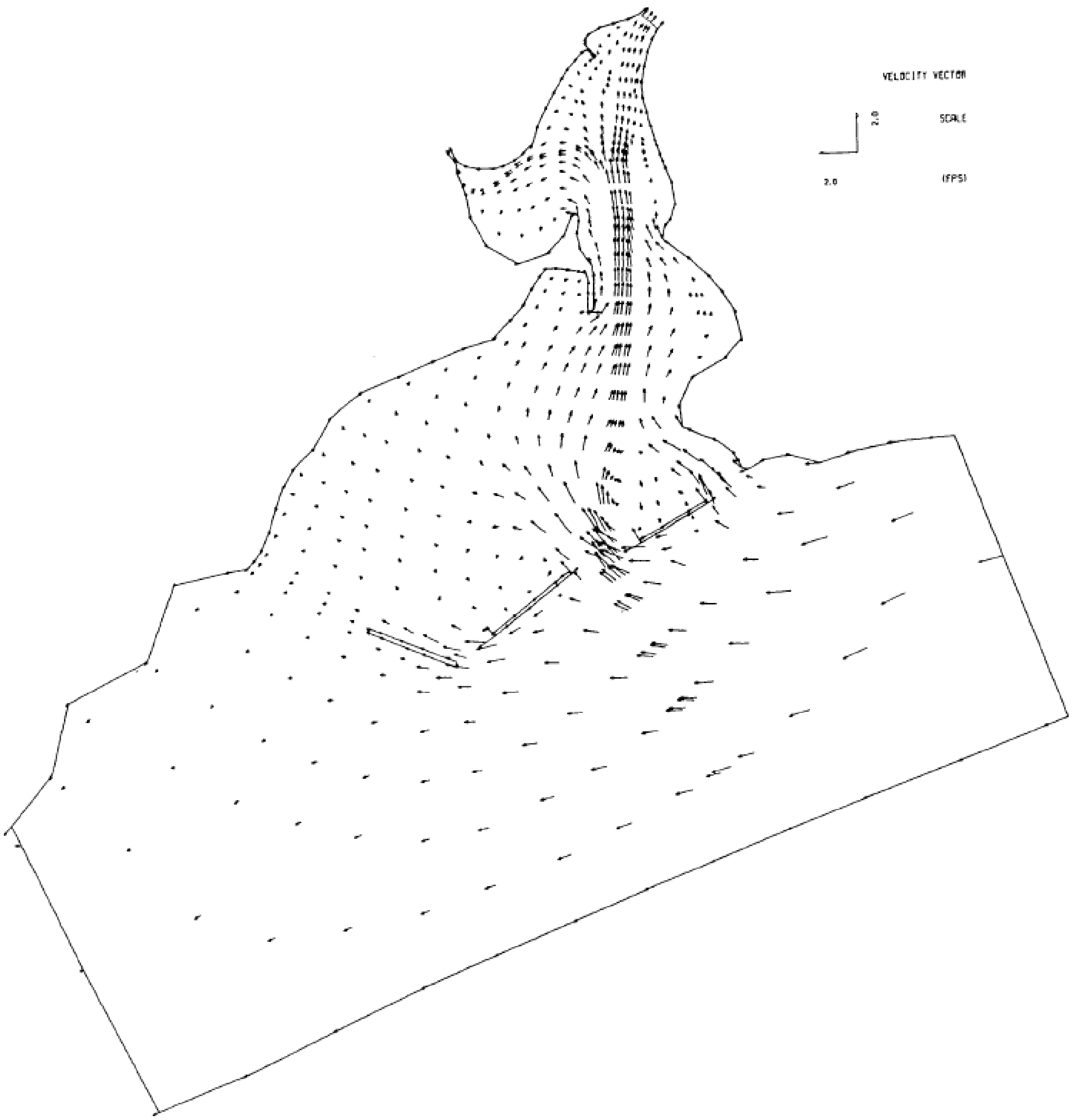

Figure 2-4. 1988 numerical model study results, maximum flood condition

## 2.3 Wind

Coastal wind data is collected at two stations in the vicinity of New Haven: Station NWHC3-8465705 within New Haven Harbor and Station 44039- Central Long Island Sound, located approximately 13 nautical miles east-southeast of the channel's breakwater crossing (Figure 2-5). All wind speeds were converted to knots at 10m equivalent height.

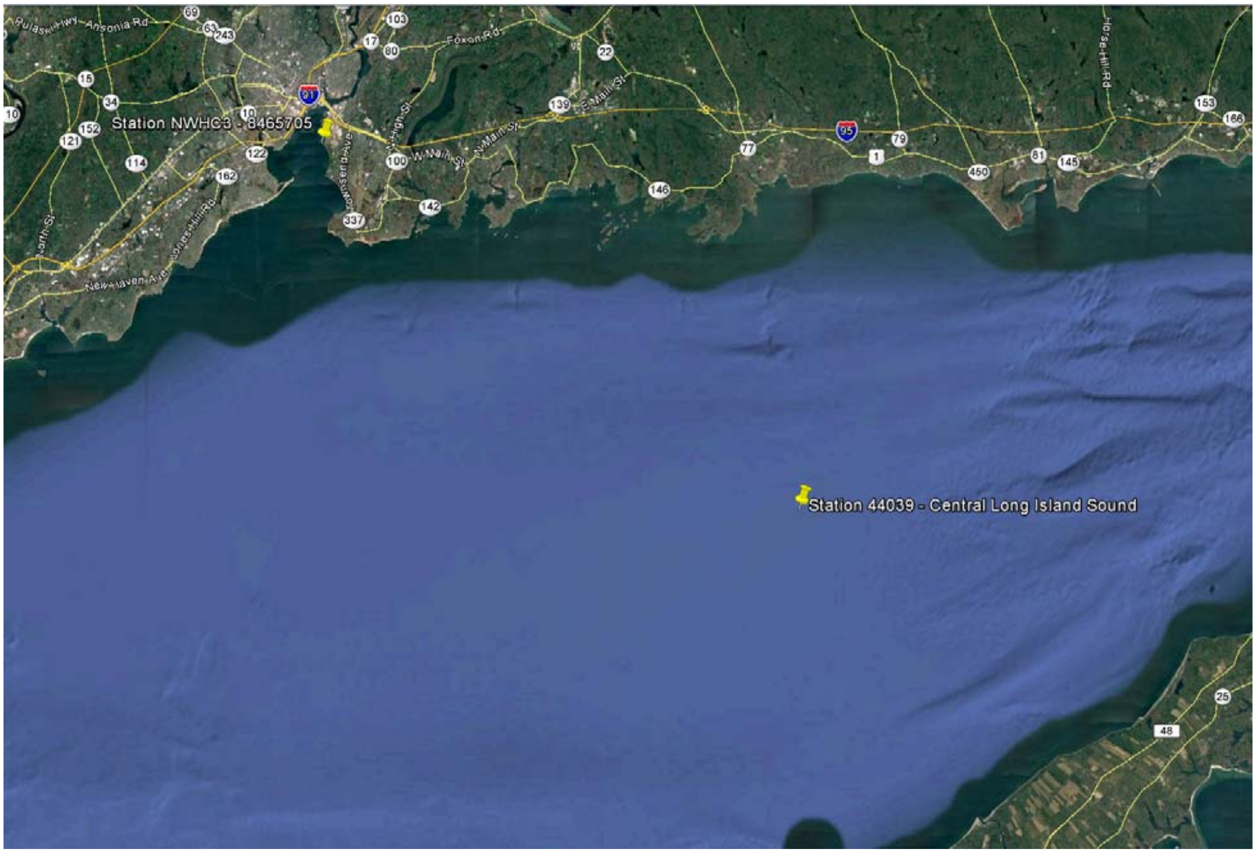

**Figure 2-5. Wind station locations**

New Haven Harbor is more sheltered than the Sound, with an average wind speed of 7.8 knots compared to the Sound's 12.7 knot average. Wind speed magnitude and direction generally vary with season within the harbor. Winter winds average 8.7 knots from the North. In the summer, winds are lighter at 6.6 knots from the Southwest. A similar seasonal trend is observed in Central Long Island Sound—winter winds average 15.6 knots from the West-Northwest; summer winds average 9.8 knots from the Southwest. Unlike the Harbor, however, prevailing winds in the Sound are out of the West. Seasonal wind characteristics for each station are presented as wind roses in Figure 2-6 and Figure 2-7.

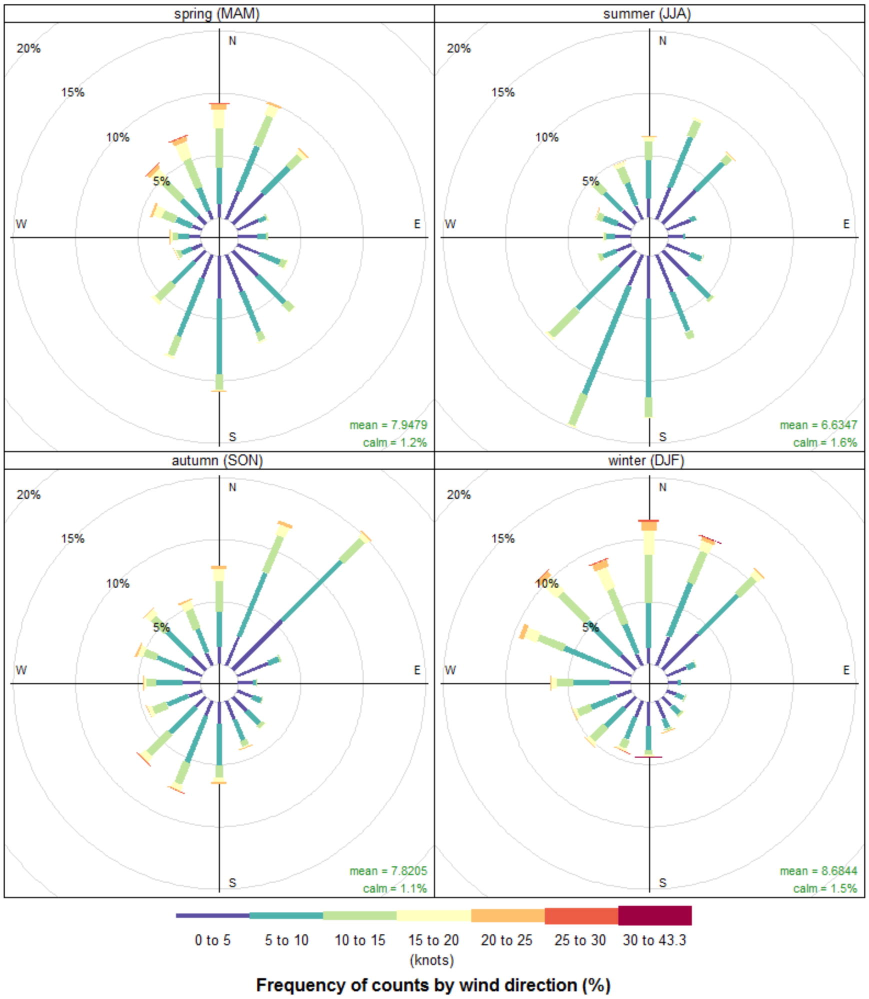

**Figure 2-6. Station NWHC3-8465705, New Haven Harbor Seasonal Wind Roses**

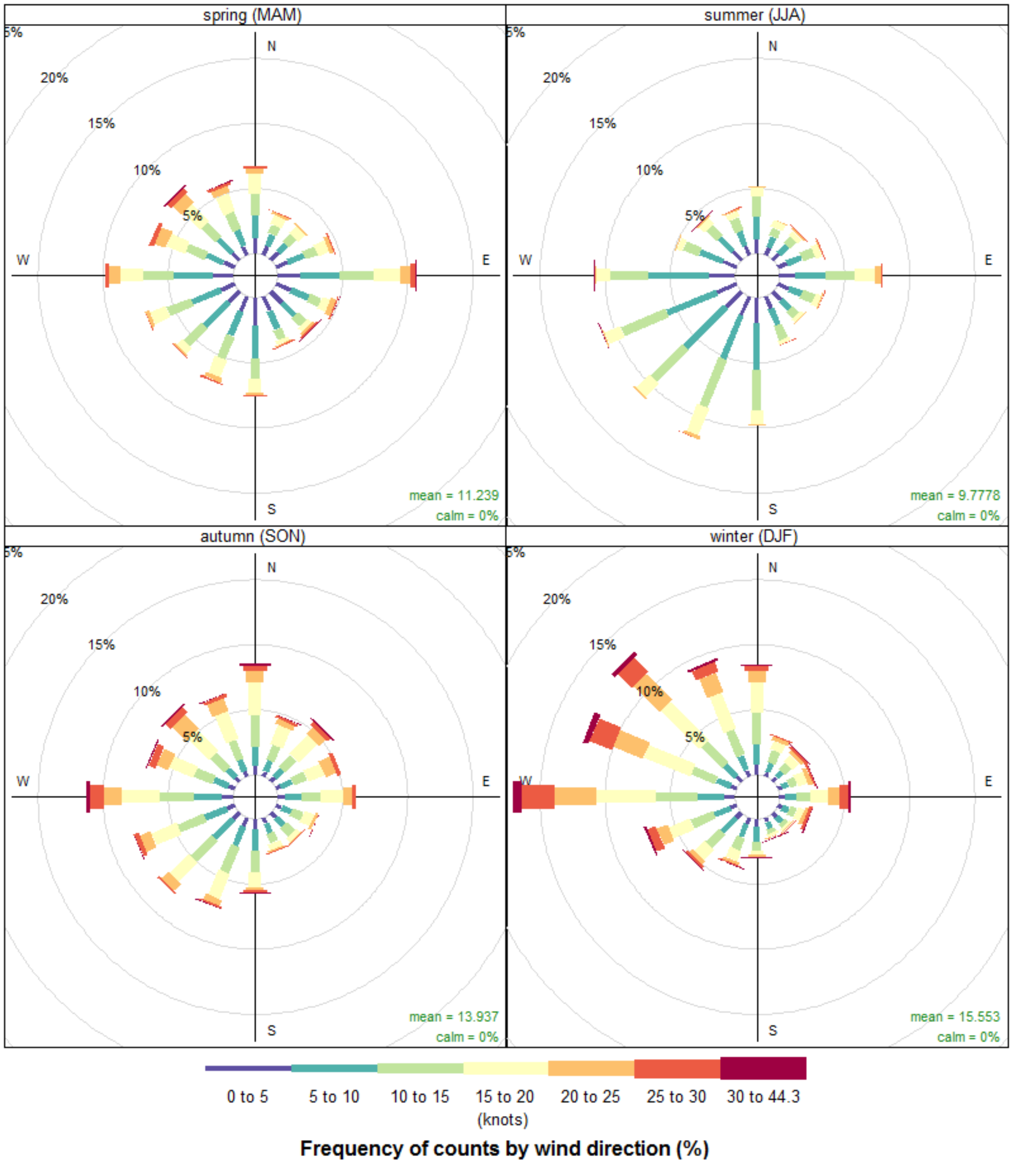

**Figure 2-7. Station 44039, Central Long Island Sound Seasonal Wind Roses**

## 2.4 Wave Climate

Long Island shelters the New Haven shoreline from long period waves from the Atlantic Ocean. Therefore, waves in the New Haven Harbor vicinity are fetch-limited only, driven by winds blowing over a length of the Sound. The breakwater system at the southern limits of the harbor provides protection within the harbor from waves approaching from southerly directions. Fetch and wave development are limited by topography in other directions. There are no wave records within New Haven Harbor and readily available wave data within Long Island Sound is limited. Station 44039 - Central Long Island Sound is the nearest wave buoy, recording wave heights, but not wave period or mean wave direction. Figure 2-8 shows the histogram of wave records from the Central Long Island Sound buoy.

From 2005-2016, the mean wave height was 0.46 meters (1.51 feet) and the significant wave height (Hs) was 0.87 meters (2.85 feet).

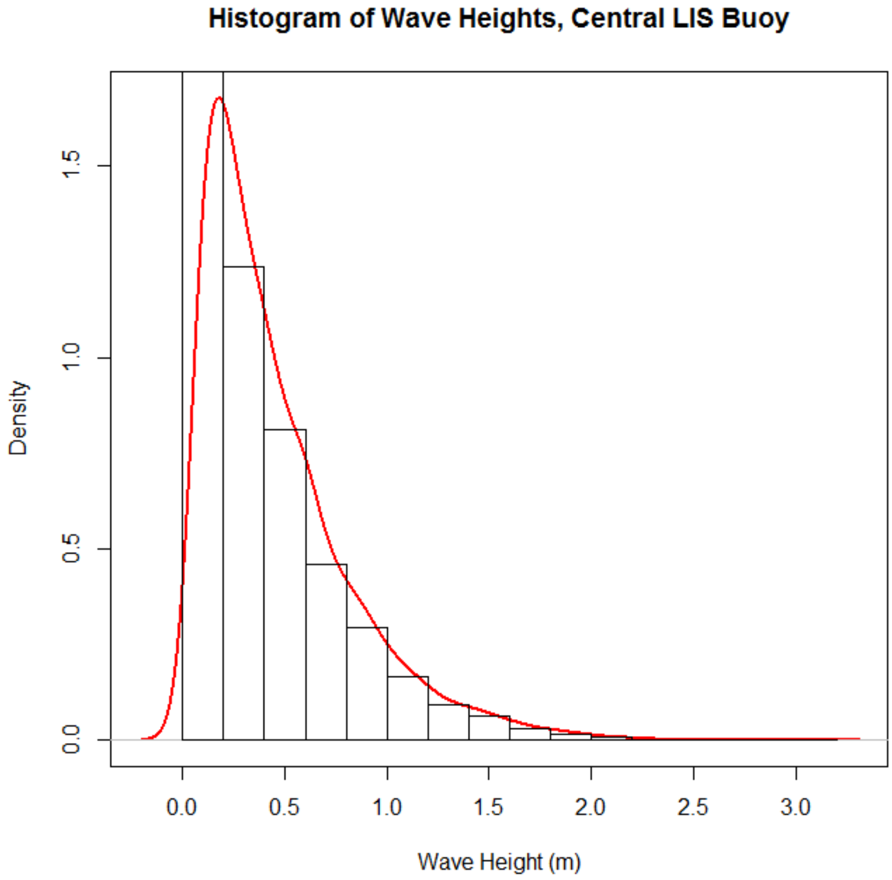

**Figure 2-8. Station 44039 Wave Height Histogram**

Other sources of wave data are available from past studies and wave modeling. The 1981 Supplemental Feasibility Report discussed the potential for 4 foot high, 5 second period waves in the harbor, but noted that these wave conditions have little effect on large ocean-going vessels. Wave heights associated with extreme storm events from the North Atlantic Coast Comprehensive Study at the harbor entrance breakwaters are provided in Table 2-3. Although these wave heights are greater, allowance for vessel pitch, roll, and heave due to wave forces are considered unnecessary because ships remain at sea or at berth and do not attempt to navigate the channel when severe storm conditions prevail.

**Table 2-3. Annual Exceedance Probability Wave Heights from NACCS Study**

| NACCS Save Point | | Annual Recurrence Interval Wave Height (feet) | | | |
|---|---|---|---|---|---|
| **Location** | **Number** | 1 | 2 | 5 | 10 |
| **East Breakwater** | 276 | 4.3 | 6.4 | 7.5 | 8.2 |
| **Central (Luddington) Breakwater** | 277 | 4.7 | 6.9 | 7.9 | 8.6 |
| **West Breakwater** | 278 | 4.7 | 6.6 | 7.7 | 8.4 |

### 2.5 Sediment Transport and Shoreline Change

A number of small rivers empty into New Haven Harbor, including the Mill, Quinnipiac, and West Rivers, and Morris Creek, which contribute silty shoal material to the harbor. Since the 35 foot main channel was initially completed in 1950, maintenance dredging has occurred nine times, with smaller additional actions over the years to remove unclassified hard material. Harbor maintenance dredging within the main channel and maneuvering area last occurred in 2013-2014 with about 831,000 CY removed. Over the 63 year project life between 1950 and 2013, dredge records indicate a shoaling rate of 88,000 CY annually. Harbor maintenance dredging will be assumed to continue once every 10 years, consistent with the most recent dredge cycles.

Aside from the fine grain material entering from the river systems, sediment transport along the study area is generally from west to east as indicated by the growth of Sandy Point to the northeast over time. This sand originated from updrift beaches in West Haven and the present form of the spit is undoubtedly influenced by the presence of Sandy Point dike.

## 3.0 Alternatives Considered

Considering the information from the previous sections, alternatives to improve harbor efficiency and navigability were considered as part of the planning process. Each of the measures is discussed in the sections below as well as their impacts on the harbor's hydrodynamics and navigability.

### 3.1 No Action

Selection of the no action alternative would hinder further development of the port and would reduce the port's economic effectiveness. It is assumed that the current vessel traffic in New Haven Harbor will continue to experience navigational difficulties with the existing 35 foot channel as they currently push its limits. And, as the trend toward larger vessels continues, a corresponding increase in frequency of lightering and tidal delays can be expected. There will continue to be a need for channel widening and enlargement of the turning basin to safely accommodate today's size vessels. Harbor pilots note that there is currently and will continue to be very little room for error and adjustment in navigating the bend in particular. Although navigability will be affected, taking no action would not alter the harbor's tidal dynamics and wave climate.

## 3.2 Dredging and Disposal

Based on the vessel forecast and civil engineering calculations, proposed channel improvements include deepening the channel over its length, widening the approach channel from 400 to 500 feet, widening the entrance channel from 500 to 600 feet and widening the channel bend between the breakwaters from 560 to 700 feet. The design also included expanding the turning basin near the head of navigation.

### 3.2.1 Dredging

Dredging to a range of depths from 37 to 42 feet was considered for the improvements described above. The recommended channel depth of 40 feet (approximately 4.3 million cubic yards of material to be dredged) was selected as it provided the greatest economic benefits. These improvements would permit transportation savings by allowing deep draft tankers and bulk cargo carriers to enter the harbor with fewer tidal restrictions and to maneuver more safety.

While the proposed improvements will increase access to and navigability of the channel, no discernable changes in tidal and wave hydrodynamics are expected. The 1988 Numerical Model Study conducted by the USACE Waterways Experiment Station Hydraulics Laboratory modeled the differences in tide and current velocities between the existing 35 foot channel and a similar 40 foot design channel. The results showed virtually no difference in tidal phase, amplitude and plane between the base and plan conditions. This was somewhat predictable since the harbor tide is dominated by the conditions in Long Island Sound with very little tidal phase or amplitude change within the harbor. As for current velocities and circulation patterns, the differences between the base and plan conditions were quite small. The largest changes in velocity (approximately 0.1 fps) were observed within the deepened channels where the plan condition exhibited slightly lower current speeds, so navigation would not be adversely affected.

Historically, channel deepening and widening projects result in a net increase in Operations & Maintenance dredging requirements (Rosati 2005; Vincente and Uva 1984). However, given the sediment starved nature of New Haven Harbor, channel deepening would not change the sediment discharge loads of the harbor tributaries or the longshore sediment transport patterns. Therefore, the increase in cross section associated with the channel deepening is expected to have negligible effects on the resulting channel shoaling rate. However, for the purposes of this analysis it was decided to allocate a small increase to the current shoaling rate equal to 1 percent of the improvement dredging volume. This shoaling rate may be refined as the study progresses. The frequency of maintenance dredging would remain at 10 years.

### 3.2.2 Disposal

Dredging to the proposed depth and widths associated with the channel improvements requires the handling and disposal of nearly 4.3 million cubic yards of dredge material. While the dredge material samples were almost exclusively clean and suitable for open water placement, all efforts were made to beneficially reuse dredge material in a cost effective manner and reduce the quantity of material designated for open water placement. Although the majority of the dredge material is chemically and biologically suitable, its physical composition with a large percent fines content makes incompatible with beach placement opportunities. Each of the selected placement options for dredge material are described below.

Two borrow pits in New Haven Harbor—one in Morris Cove and the other off the West River Channel—have approximately 623,000 and 88,000 CY of capacity, respectively, to bring them up to adjacent grade. The Morris Cove borrow pit is approximately 650 ft wide by 2450 ft in length. Depths within the pit are approximately 11 to 20 feet deeper than the surrounding bottom, suggesting the pit could contain a substantial amount of dredged material. The pit's distinct margins currently limit water flow within the pit and have created anoxic conditions with little flushing. By filling the pit, these anoxic conditions will be removed, improving bottom habitat. The West River borrow pit covers an area of approximately 8.2 acres and is up to 11 feet deeper than the surrounding bottom. Clean material within the harbor could be placed at either of these locations.

Dredge material from the entrance channel is sandier than the inner harbor material and will be used for oyster habitat creation behind the east breakwater. For the 40 foot deep channel improvement, approximately 351,000 CY of material from the entrance channel would be available for this use.

The sheltered mud flat north of Sandy Point Dike has previously been identified as a location for salt marsh creation in USACE's Long Island Sound Dredged Material Management Plan (2016) and the Connecticut Department of Energy & Environmental Protection's Section 1122 beneficial reuse pilot proposal. Using the proposed footprints from each, the Environmental Resources Section approximated the potential capacity for dredge material to be placed north of Sandy Point Dike using a fill elevation of 4.5 feet NAVD88 (8.1 feet MLLW) for high marsh. It is expected that the marsh creation at Sandy Point could accommodate approximately 800,000 CY of fine, suitable material, provided a form of containment is constructed north of Sandy Point. The containment will need to resist wave forces to ensure that the material stays within the marsh, and does not wash away. Options for containment included coconut fiber coir logs and fillable geotubes. Diking with sheetwall, rock, and other structural methods of containment were screened out due to their high cost of construction. Fillable geotubes were considered more resistant to wave forces over time than coir logs and were selected as the containment method for the tentatively selected plan.

The containment geotubes can be filled in place in water and dredged materials can be deposited within the containment footprint. Hydraulic placement techniques were assumed for filling the wetland cell. It should be noted that wetland cell construction requires a highly ordered and controlled sequence of dredge material placement to assure that wetland cells are not overloaded beyond the quantities required to achieve the target wetland surface elevation. Further, the time allotted for wetland cell development (i.e. placement of dredged materials, grading and initial planting) is a function of dredged material thickness. Greater dredged material thickness will increase the time required to reach a stable surface ready for planting and will decrease the probability of achieving any particular target surface elevation as dredge materials consolidate.

The Water Management Section and Environmental Resources Section will see that the salt marsh creation includes a system of channels with a range of widths and depths dictated by hydraulic analyses and empirical information for existing wetlands to accommodate the outflow from Old Field Creek. The materials excavated from these channels must be placed within the wetland cells in a manner that is consistent with the required final grades.

Historically, material from maintenance dredging of New Haven Harbor has been suitable for open water placement. The nearest open water placement site is the Central Long Island Disposal Site (CLDS), approximately 4.5 nautical miles south of the entrance channel buoy R "2". The remaining suitable material will be designated for open water placement and would be hauled by a bottom dump scow barge to CLDS to cap historic pre-NEPA disposal mounds.

At the channel bend between the breakwaters, rock ledge will require blasting. Blasted rubble will be placed at the toe of the western breakwater as added protection and to serve as a rock reef.

Table 3-1 summarizes the placement locations and quantities associated with the recommended plan to deepen New Haven Harbor to 40 feet. If the opportunity for salt marsh creation north of Sandy Point is included, the volume of dredge material designated for open water placement at CLDS is reduced by approximately one quarter.

**Table 3-1. Dredge Material Volumes by Placement Site**

| Placement Site | Volume (CY) for 40 FT Improvement, Federal Base Plan | Volume (CY) for 40 FT Improvement with Salt Marsh Creation |
|---|---|---|
| CLDS | 3,173,490 | 2,333,059 |
| Morris Cove Borrow Pit | 623,310 | 623,310 |
| West River Borrow Pit | 87,800 | 87,800 |
| Oyster Habitat | 351,300 | 351,300 |
| Rock Reef | 32,700 | 32,700 |
| Salt Marsh Creation | -- | 840,431 |
|  | 4,268,600 | 4,268,600 |

# 4.0 Ship Simulation

A feasibility level ship simulator study was performed for the proposed channel improvements outlined in Section 3.2 for New Haven Harbor at the USACE Engineer Research and Development Center (ERDC), Coastal Hydraulics Laboratory (CHL) 13-16 February 2018. Representatives from ERDC, the Connecticut Pilots (Capt. Charlie Jonas and Capt. DJ Toby), and the New England District participated for the duration of the simulation which tested the navigability of the proposed improvements using a limited set of design ships and tidal and wave forcing across the range of proposed project depths from 37 to 42 feet. Feedback from the pilots on the proposed design resulted in confirmation of the design widths of the entrance and inner channels as well as the configuration of the maneuvering area. Iterative testing of the channel bend and turning basin designs resulted in the modifications described below.

## 4.1 Channel Bend at Breakwaters

The proposed bend widening was performed for the 37, 38, 40, and 42 foot project depths. While the widened condition allowed the pilots to make the turn at the breakwater entrance, the turn still required the pilots to use all their rudder, leaving no additional rudder control to respond to unexpected changes in environmental conditions (wind, waves, current, etc.) and little room for error. For this reason, the proposed bend design was widened by shifting the locations of the R “6” and R “8” buoys east 100 feet. This resulted in an increase in bend width from the proposed 700 foot width to 800 feet, and allowed the pilots to make the turn without bank effects. This proposed bend widening resulted in a significant increase of rock material and will be further optimized during the Feasibility Level Design phase.

## 4.2 Turning Basin

The proposed turning basin was tested conservatively using a 750 foot LOA tanker (50 feet longer than the design vessel used for the economic analysis), with the assistance of two tugs coming off the Magellan T-Dock. The pilots indicated that the longest ships typically berth at the Magellan T-Dock at the center of the harbor. While the pilots were able to maneuver within the proposed turning basin at the head of the harbor, it was determined that the existing turning basin, with a small enlargement, would be better suited given its more central location. The proposed enlargement would lengthen the turning basin 200 feet by shifting it existing northeastern and northwestern corners approximately 200 feet toward the head of the harbor to points 1 and 2 as depicted in Figure 4-1.

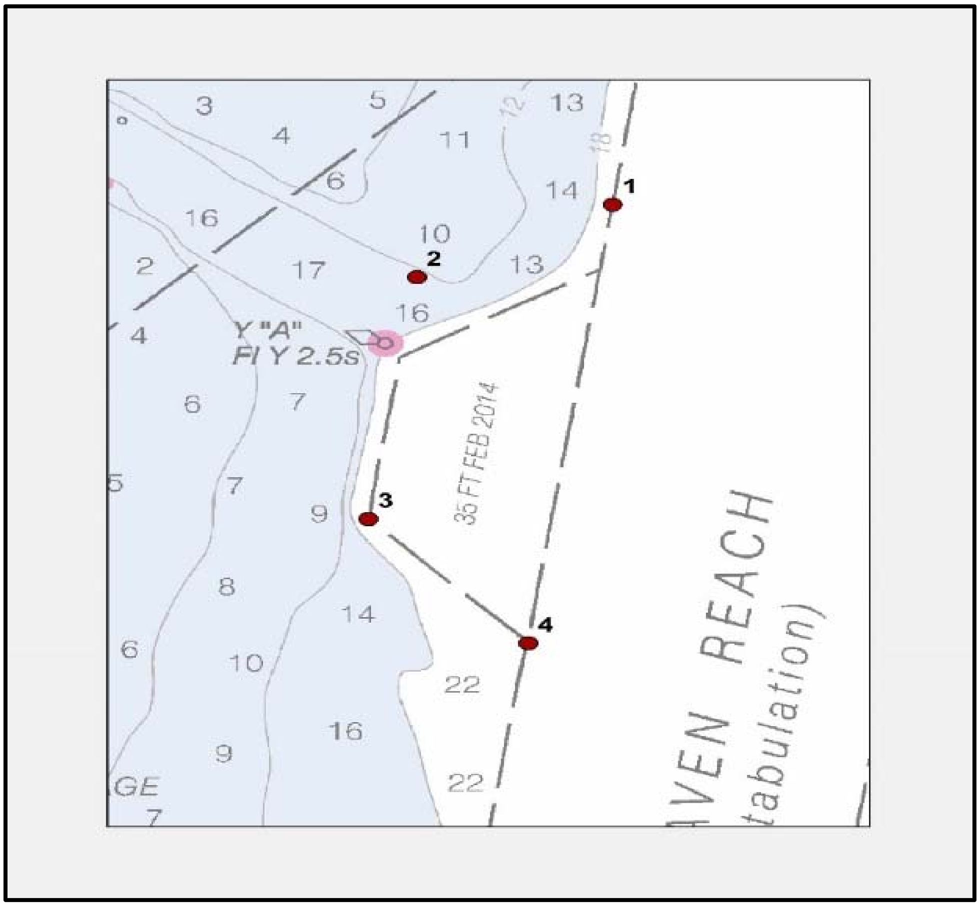

**Figure 4-1. Ship Simulation Proposed Turning Basin**

# 5.0 Sea Level Change

The USACE Sea Level Change Curve Calculator (2015.46) was used to predict three local relative sea level change (SLC) scenarios per ER 1100-2-8162: Incorporating Sea Level Change in Civil Works Programs. The purpose of the ER is to incorporate relative sea level changes into the project alternatives and design. The three SLC scenarios are illustrated by curves representing the low (historic) rate of SLC at the project area, an intermediate rate (modified NRC Curve I), and a high rate of SLC (modified NRC Curve III). All three local SLC curves include the global (eustatic) sea level rise rate (approximately 1.7 mm/year according to IPCC 2007) as well as local vertical land movement.

The length of tide station record is important to consider when estimating historic relative SLC because inter-annual, decadal, and multi-decadal variations in sea level are sufficiently large that misleading or erroneous sea level trends can be derived from periods of record that are too short. A minimum record length of 40 years is recommended to determine reasonable trends. For this reason, the nearest long-term NOAA tide gage, located approximately 16 miles southwest in Bridgeport, CT (Station 8467150, 84 year record), was deemed more suitable for estimating the historic SLC rate than the New Haven gage (17 year record). The historic mean sea level trend at Bridgeport from 1964 to 2016 is 0.00928 feet/year (2.83 mm/year) or 0.93 feet per century. The mean trend is shown in Figure 5-1 which was taken from the NOAA Sea Level Trend web page https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8467150. As shown in the plot there are yearly and decadal cycles that cause the short term rate to vary. These observations illustrate that water levels are rising, but that the variations in the data are large, making it difficult to discern a statistically significant change from the historic rate or any of the future sea level rise scenarios at this time. Over the next 50 years (2020-2070), sea level at New Haven is projected to rise 0.46 feet, 0.94 feet, and 2.43 feet under the USACE low, intermediate, and high scenarios, respectively. Projections through 2120 are provided in Figure 5-2 and Table 5-1.

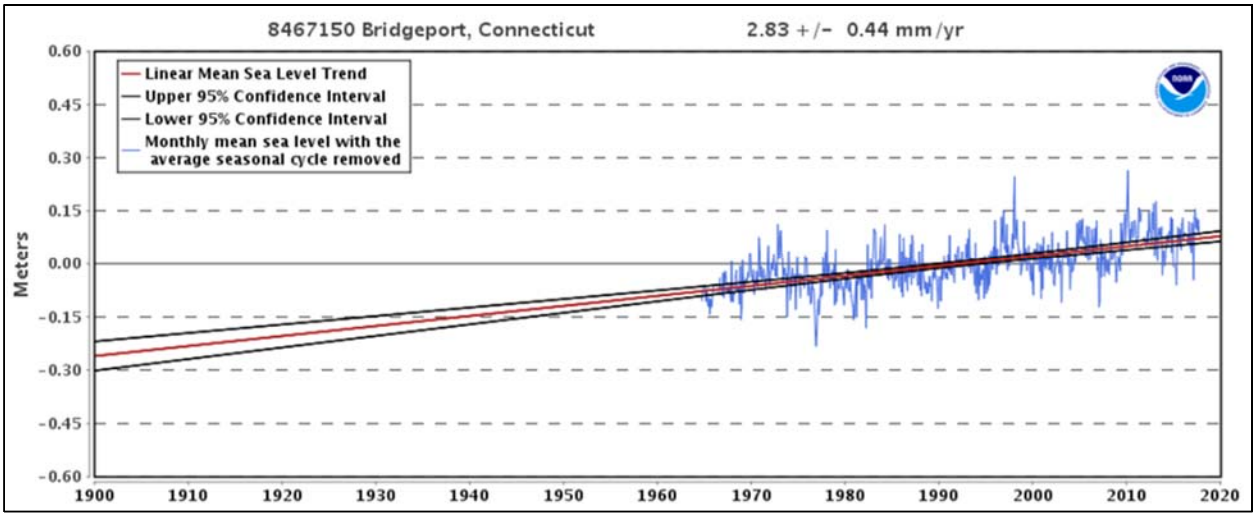

**Figure 5-1. Historic sea level change at Bridgeport 1964-2016 (from NOAA/NOS CO-OPS)**

**Figure 5-2. Relative Sea Level Change Projections at Bridgeport**

**Table 5-1. USACE sea level change rates – future scenarios**

**Estimated Relative Sea Level Change from 2020 To 2120**
8467150, Bridgeport, CT
User Defined Rate: 0.00928 feet/yr
All values are expressed in feet

| Year | USACE Low | USACE Int | USACE High |
|---|---|---|---|
| 2020 | 0.00 | 0.00 | 0.00 |
| 2025 | 0.05 | 0.07 | 0.16 |
| 2030 | 0.09 | 0.15 | 0.34 |
| 2035 | 0.14 | 0.23 | 0.53 |
| 2040 | 0.19 | 0.32 | 0.75 |
| 2045 | 0.23 | 0.41 | 0.98 |
| 2050 | 0.28 | 0.51 | 1.24 |
| 2055 | 0.33 | 0.61 | 1.51 |
| 2060 | 0.37 | 0.71 | 1.80 |
| 2065 | 0.42 | 0.82 | 2.10 |
| 2070 | 0.46 | 0.94 | 2.43 |
| 2075 | 0.51 | 1.05 | 2.77 |
| 2080 | 0.56 | 1.18 | 3.14 |
| 2085 | 0.60 | 1.30 | 3.52 |
| 2090 | 0.65 | 1.43 | 3.92 |
| 2095 | 0.70 | 1.57 | 4.34 |
| 2100 | 0.74 | 1.71 | 4.78 |
| 2105 | 0.79 | 1.85 | 5.23 |
| 2110 | 0.84 | 2.00 | 5.71 |
| 2115 | 0.88 | 2.16 | 6.20 |
| 2120 | 0.93 | 2.32 | 6.71 |

## 5.1 Impacts of Sea Level Change

Sea level change will increase the navigable depth of the channel over time and, given the low sedimentation rate of the waterway, reduce the amount of maintenance dredging required to maintain the authorized channel depth. However, the amount of SLC alone would not significantly improve conditions in the waterway to achieve project objectives. Although sea level rise will provide a benefit to the project in the form of additional channel depth it may impact local service facilities (LSF) and port operations. Critical infrastructure elevations for each terminal were obtained from the New Haven Port Authority to assess anticipated project performance relative to the three SLC scenarios. The magnitude of SLC is expected to have a greater impact on the LSF than the navigation structures such as the harbor entrance breakwater system or Sandy Point Dike.

### 5.1.1 Local Service Facilities

With no bridge clearance concerns, the greatest potential risk associated with sea level change is inundation to the local service facilities (LSF), including the piers and utilities serving the berthing areas. Impacts to the LSF were assessed using the tidal datums at New Haven and the statistical water levels in New Haven Harbor from the North Atlantic Coast Comprehensive Study, combined with the predicted sea level change scenarios. The Mean Higher High Water (MHHW) level and the 99% annual exceedance probability (AEP; or 1-year annual recurrence interval) of the measured water level were added to each sea level change scenario. If sea level change coupled with the MHHW and the 99% AEP water level exceeded the deck height of the terminals on the waterway, it was assumed to be in a condition that would affect regular port operation and require structural modifications.

The deck height of each terminal is given in Table 5-2 relative to the predicted water levels. For all SLC scenarios, the terminal deck elevations are presently high enough to avoid inundation at MHHW through 2070. All terminal deck elevations are also expected to exceed the 99% AEP water level under the low and intermediate SLC scenarios through 2070. However, LSF at one terminal, Magellan Pink Tanks, is expected to be inundated by the 99% AEP water level under the high SLC scenario by 2070. Overall, this assessment indicates there is a low risk to the LSF at the project over the 50-year project life.

Looking out to 2120, inundation at MHHW is not projected to affect the terminals under the low and intermediate SLC scenarios. The MHHW level for the high SLC scenario, however, is expected to affect all terminals but Gateway and the Magellan T-Dock, unless infrastructure improvements are made. Under the low SLC scenario, all terminal LSF elevations will exceed the 99% AEP water level. The 99% AEP water level is projected to impact LSF at Magellan Pink Tanks under the intermediate SLC scenario after 2075. However, LSF at all other terminals are not anticipated to be affected by the intermediate SLC scenario 99% AEP water level through 2120. The high SLC scenario projects LSF at all terminals in New Haven will be impacted by the 99% AEP water level in 2120. Figures 5-3 and 5-4 depict the changes in the MHHW and 99% AEP water levels over time relative to the two lowest terminal decks. LSF will become increasingly vulnerable to the effects of climate change and sea level rise beyond the 50-year project life.

**Table 5-2. Terminal Deck Elevations and Projected Water Surface Elevations**

| Terminal | Deck Elevation (ft, NAVD88) | 2070 Low/Int./High MHHW (ft, NAVD88) | 2070 Low/Int./High 99% AEP (ft, NAVD88) | 2120 Low/Int./High MHHW (ft, NAVD88) | 2070 Low/Int./High 99% AEP (ft, NAVD88) |
|---|---|---|---|---|---|
| Motiva | 9.6 | 3.8 / 4.4 / 6.1 | 6.0 / 6.6 / 8.3 | 4.3 / 5.7 / 10.4 | 6.5 / 8.0 / 12.6 |
| Harbor | 9.0 | | | | |
| New Haven | 9.0 | | | | |
| Magellan T-Dock | 12.3 | | | | |
| Gateway | 11.0 | | | | |
| Gulf | 8.5 | | | | |
| Magellan Pink Tanks | 6.7 | | | | |

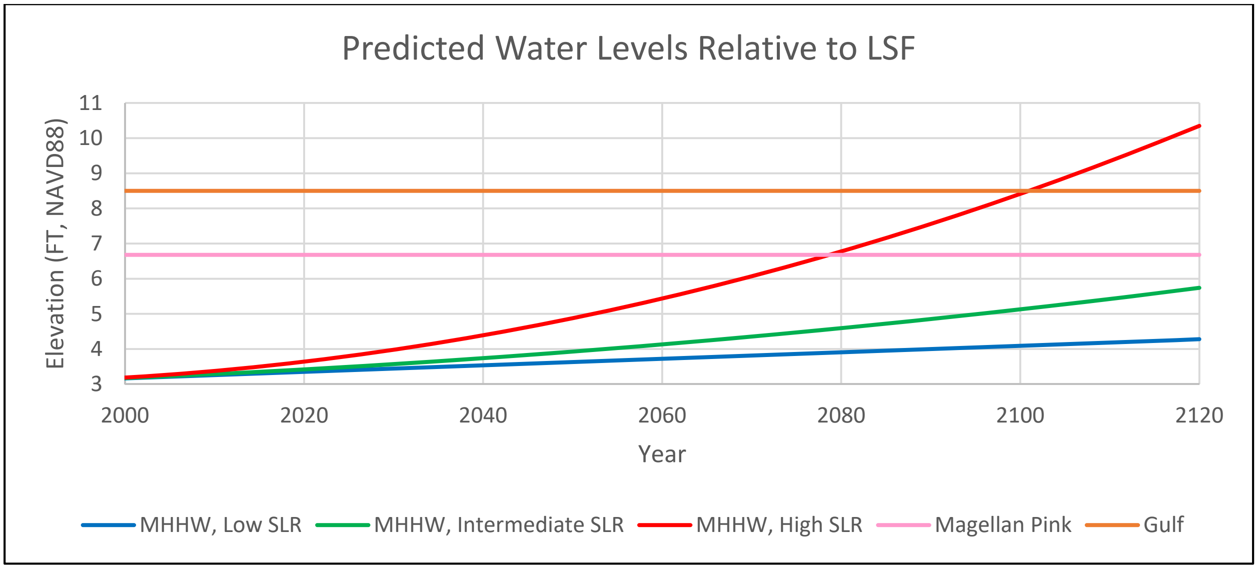

**Figure 5-3. Mean Higher High Water Level and Terminal Deck Elevations**

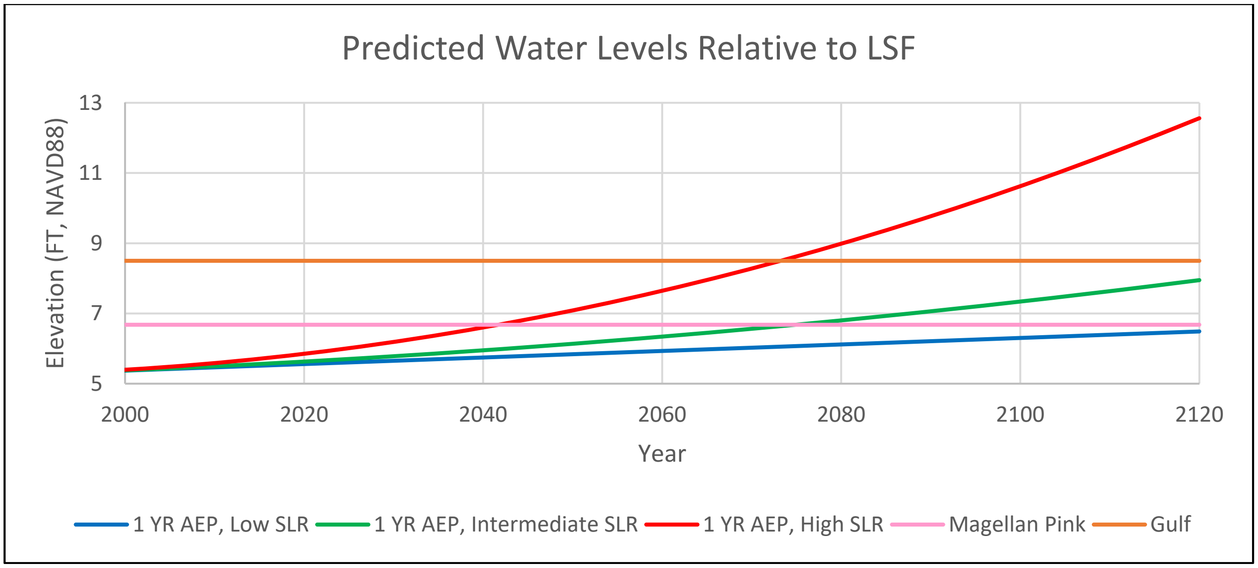

**Figure 5-4. 1-Year Annual Exceedance Probability Water Level and Terminal Deck Elevations**

### 5.1.2 Harbor Breakwaters

The three armor stone breakwaters at the harbor entrance currently provide a harbor of refuge at the mouth of the harbor and afford protection to the harbor from all but southwest storms. The breakwaters have a uniform cross section (Figure 5-5), with a 12 foot wide crest at elevation 12.25 feet MLLW and a seaward slope of 1:1.5 (vertical: horizontal). Sea level change will increase water levels and reduce freeboard at the breakwaters. However, given the fetch-limited wave generation within Long Island Sound, wave conditions are not anticipated to increase. The breakwater armor stone sizing will therefore remain sufficient.

The impacts of rising sea levels on wave runup and overtopping on and wave transmission over the breakwaters from Long Island Sound into New Haven Harbor were examined for future MSL and MHHW water levels. Potential changes in wave diffraction through the breakwater openings were also investigated.

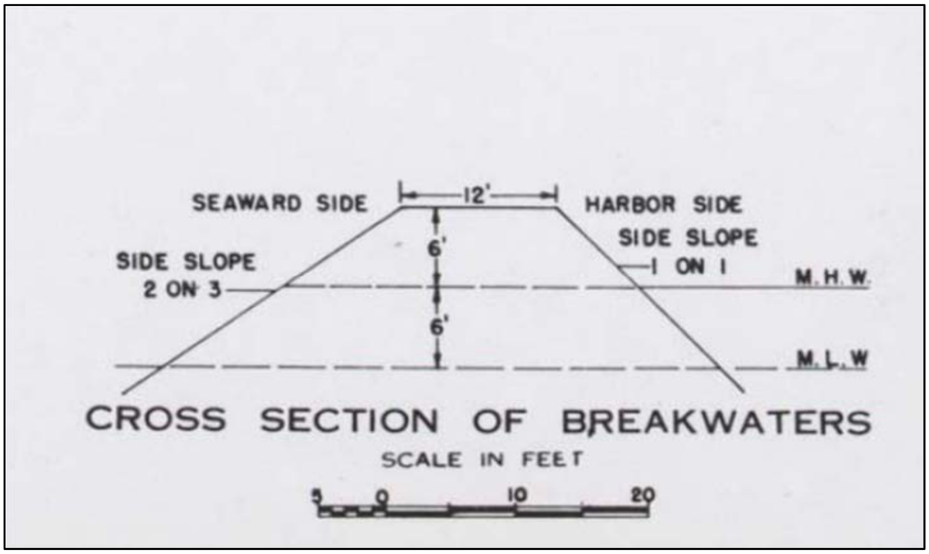

**Figure 5-5. Harbor breakwater cross section**

Wave transmission was calculated using CEM Equation VI-5-54. Overtopping rates were computed using CEM Equation VI-5-22. Wave transmission coefficients and volumetric overtopping rates are presented in Table 5-3 for MHHW and MSL water levels under present and future sea level rise conditions. While wave transmission over the breakwaters will increase, the wave heights within the harbor will continue to be significantly reduced compared to the wave heights in Long Island Sound. Similarly, wave overtopping rates are expected to increase, but not considerably enough to affect the structural integrity of the breakwaters or the harbor's navigability.

**Table 5-3. SLC Impacts on Wave Transmission and Overtopping**

| | **Freeboard (ft)** | | **Wave Transmission Coefficient** | | **Wave Overtopping Rate (cfs/ft)** | |
|---|---|---|---|---|---|---|
| | MSL | MHHW | MSL | MHHW | MSL | MHHW |
| Present | 8.9 | 5.5 | -- | 0.05 | 0.011 | 0.118 |
| 2070 Low | 8.5 | 5.1 | -- | 0.07 | 0.015 | 0.163 |
| 2070 Intermediate | 8.0 | 4.6 | -- | 0.10 | 0.021 | 0.229 |
| 2070 High | 6.5 | 3.1 | -- | 0.19 | 0.060 | 0.655 |

### 5.1.3 Sandy Point Dike

At present, the shore arm is mostly submerged at MSL while most of the channel arm is visible (emergent). However, at MHHW, the channel arm is mostly submerged. The purpose of the dike is to keep the channel cross section narrow enough to keep channel velocities up and prevent sedimentation of the channel. The dike's 2012 inspection noted structural settlement, as well as displacement and loss of stone riprap units. Generally, the top stones are missing and the slopes have flattened. However, the dike continues to function in accordance with its authorization. Given the structure's continued performance in spite of its deterioration, increases in sea level are not anticipated to compromise the dike's future performance.

# 6.0 Summary and Conclusions

The Water Management Section's coastal assessment inventoried available tidal and wave hydrodynamic data to inform the civil engineering design of the channel improvements. Alternatives were evaluated with changes to the harbor hydrodynamics and improvements to navigability in mind. The feasibility of the proposed design was also tested in ERDC CHL's ship simulator, with minor modifications suggested to the turning basin and channel bend through the breakwater, and its resilience to sea level change was evaluated. The proposed design will improve navigation of the channel and reduce inefficiencies associated with inadequate channel depth.

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