Sustainable Coastal Solutions, Inc.
107A County Road
North Falmouth, MA 02556
508-365-2900
sustainablecoastalsolutions.com

November 21, 2023

MEMORANDUM

To: Carlos G. Peña, P.E., Foth Infrastructure & Environment, LLC

From: John Ramsey, P.E. and Sean W. Kelley, P.E.

Re: Summary of Hingham waterfront design water levels and wave conditions

As requested by the Town of Hingham, the following summarizes the findings of the "Hingham Waterfront Design Water Levels and Wave Conditions" report:

- Updated sea level rise projections from NOAA indicate that the rate of sea level rise will be slower than estimated previously (i.e., previous analyses performed 4-to-5 years ago).
- The anticipated 100-year flood level in 2050 will be about 1-ft higher than present.
- Flood protection to the level of the 100-year storm surge in 2050 provides an appropriate elevation to mitigate flood damage along the shoreline (elevation = 11 feet NAVD)
- In addition to storm surge, waves during nor'easter also can elevate coastal flood levels along the Hingham shoreline.
- Site-specific wave analyses for reconstructed seawalls, revetments, and dunes (to the west) indicate that future design elevations could be higher than the 11-ft NAVD level to ensure protection from wave damage, especially in areas where infrastructure may be at risk.
- In areas without major upland infrastructure concerns (e.g., Whitney Wharf), some storm wave overtopping could be allowed.

Sustainable Coastal Solutions, Inc.
107A County Road
North Falmouth, MA 02556
508-365-2900
sustainablecoastalsolutions.com

November 15, 2023

TECHNICAL MEMORANDUM

To: Carlos G. Peña, P.E., Foth Infrastructure & Environment, LLC

From: John Ramsey, P.E. and Sean W. Kelley, P.E.

Re: Hingham waterfront design water levels and wave conditions

Storm generated flood inundation is not a new challenge for communities surrounding Boston Harbor. Flood records dating back to the mid-1800s detail episodic storm events that have generated catastrophic storm surge and subsequently causing damage to residential and commercial infrastructure, roadways, and the natural environment. However, rising sea levels threaten to increase the occurrence of these events as well as chronic nuisance flooding from periodic spring tide cycles. East facing shorelines are most susceptible to flooding induced by extratropical storms (or Nor'easters), which may last as long as multiple days, creating prolonged exposure to atypical water elevations over and above normal astronomical tide levels, as well as storm wave action. The timescale of these storms often results in longer duration flooding that may persist until the storm has passed.

Due to the existence of the Nantasket Beach barrier complex and the series of Harbor Islands, the mainland shoreline of Hingham Harbor is protected from storm wave conditions often associated with the open Atlantic Ocean, providing relatively safe conditions for development of communities along the shoreline. However, this stretch of coastline is particularly susceptible to coastal flooding due to the low-lying topography in some areas. Based upon the topography of the Hingham downtown shoreline, much of the site is presently between 7 and 11 feet NAVD. The FEMA Stillwater 100-year flood elevation for the area is 10 feet NAVD, where nearby Boston Harbor recorded water elevations of 9.6 feet NAVD in both February 1978 and January 2018. A portion of the effective FEMA Flood Insurance Rate Map (FIRM) is shown in Figure 1. Portions of the downtown area with FEMA Zone AE at elevation 11 feet NAVD indicate low-lying areas that are inundated to approximately 10 feet NAVD with a 1-ft storm wave envelope above the still water flood elevation.

With the above understanding, most coastal flood mitigation efforts for site improvements can be focused specifically on elevating the infrastructure. As depicted in Figure 1, the seaward edge of the site is exposed to storm wave action; however, according to FEMA, waves impacting the site are relatively small and wave action within developed areas is limited, with only minor influence in the developed areas beyond the wharves. Elevating the flood protection infrastructure along the harbor shoreline can provide effective means for eliminating storm tide pathways through the downtown Hingham area.

To quantify design requirements for both coastal storm surge and wave action, an analysis of potential future sea level rise impacts and storm wave impacts was performed for the site-specific conditions. In support of the coastal engineering design analysis, and the development of management alternatives, past and future sea level rise (SLR) trends were analyzed. The analysis of projected SLR is necessary to understand appropriate design levels for future infrastructure improvements. In addition, an assessment of storm wave conditions associated with existing and future storm surge levels is necessary to design the level of shore protection necessary for future conditions.

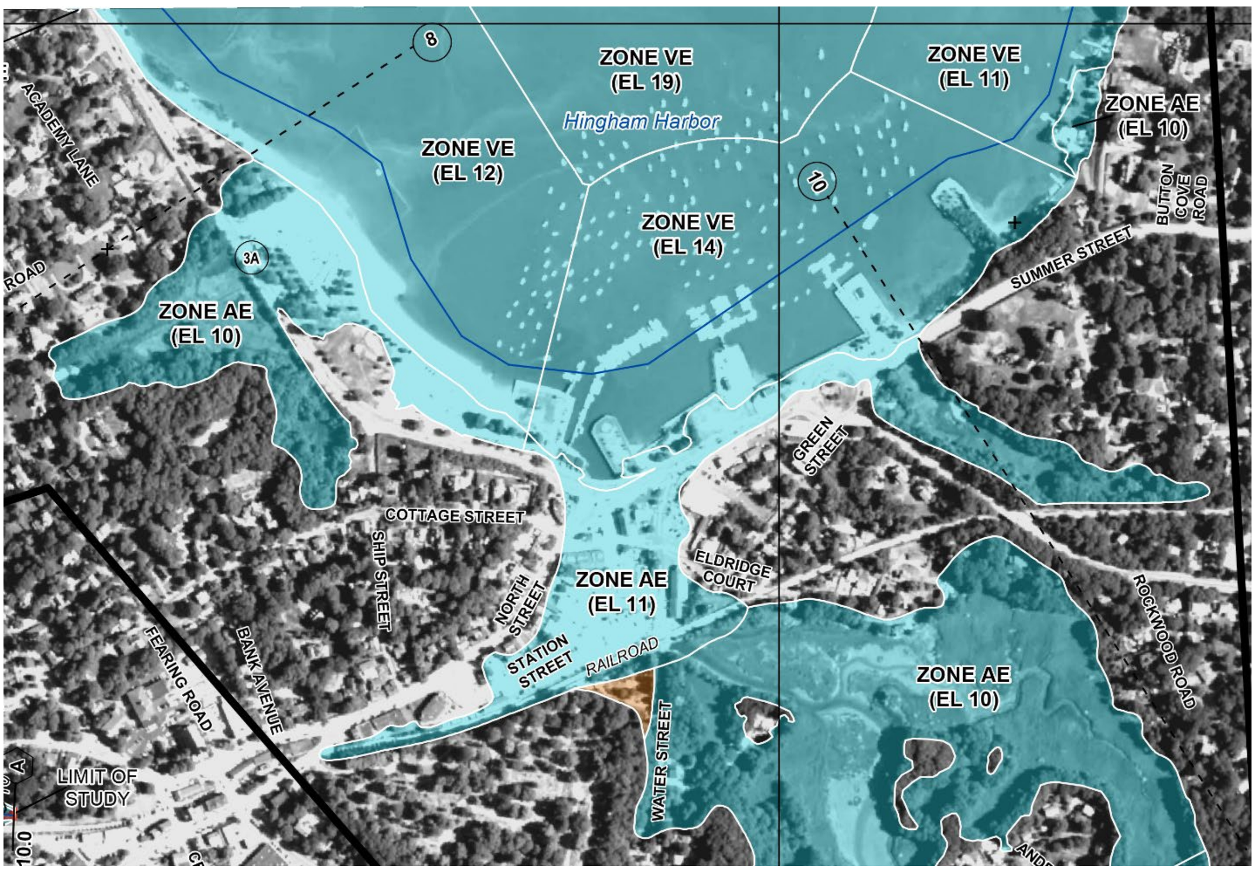

Figure 1. Portion of updated FEMA Flood Insurance Rate Map (FIRM) for Hingham, last updated on August 14, 2015
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A. Updated Sea Level Rise Analysis

The exposure of population and infrastructure to flooding along the Hingham Harbor shoreline has significantly increased over the last several decades. Several factors including coastal urbanization, aging infrastructure, alterations to the natural environment, and sea level rise have all contributed to the increase in flood exposure and are anticipated to continue as mechanisms promoting the acceleration of future flood vulnerability (Sundermann et al., 2014). Indeed, it has been concluded that sea levels are rising; however, the pace and extent to which they may rise over the next 60 to 80 years are the topic of much scientific debate. Historical evidence indicates that over the past 100 years the relative sea level in Boston, Massachusetts has been rising generally in a linear fashion, with an average rate of approximately 0.114 inches per year or 0.95 feet per century (Figure 2).

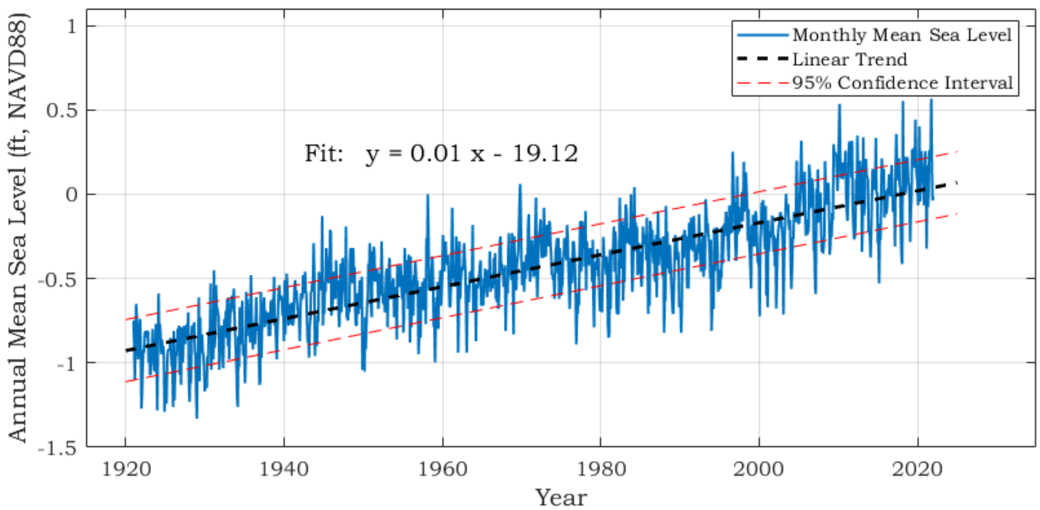

Figure 2. Monthly mean water levels recorded in Boston Harbor between 1921 and 2021 indicate a linear trend in sea level rise over the past 100 years of approximately 0.01 feet per year (*Source: NOAA*)

While long-term tide records (e.g., Boston Harbor) provide valuable insight into historical changes over the past century, they do not necessarily dictate future response of sea level rise due to changing environmental and anthropogenic conditions. Predictive models have been developed to project the effects of climate change on relative sea level rise in coming decades. New and existing models used to predict sea level rise are continually refined with augmented data sets to reduce output uncertainty; however, there still exists a large range of potential sea level rise scenarios.

Based on the Massachusetts Sea Level Assessment and Projections technical memorandum (DeConto and Kopp, 2017) regarding local mean sea level rise, plots were developed for the Commonwealth of Massachusetts to provide guidance regarding future projections of sea level rise in Boston Harbor (Figure 3). The range of varying projections are determined based on the probability of exceedance given two future atmospheric greenhouse gas concentration pathways, medium (RCP4.5) and high (RCP8.5; van Vuuren et al., 2011), and for two methods of accounting for Antarctic ice sheet projections: one based on expert elicitation (Kopp et al., 2014) and one where Antarctic ice sheet projections are driven by a more recent, process-based numerical ice sheet model simulations (DeConto and Pollard, 2016; Kopp, 2017). These localized projections are downscaled from regional and international projections. A brief description of the probabilistic projections is provided in Table 1.

These projections have been incorporated into the Resilient MA analyses tools and serve as the basis for guiding Massachusetts sea level rise policy in the near-term. Tools developed with the DeConto and Kopp (2017) sea level rise projections include the Massachusetts Coastal Flood Risk Model (MC-FRM) and the Resilient Massachusetts Action Team (RMAT) Design Guidance. Therefore, all quantitative analyses depicted by the tools represented in Resilient MA are directly dependent upon the selected sea level rise scenarios. In this case, the state selected the "High" or 99.5% chance of non-occurrence set of sea-level scenarios from Table 1 as the baseline. As indicated below, this sea level rise scenario is shown to substantially over-predict actual water levels in 2020 and more recent NOAA analyses of sea level rise (Sweet, et al., 2022) do not support an acceleration in sea level rise that will cause regional water levels to "catch up" to the "High" scenario depicted in Table 1. Therefore, use of MC-FRM modeling results dependent upon this sea level rise scenario is becoming increasingly moot over time.

Table 1. Relative mean sea level (feet, NAVD88) projections for Boston, MA as presented in DeConto and Kopp, 2017

Scenario	Probabilistic projections	2030	2050	2070	2100
Intermediate	Unlikely to exceed (83% probability) given a high emissions pathway (RCP 8.5)	0.7	1.4	2.3	4.0
Intermediate - High	Extremely unlikely to exceed (95% probability) given a high emission pathway (RCP 8.5)	0.8	1.7	2.9	5.0
High	Extremely unlikely to exceed (99.5% probability) given a high emission pathway (RCP 8.5)	1.2	2.4	4.2	7.6
Extreme (Maximum physically plausible)	Exceptionally unlikely to exceed (99.9% probability) given a high emissions pathway (RCP 8.5)	1.4	3.1	5.4	10.2

As the technical report for the statewide MC-FRM model has not been released (i.e., the Bosma, et al., 2020 report referenced in the MC-FRM metadata is unavailable) and the RMAT tool output (which directly depends on MC-FRM results) provides no method for the user to verify the results, it remains unclear how these tools can meaningfully inform actual coastal flood protection design efforts. Further, the MC-FRM metadata states that the model results are for "discussion and research purposes only" and "information is provided with the understanding that these data are not guaranteed to be accurate, correct or complete", which only further raises questions regarding the utility of the results to inform coastal flood protection planning efforts. Perhaps as more information is made publicly available regarding the technical assumptions and calibration of the MC-FRM model (e.g., storm surge calibrations for numerous tropical/extra-tropical storm events for locations around the state, wave overtopping and runup methodology/calibration for a variety of shoreline types and storm wave conditions, etc.) and the model developers provide more detailed information regarding computational accuracy and uncertainties, the results could be more meaningful for coastal resiliency planning.

Understandably, accurate projections of sea level rise are critical for engineers and coastal managers responsible for developing future coastal hazard mitigation and improvement strategies. Enhanced accuracy in the prediction of future storm driven flood and tidal elevations ensures the consideration of sufficient safety measures, while also maintaining economic feasibility and reducing the potential for adverse environmental impacts. Using the recorded water elevations measured in Boston Harbor for 2020, a direct comparison between measured and projected relative sea level can be evaluated to assess the near-term accuracy of the sea level rise projection from Resilient MA (Figure 4). The results of this assessment indicate that sea level projections over the first decade, when utilizing the recommended "High" scenario, are overestimated by nearly an order of magnitude relative to the NAVD88 datum.

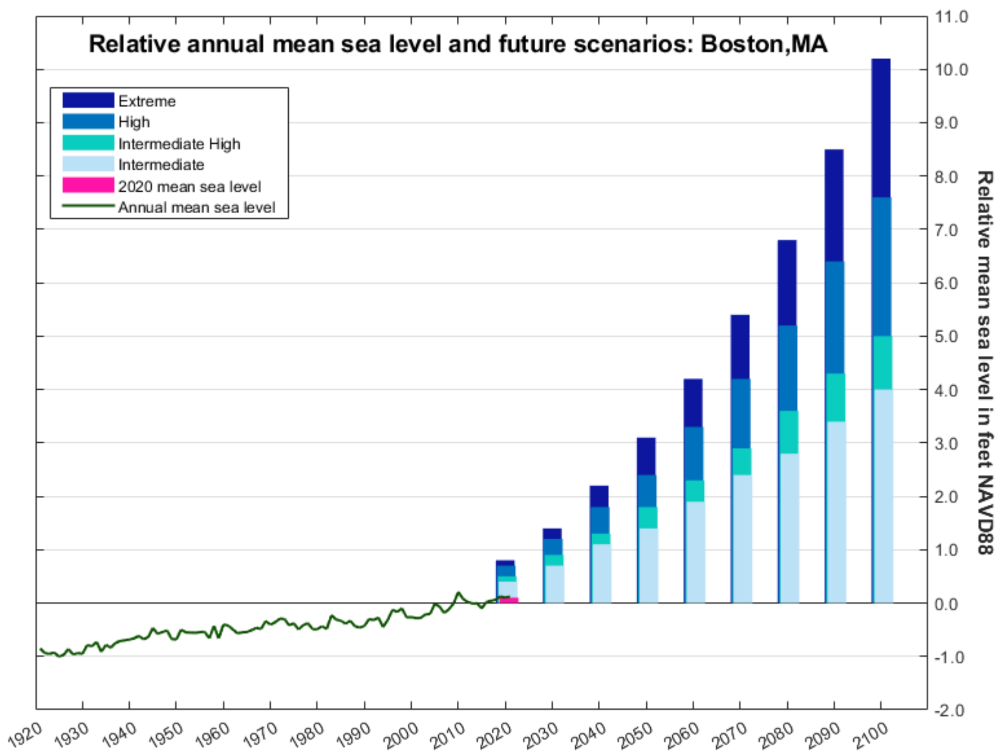

Figure 3. Relative mean sea level projections for the Boston, MA tide station based on four National Climate Assessment global scenarios with associated probabilistic model outputs from the Northeast Climate Science Center. The probabilistic projections are listed in Table 1. The pink bar denotes the 2020 recorded mean sea level in Boston Harbor. The green curve represents the annual mean sea level calculated from the data record presented in Figure 2.

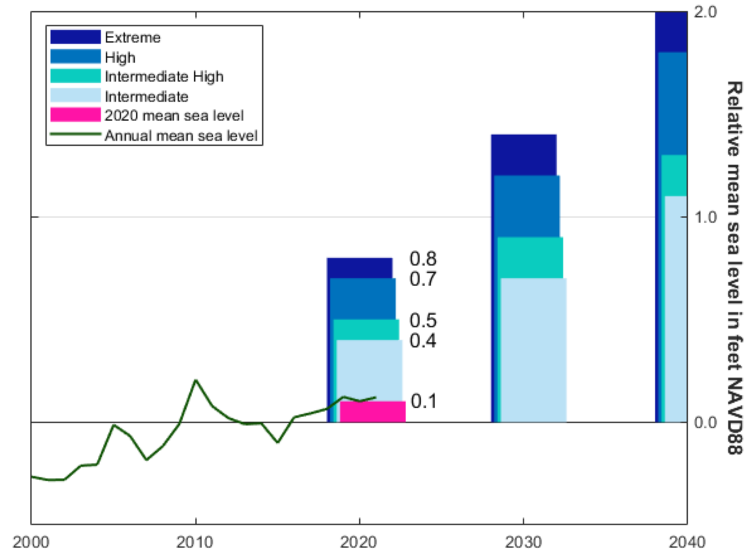

Figure 4. Comparison of probabilistic sea level rise projections from Resilient MA (DeConto and Kopp, 2017) and measured annual mean sea level for Boston Harbor, Massachusetts.

More recent sea level rise projections from NOAA (Sweet, et al., 2022) suggest significantly lower projected future sea level rise rates for Boston (downscaled from the full U.S. analysis), especially between the present and 2050. Figure 5 provides the updated NOAA projections, where the 'intermediate' projection represents conditions that are about as likely as not to occur or, in other words, a 50% chance of occurrence. It should be noted that the NOAA utilization of the term 'intermediate' follows standard statistical terminology, where the intermediate result represents the middle curve between the two extremes (high and low) or the 50% chance of occurrence. The Resilient MA documents use a different definition of the 'intermediate' scenario, which likely leads to further confusion when attempting to compare the various sea level rise projections. In the case of Resilient MA, the 'intermediate' sea level rise projection represents a more unlikely scenario, i.e., the 'unlikely to exceed' threshold or a 17% probability of exceedance, rather than the 50% probability of exceedance used by NOAA.

As illustrated in Figure 5, the 'intermediate' NOAA sea level rise projection generally matches the 'observed trajectory' projection to 2050, which was based upon extrapolating the observed sea level rise trends between 1970 and 2020. Further, Figure 6 demonstrates the applicability of utilizing more moderate sea level rise projections, as the observed sea level rise in Boston between 2000 and 2020 (shown in gray) is below all of the projections evaluated by Sweet, et. al. (2022). Based on the NOAA tide data, the Boston sea level rose 0.33 feet between 2000 and 2020; therefore, in 2020, the mean sea level was 0.03 feet NAVD88 since the mean sea level in 2000 was -0.30 feet NAVD88.

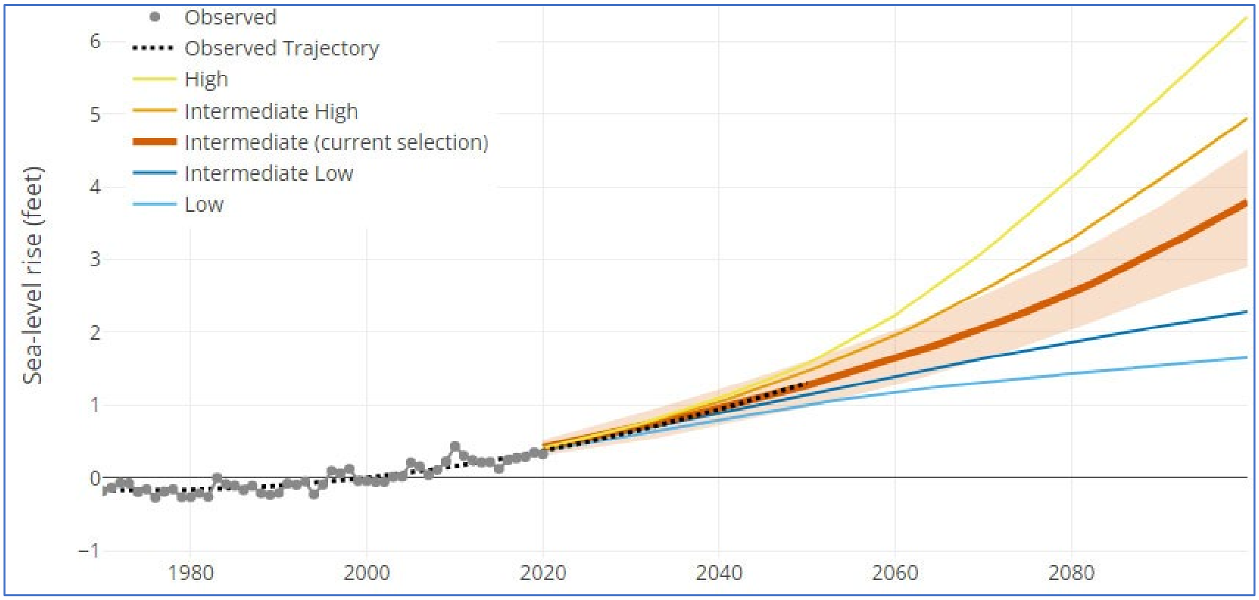

Figure 5. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding?

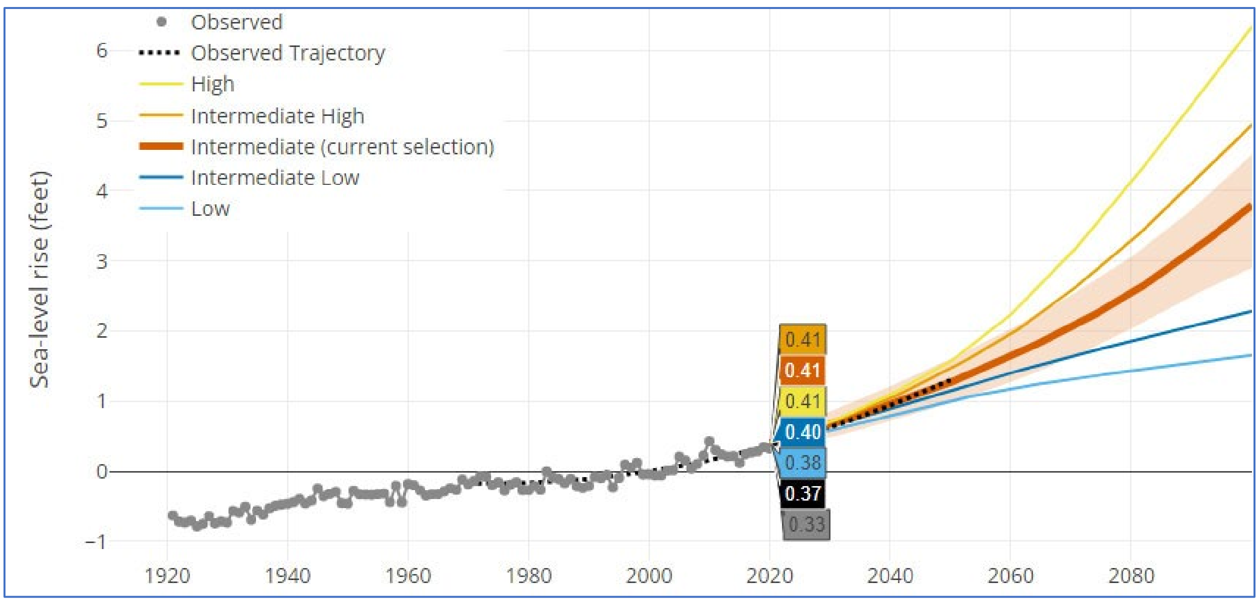

Figure 6. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). The colored numbers represent the modeling results for the various scenarios for 2020, as well as the observed mean sea level. Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding?

For Boston, the NOAA projections for 2050 are shown in Figure 7. According to Sweet, et al. (2022):

> *As a result of improved science and the updated framework and procedure for generating the Global Mean Sea Level (GMSL) scenarios, the time path of the scenarios - particularly the higher scenarios - is now more realistic and consistent with current process-based understanding. In this report, the range between the Low and High scenarios in 2020, 2030, 2040, and 2050 is now 0.02 m [0.07 feet], 0.06 m [0.20 feet], 0.15 m [0.49 feet], and 0.28 m [0.92 feet], respectively. In other words, there is less divergence between the GMSL scenarios in this near-term time period, which reduces uncertainty in the projected amount of GMSL rise up to the year 2050. The Low scenario remains largely the same between this report and Sweet et al. (2017); this range reduction reflects a downward shift in the higher scenarios in 2050 and times prior, as discussed above. As an example, the projected value in 2050 for the High scenario in this report (~0.4 m [1.31 feet]) is the same as that for the Intermediate-High projected value in 2050 in Sweet et al. (2017).*

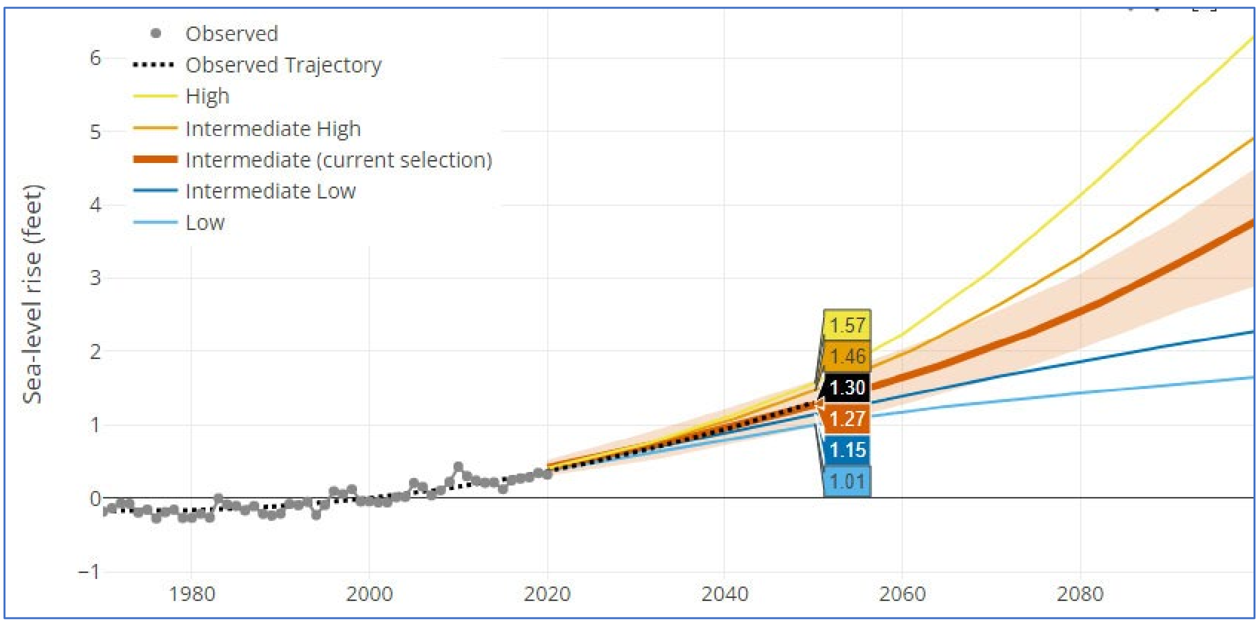

Figure 7. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). The colored numbers represent the modeling results for the various scenarios for 2050. Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding?

Based on this updated information, a reasonable expectation for near-term (through 2050) sea level rise in the Boston region, inclusive of the project area, is within the range of sea level rise projections illustrated in Figure 7. In this case, the 2050 mean sea level can be expected to be approximately 1.3 feet above the 2000 level or approximately 1.0±0.3 feet NAVD88. This value is substantially lower than the projections provided in the Resilient MA documentation (Table 1). Specifically, the updated NOAA evaluation indicates that expected sea level rise in Boston by 2050 is ~40% of the value recommended for planning by Resilient MA.

For planning of future infrastructure, incorporating a safety factor to accommodate potential future sea level rise is warranted; therefore, the Resilient MA 'High' sea level rise projections are useful to ensure that future development is safe from the impacts of sea level rise. However, when developing flood mitigation strategies for existing infrastructure, designing for future sea level conditions that are 'extremely unlikely to occur' can be both cost-prohibitive and unnecessary. Specifically for the sites evaluated along the Hingham Harbor shoreline, appropriate design levels for flood mitigation strategies should be based upon expected future sea levels, which NOAA project to be approximately 1.0 feet NAVD in 2050 and 1.8 feet NAVD in 2070. As the proposed flood mitigation strategies involve elevating seawalls, revetments, and coastal dunes, it will be a simple process to modify the design if future sea level rise exceeds the intermediate projections developed by NOAA (Sweet, et al., 2022). Table 2 provides expected future sea level rise for 2030, 2050, and 2070, based upon NOAA estimates (Sweet, *et al.*, 2022). Figure 8 provides both the 2022 NOAA projections and the projections that have been utilized for project planning by SCS engineers over the past decade that was based on Intergovernmental Panel on Climate Change (IPCC) modeling with the addition of ice sheet contribution from Rignot et al., 2011. Good agreement between these two sets of projections indicates that this pragmatic approach continues to provide a valid science-based methodology for evaluating future sea level rise, especially in the near-term (next 30 to 40 years).

Table 2. Relative mean sea level (feet, NAVD88) projections for Boston, MA as presented in Sweet, et al., 2022

Scenario	Probabilistic projections	2030	2050	2070
NOAA - Intermediate	Conditions that are about as likely as not to occur or, in other words, a 50% chance of occurrence (RCP 8.5)	0.4	1.0	1.8

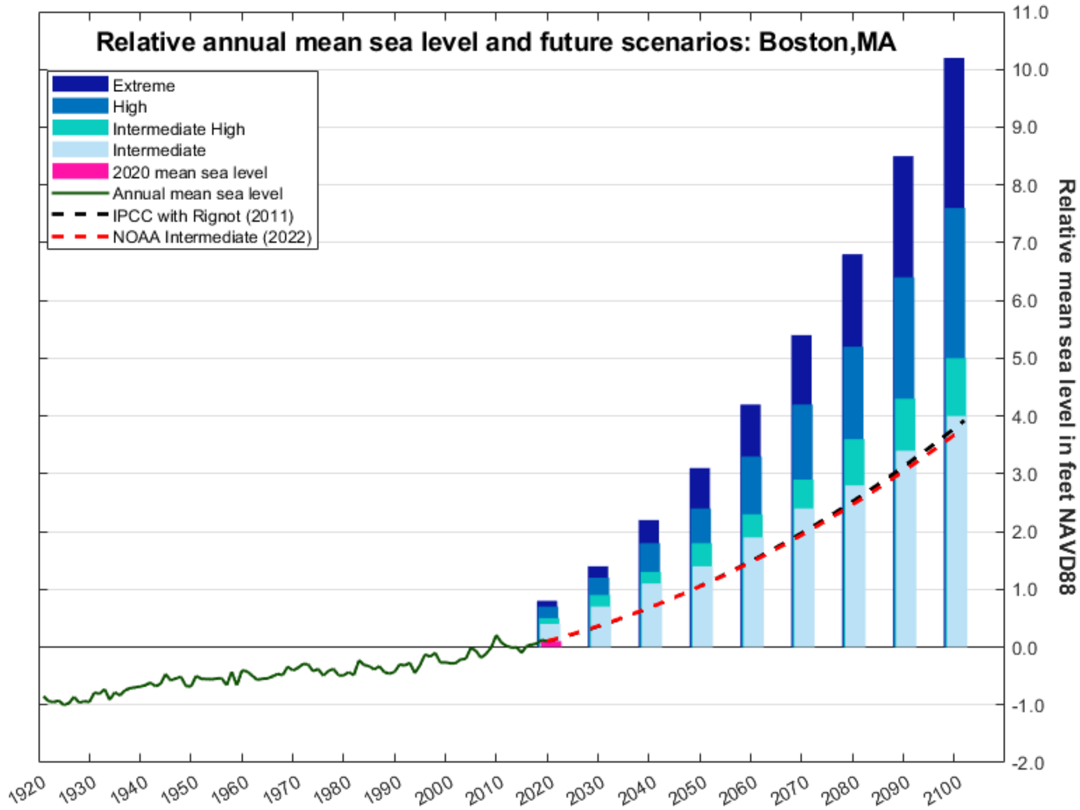

Figure 8. Sea level rise projections with the latest NOAA projections (adjusted to account for current mean sea level; dashed red line) and a curve representing flood projections from the IPCC augmented by sheet ice contributions determined by Rignot et al. (2011; dashed black line). The bar plot represents the sea level rise projections presented in Resilient MA.

B. Design Wave and Overtopping Analysis

A coastal engineering analysis was performed at 10 transects along the Hingham Harbor waterfront (Figure 9) to determine specifications for structural and soft-engineering interventions to improve storm resiliency in this area. General information about each transect is provided in Table 3. For this analysis, a two-dimensional (2D) wave model was developed in order to determine storm wave conditions along the Hingham Harbor waterfront. For shoreline reaches where hard engineering structures are in place, a wave overtopping analysis was performed in order to determine structure heights that would reduce wave overtopping discharges to levels that would be safe for paved surfaces during storms. At the two analysis transects placed at Bathing Beach, a cross-shore morphological model analysis was performed in order to determine attributes of a dune that would be necessary to withstand storms and be an effective barrier to storm surges and waves in Boston Harbor.

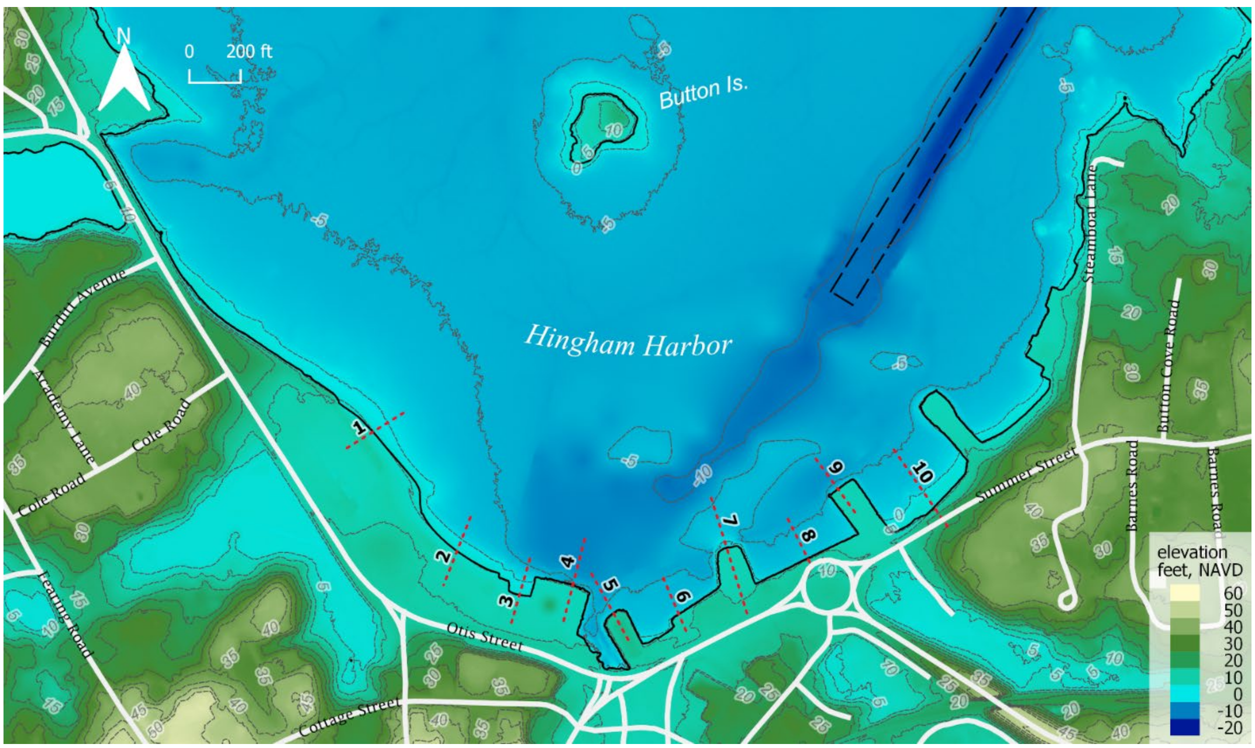

Figure 9. Map of Hingham Harbor waterfront with the location of the ten coastal analysis transects along the study area shoreline. The US Army Corps of Engineers' navigation channel limits are indicated by the black-dashed line.

Table 3. Coastal analysis transects (as mapped in Figure 9).

Transect no.	Transect description	Foth plan wall station	present condition	present crest elev. ft, NAVD	proposed intervention
1	Bathing Beach W, dune		beach	10.8	dune
2	Bathing Beach E, no dune		beach	8.5	dune
3	Otis Street	0+50	beach	8.7	dune/berm
4	Town Wharf	3+25	vertical wall	7.2	wall crest extension
5	Witney Wharf	11+50	vertical wall	10.5	wall crest extension
6	Summer Street, W of rotary	15+00	vertical wall	7.3	revetment
7	Kimball's Wharf	18+25	vertical wall/toe revetment	8.6	wall crest extension
8	Rotary	21+00	vertical wall	10.6	wall crest extension
9	Barnes Wharf	25+75	vertical wall	7.2	wall crest extension
10	Summer Street, E of rotary	31+00	vertical wall	9.6	wall crest extension

Data Sources

Several data sets were compiled as part of this analysis. These data are intended to represent the present, site-specific physical conditions in Hingham Harbor and along the shoreline reach of this study. Most data used in this analysis were retrieved from public sources of quality-controlled data (for example, bathymetry, tide, and wind data). Some data used in this analysis were available from other work funded by the Town (for example, sediment grain size data and an elevation survey of the waterfront).

Elevation Data. Though recent LiDAR topography is available for the study area, topobathy LiDAR surveys in this region of Boston Harbor do not provide complete coverage of ocean bottom elevations in Hingham Harbor. Therefore, the main source of topography and bathymetry depended upon as the main source of elevation data is the 2016 USGS Coastal National Elevation Database (CoNED) digital elevation model (DEM), which incorporates several data sets from many government sources to create a continuous topographic surface on a one-meter grid. Sources include recent (up to 2016) LiDAR surveys where coverage is available, and NOAA single-beam fathometer measurements in areas that have no LiDAR data. A contour map of the 2016 USGS DEM data in the vicinity of Hingham Harbor is shown in Figure 10.

Figure 10. Map of 2016 USGS CoNED elevation data, in the vicinity of Hingham Harbor. Contours lines are shown at 10-foot intervals.

Wave Data. The USACE Wave Information Study (WIS) hindcast provides wave data time series at dozens of stations along the US coastline. Wave parameters (including Hs wave height, T_p Peak Period, and mean direction for sea and swell components of the sea state) are available at a regular hourly interval starting January 1, 1980 through to January 1, 2021. Though NOAA (through is National Data Buoy Center, NDBC) maintains a wave buoy in Massachusetts Bay (station 44013), this record does not have directional wave data until June 2012, and there are significant periods within the time span of the record (1984 to present) where no data are available. Because of this, WIS hindcast is better suited for the development of the extreme wave conditions.

The hindcast record from WIS station 63052 (mapped in Figure 11) was used for this study. This station is about 13 nautical miles northeast of the entrance to Boston Harbor, in Massachusetts Bay, in an area with ocean depths of about 180 feet. 63052 is the closest WIS station to Boston Light on Little Brewster Island, at the entrance to Boston Harbor. Rose plots showing the occurrence of wave height and periods by compass sector is shown in Figure 12. From this plot is it seen that the most commonly occurring wave direction is the east sector, from where wave come from 26.6% of the record. 72.6% of wave heights in the record have a Hs significant wave height that is less than 3 feet. In 43.7% of the span of the record, wave periods are between 6.5 and 9.5 seconds.

An extremal analysis of wave heights was performed to develop appropriate wave heights and periods to represent storm conditions of various return periods (for example, the 10-year or 100-year storm events). The largest Hs wave height in each compass sector for every year of the 41-year-long hindcast record were determined sorted from smallest to largest. Weibull and Fischer-Tippet (FT) probability density functions (PDF) where used to fit the sorted extreme wave height data. The FT PDF provides the best fit of the data with an R^2 correlation of the FT PDF is 0.99 and an RMS error of 0.2 feet for waves from the north. This analysis results in a 100-year offshore wave height from the SE of 14.8 feet. Extreme periods were determined using a linear fit of wave height vs. mean period for all wave records in the WIS hindcast. Using this linear fit, the mean period of the 100-year wave from the north sector is calculated to be 11.5 feet. A linear regression of extreme wave heights and associated periods from the WIS record was used to determine a mean period of 7.4 seconds for this particular wave height at station 63052.

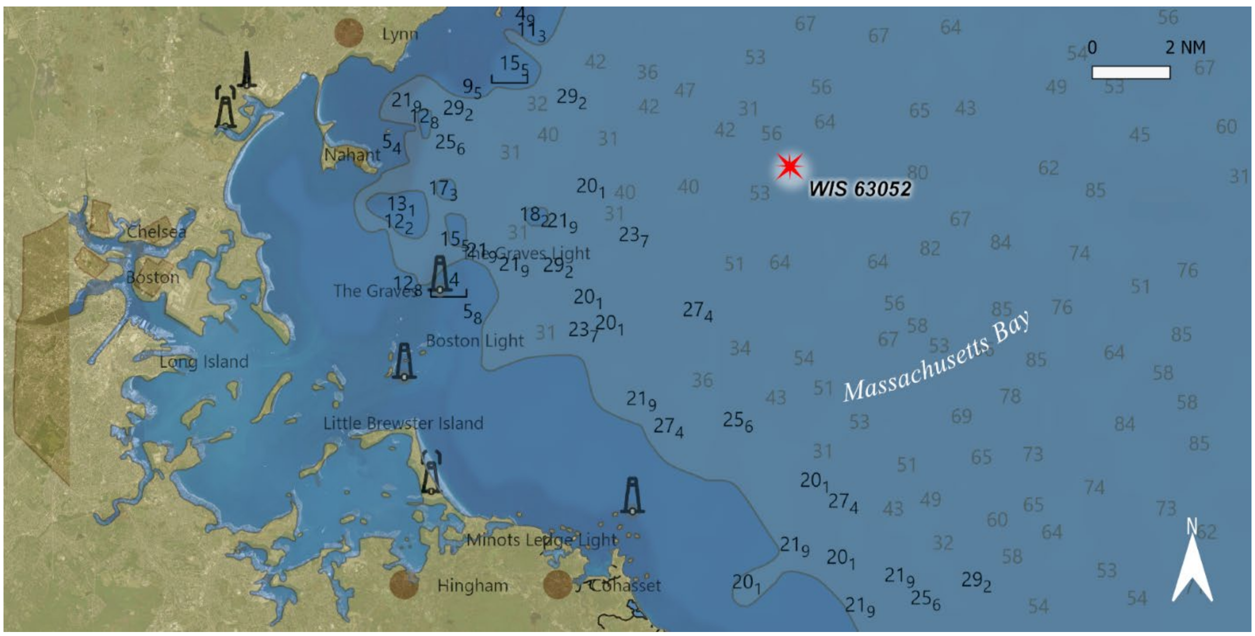

Figure 11. Location of WIS hindcast station 63052 in Massachusetts Bay, overlain on NOAA ENC chart of Massachusetts Bay (depths in meters and tenths).

Wind Data. Sources of wind data in the Boston Harbor region include the WIS hindcast, the Massachusetts Bay wave buoy (station 44013), and the record from Boston Logan International Airport (BOS). The record from BOS starts in 1943, and the record from buoy 44013 starts in 1984. Of these three sources, the WIS record is considered the best available option due to its offshore location, length of the record (because it is a reliably continuous record), and because it both wind speed and wave parameters together for each record. A rose plot of wind records from the WIS hindcast is presented in Figure 13. Most (50.2%) of the records are broadly distributed between the SSW and NW compass sectors, and the predominant direction is the SSW. The Fischer-Tippet II (FT) PDF is the best fit of annual extreme wind speeds taken from the WIS record. A plot of extreme return period winds from the north, based on the WIS record is presented in Figure 14. For the north sector, the 100-year sustained wind speed is 52.0 knots

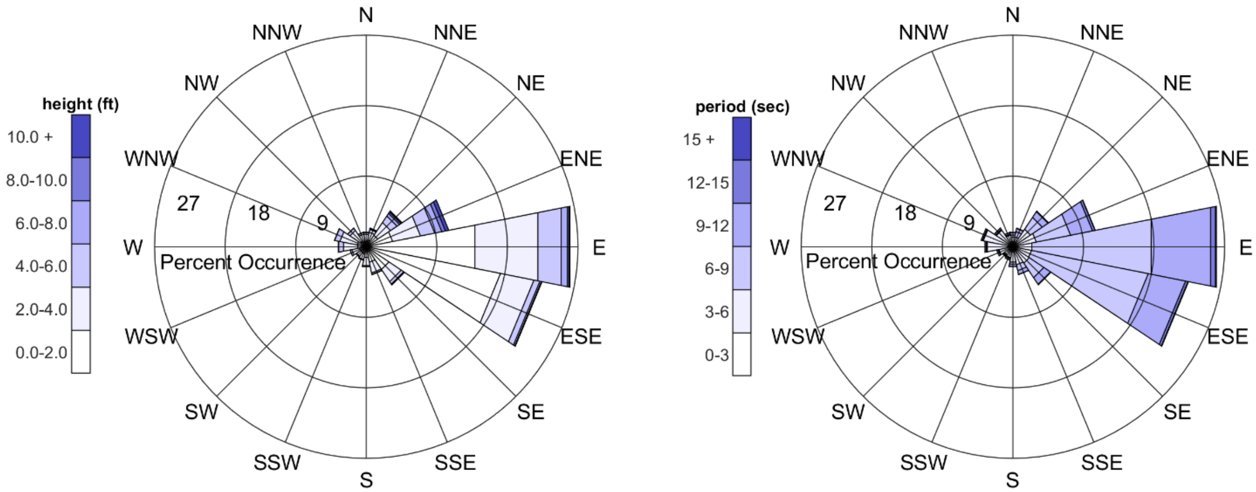

Figure 12. Rose plots of significant wave height (Hs, left) and peak wave period (Tp, right), for the WIS hindcast record at station 63052. Grey-tone segments indicate the percentage of time wave weights and periods in the record are within the indicated ranges for each compass sector.

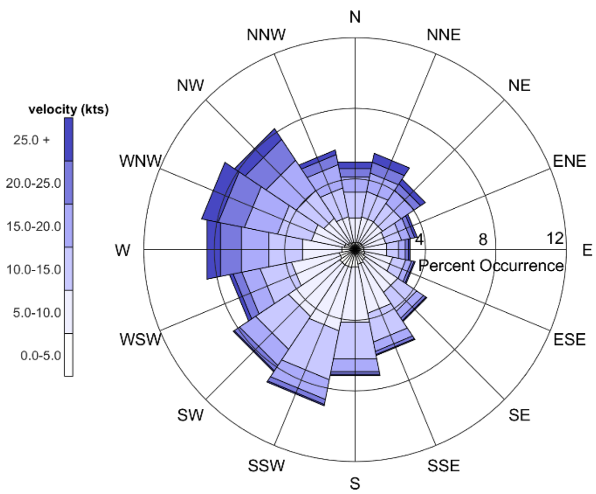

Figure 13. Rose plots of wind speed (knots) for the WIS hindcast record at station 63052. Grey-tone segments indicate the percentage of time winds in the record blow within the indicated speed range from the indicated compass sector.

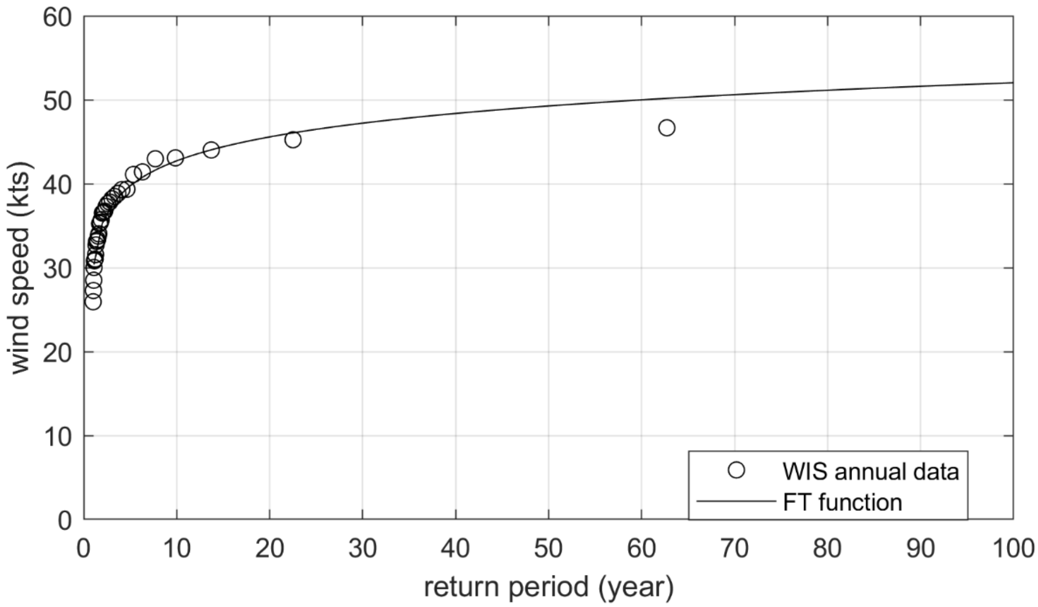

Figure 14. Plot of return period wind speeds for the north compass sector, using the WIS hindcast record (1980 through 2020) at station 63052. Sorted annual maximum windspeeds are indicated by the circle markers, and the Fischer-Tippet (FT) fit of the data is shown as the solid line. R^2 correlation of the FT PDF is 0.98, with an RMS error of 1.1 knots.

Water Level Data. Water elevation data used in this analysis include tide data available from the NOAA tide station in Boston Harbor, and extremal return period water levels available from the FEMA Flood Insurance Study (FIS) for Plymouth County (2021). NOAA Boston tide data recorded during the recent December 23, 2022 northeast storm (Figure 15) that impacted the region were downloaded from the NOAA Tides and Currents website (https://tidesandcurrents.noaa.gov). FEMA publishes return period still water elevation (SWEL) data for several transects along the shoreline of Plymouth County, including a transect in Hingham Harbor that is next to Barnes Wharf. At this transect (Plymouth County FIS Transect 10) the reported 10-year SWEL is 8.4 feet NAVD, and the 100-year SWEL is 9.7 feet NAVD. The maximum water level recorded during the Dec 23, 2023 northeast storm is 8.4 feet, equal to the 10-year SWEL Hingham Harbor. A tide time series for the 100-year return period event was created by scaling the surge component of the total water level (which is the combination of the astronomical tide + surge) so that the maximum water level reached the 100-year SWEL.

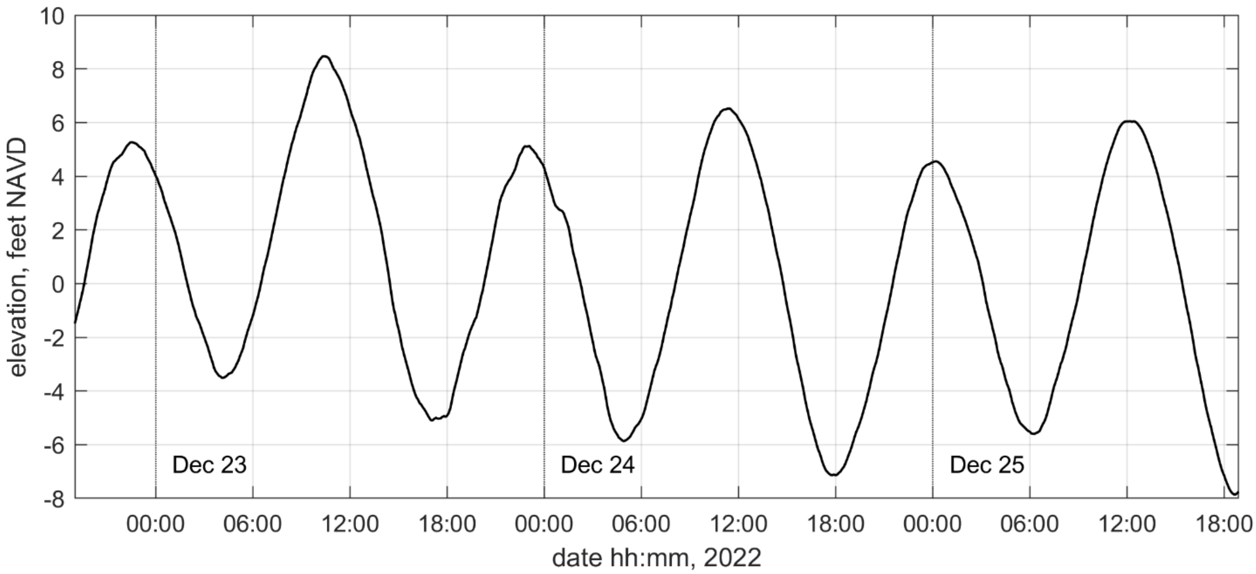

Figure 15. NOAA measured tides in Boston Harbor during the Dec 2022 northeast storm, when peak water levels reached 8.4 feet NAVD.

<u>Sediment Data</u>. For coastal analysis transects in this study that are for beach areas along the Hingham waterfront, sediment grain size data was taken from an existing construction specification for Bathing Beach. In this specification, a minimum and maximum acceptable grain size distribution is provided (Figure 16). Median (D50) sediment grain sizes from these two distributions are 0.50 mm for the minimum, and 1.18 mm for the maximum.

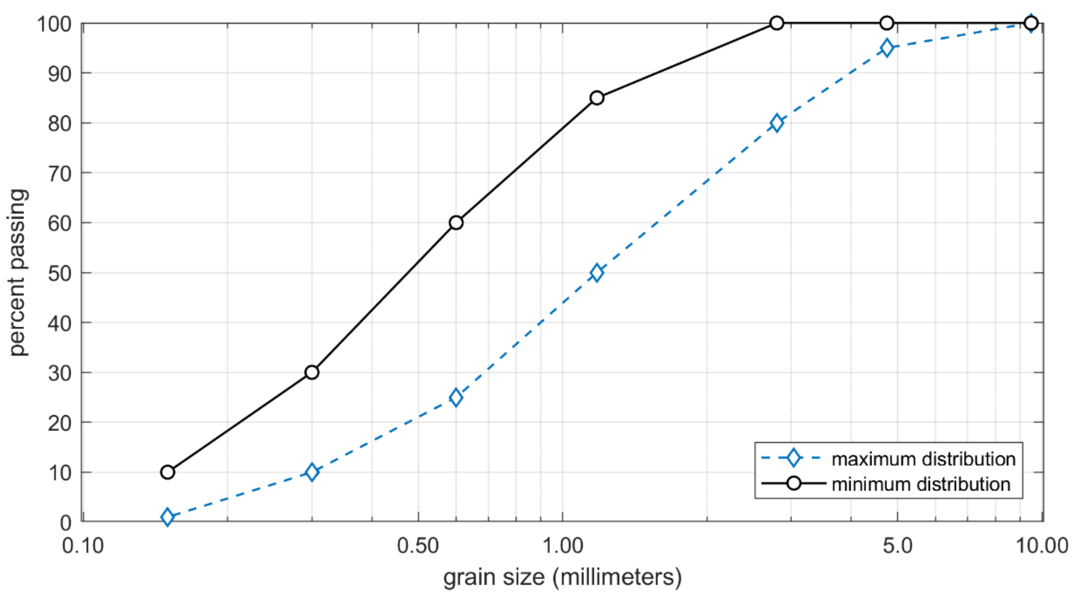

Figure 16. Bathing Beach specified grain size distribution curves that designate the minimum (solid black line) and maximum (dashed blue line) allowable percent passing for indicated sand grain sizes. The D50 grain size resulting from these two distributions is 0.50 and 1.18 mm for the minimum and maximum specified distributions, respectively.

Design Wave and Overtopping Analysis

As part of this analysis, design wave conditions were computed for the waterfront area of the Hingham Harbor using the SWAN 2D wave model (Booij, 1999). Model inputs included wind speeds and wave parameters developed from the extremal analysis of the USACE WIS wave hindcast record (Table 4). Wave model outputs were used to determine seawall height elevations that would limit wave overtopping rates in the waterfront area to levels that would not cause damage to structures or paved surfaces. SWAN wave model output was also used as inputs to 2D cross-shore profile models of two transects at Bathing Beach. These cross-shore models were used to determine dune elevation and crest widths that would be required to capably withstand extreme storm conditions.

Table 4. Storm wind and wave characteristics (1% return frequency) used in the runs of the Hingham SWAN wave model.

Storm parameter	Compass sector						
	WNW	NW	NNW	N	NNE	NE	ENE
Sustained wind speed (kts)	42.7	44.9	48.7	52.0	50.6	48.4	48.1
Offshore wave height (ft)	8.8	9.2	9.5	11.5	15.2	21.7	23.3
Offshore wave mean period (sec)	6.8	6.9	7.0	7.4	8.3	9.9	10.3
Still water level (ft, NAVD)	9.7	9.7	9.7	9.7	9.7	9.7	9.7

SWAN Model Development. Development of the Hingham Harbor SWAN model proceeded by first creating the numerical grid, using available topography and bathymetry elevation data. Storm conditions run with the model were developed from the extremal analysis of winds and waves from the WIS hindcast record in Massachusetts Bay, at station 63052. The SWAN model for Hingham Harbor consists of three cartesian grid meshes. They range from a coarse mesh with a 131-foot (40-meter) mesh that covers all of Boston Harbor and its entrance to Massachusetts Bay, a 49-foot (15-meter) mesh intermediate mesh that covers Hingham Bay, and finally a 2.2-foot (2-meter) fine-scale mesh in the area of the Hingham Harbor waterfront. The bathymetry and extents of these three grids is shown in Figure 17. Boundary conditions for each of the finer scale grids is extracted from the next-courser grid, which allows for a high level of grid refinement n the particular area of interest, while allowing for a larger grid mesh in areas where fine detail is not needed. In this case the Hingham Harbor grid is nested within the Hingham Bay grid, which in turn is nested within the Boston Harbor/Massachusetts Bay grid.

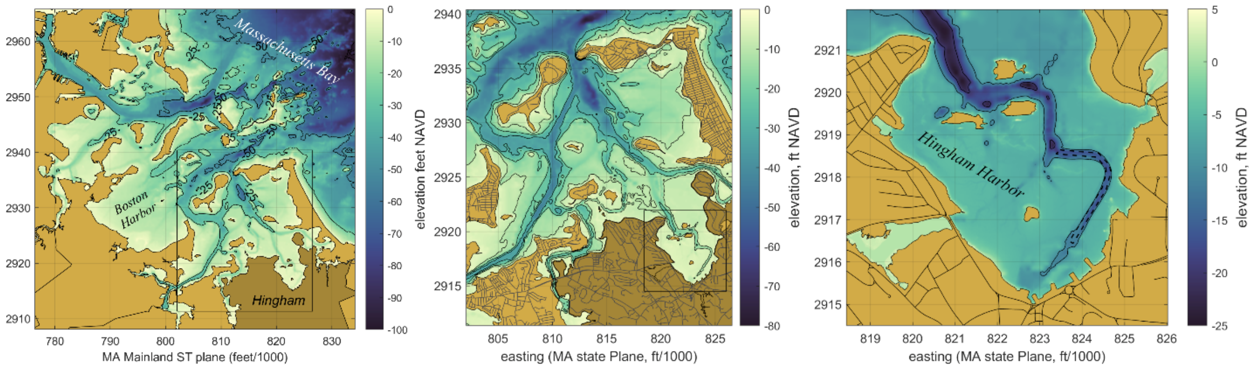

Figure 17. Contour plots of bathymetry used in the wave model coarse 40-meter grid of Boston Harbor, the intermediate 15-meter grid of Hingham Bay, and the fine nested 2-meter grid of Hingham Harbor, including the shoreline of the project area.

Winds blowing from the north compass sector generate the largest waves in Hingham Harbor. For this wave case, significant Hs wave heights range between 2.5 and 2.8 feet between Bathing Beach and Barnes Wharf. Peak wave periods range between 2.7 and 3.3 seconds. In addition to the 1% storm with present mean sea level, the same wave model cases were run for expected 2050 and 2070 mean sea levels. Wave heights in the harbor do increase slightly for these projected future conditions, but by only about a maximum of 5% even for 2070 water levels.

Shaded contour plots of wave heights in Boston Harbor, Hingham Bay, and Hingham Harbor are presented in Figure 18 for 100-year storm conditions with winds blowing from the north, and with present mean sea level.

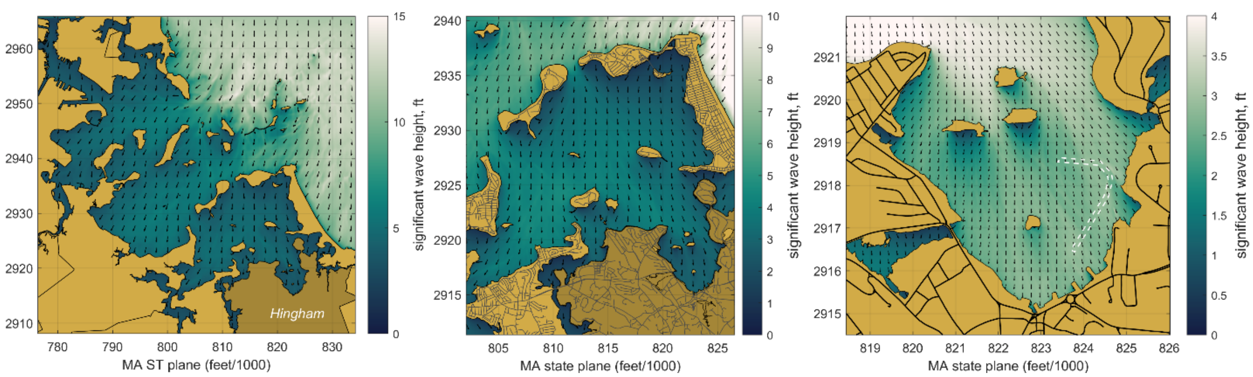

Figure 18. Contour plots of wave height (Hs) and direction (arrows) for the modeled 100-year storm conditions with winds blowing from the north, for the Boston Harbor grid (left), Hingham Bay grid (center), and the Hingham Habor fine grid (right).

Wave Overtopping of Structures. For the eight total analysis transects where coastal structure improvements are being considered, wall crest elevations were determined that limit the amount of wave overtopping flows to acceptable rates. Basically, given wave conditions and water levels that occur at each analysis transect, wall crest elevations were iterated to reduce overtopping rates to 50 liters/second per meter length of wall (0.54 cfs/foot), which according to Table VI-5-6 of the USACE Coastal Engineering Manual (2011) is the upper limit where paved surfaces will resist damage.

Wall crest height determinations were performed using methods available from the EurOtop Manual (2018), for vertical walls (transects 4, 5, and 7 through 10) and for sloped revetment (transect 6).

*Vertical Wall Transects***.** From the EurOtop Manual, the overtopping rate (q) on a vertical wall is found using the equation:

$$\frac{q}{\sqrt{g \cdot H_{mo}^3}} = 0.054\, exp\left[-\left(2.12\,\frac{R_c}{H_{mo}}\right)^{1.3}\right]$$

where R_c is the structure freeboard

H_{mo} is the offshore significant wave height

Revetted Transects. The discharge of water from waves over the crest of a structure is referred to as wave overtopping. Methods presented in the EurOtop manual (2018) were used to determine overtopping rates for

From the EurOtop Manual, the overtopping rate (q) on a simple slope is found using the equation:

$$\frac{q}{\sqrt{g \cdot H_{mo}^3}} = \frac{0.026}{\sqrt{\tan\alpha}} \cdot \xi_{m-1.0} \cdot exp\left[-\left(2.5\,\frac{R_c}{\xi_{m-1.0} \cdot H_{mo}}\right)^{1.3}\right]$$

where R_c is the structure freeboard

H_{mo} is the offshore significant wave height

α is the structure slope angle

ξ is the surf similarity parameter, as before

and h_{wall} as the crown wall height above the revetment.

For the two revetment transects, wall crest elevations were determined for slopes of 1:1.5 (v:h) and 1:2.0 (v:h). 1:1.5 is generally accepted as the maximum slope for stone revetments. Flatter slopes generally reduce wave runup elevations and overtopping volumes for walls with the same crest elevation.

Overtopping Analysis Results. Wall crest elevation determined using the EurOtop methodology are resented in Table 5 for the vertical wall transects and Table 6 for revetment sections.

Table 5. Vertical wall crest elevations, in feet NAVD88, to prevent damage to paved surfaces from wave overtopping, for present, 2050, and 2070 sea level scenarios.

	Sea level scenario		
transect	present	2050	2070
4	11.0	12.1	12.9
5	11.0	12.0	12.9
7	10.9	12.0	12.9
8	10.9	12.0	12.8
9	10.9	12.0	12.8
10	11.0	12.1	12.9

Table 6. Revetment slope crest elevations, in feet NAVD88, to prevent damage to paved surfaces from wave overtopping, for structures with 1:1.5 and 1:2.0 slopes, and for present, 2050, and 2070 sea level scenarios.

	Sea level scenario					
	present		2050		2070	
slope	1.5	2.0	1.5	2.0	1.5	2.0
transect						
6	13.0	11.9	14.0	12.9	14.8	13.7

Beach Transects. For the two beach transects at Bathing Beach (transects 1 and 2), a cross-shore morphological model was employed to determine the dimensions of a dune which would serve as an erodible barrier to ocean surges up to the 1% (100-year) still water level (SWEL), for the same three different MSL scenarios used in the overtopping analysis. The cross-shore transport model XBeach-X (Roelvink, *et al.*, 2015) was used to determine a dune fill elevation and crest width which would withstand a major storm event with some remaining flood protection capacity. 1-percent wave conditions applied to the model open boundary were derived from the SWAN wave model of Boston and Hingham Harbors, by applying 1-percent winds from the north (52.0 kts). The Boston tide record from the December 23, 2022 northeast storm was used as the source of input water levels during the XBeach simulation. The storm surge component of the recorded Boston tide was scaled up so that the peak total water level would reach the present FEMA-designated 1-percent SWEL (9.7 feet NAVD for present MSL conditions). Circa 2016 topography/bathymetry elevation data from the USGS CoNED DEM was interpolated to the Bathing Beach Point XBeach model transects.

Constructed dune crest width and elevation were iterated with the goal finding a configuration which would have some portion of the dune remain at its original height after the duration of the storm. For present sea levels, the existing dune at Bathing Beach is able to withstand the 1-percent storm (Figure 19). The present dune has a foreshore and backside slope of approximately 1:4, a dune crest of 10.7 feet NAVD, and a crest width of about 22 feet. The dune toe (start of the foreshore slope on the beach) is at an elevation of about +7 feet NAVD. For 2050 MSL conditions, the dune is able to withstand the 1-percent storm if the crest elevation is increased to +11 feet NAVD. For 2070 MSL conditions, the dune crest elevation would need to be increased to +12 feet NAVD to withstand the 1-percent storm (Figure 20).

At Transect 2 (Figure 21), there is presently no dune in place, and the beach berm has a crest elevation of +8.5 feet NAVD. A dune with similar dimensions to the existing dune at Transect 1 was added to the profile of Transect 2 (+11 feet NAVD crest, 22-foot crest width, with 1:4 foreshore and backside slopes). Similar to Transect 1, this dune is adequate for present and 2050 projected MSL with 1-percent storm conditions. For projected 2070 MSL, the dune crest must be raised to +12 feet NAVD in order to withstand the 1-percent storm (Figure 22), similar to Transect 1. A summary of dune design requirements to withstand coastal erosion and wave overtopping during 100-year storm events is provided in Table 7.

For Transect 3 (Figure 9), located between Town Wharf and the boat ramp, incorporation of a dune with similar dimensions to Transects 1 and 2 would be required to provide upland flood protection. However, this dune feature would not be effective as coastal flood mitigation if the storm tide pathway through the boat ramp is not addressed. Additional engineering analyses will be required to ensure that potential incorporation of a dune/berm west of Town Wharf is incorporated into flood mitigation improvements at the boat ramp.

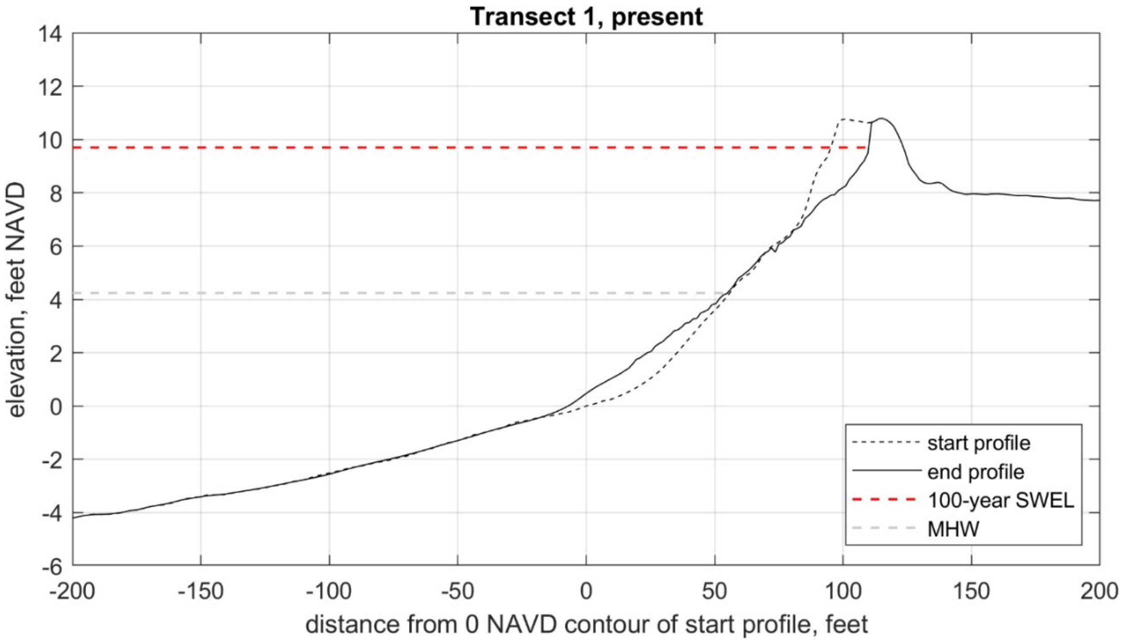

Figure 19. Xbeach model output for the modeled 1-percent (100-year) storm for Transect 1 at Bathing Beach, with existing topography, for present MSL. The start profile is indicated by the dashed black line, and the shoreline at the end of the simulation is indicated by the solid black line. Present MHW and the present 1-percent SWEL are also indicated.

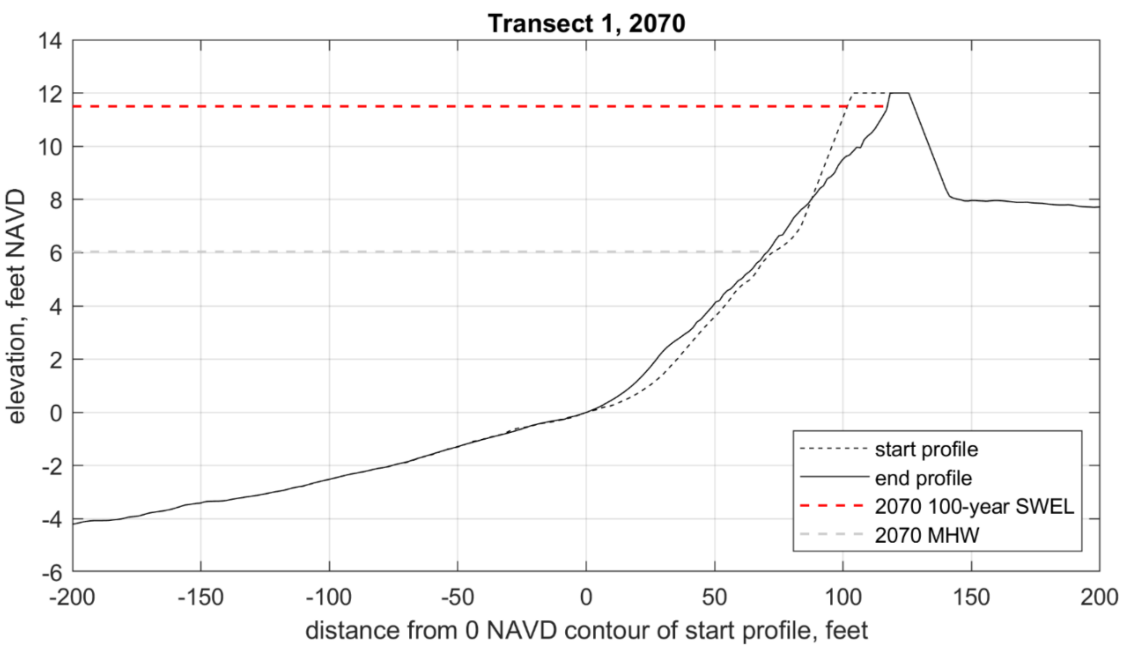

Figure 20. Xbeach model output for the modeled 1-percent (100-year) storm for Transect 1 at Bathing Beach, with existing topography, for projected 2070 MSL. The start profile is indicated by the dashed black line, and the shoreline at the end of the simulation is indicated by the solid black line. 2070 MHW and the 2070 1-percent SWEL are also indicated.

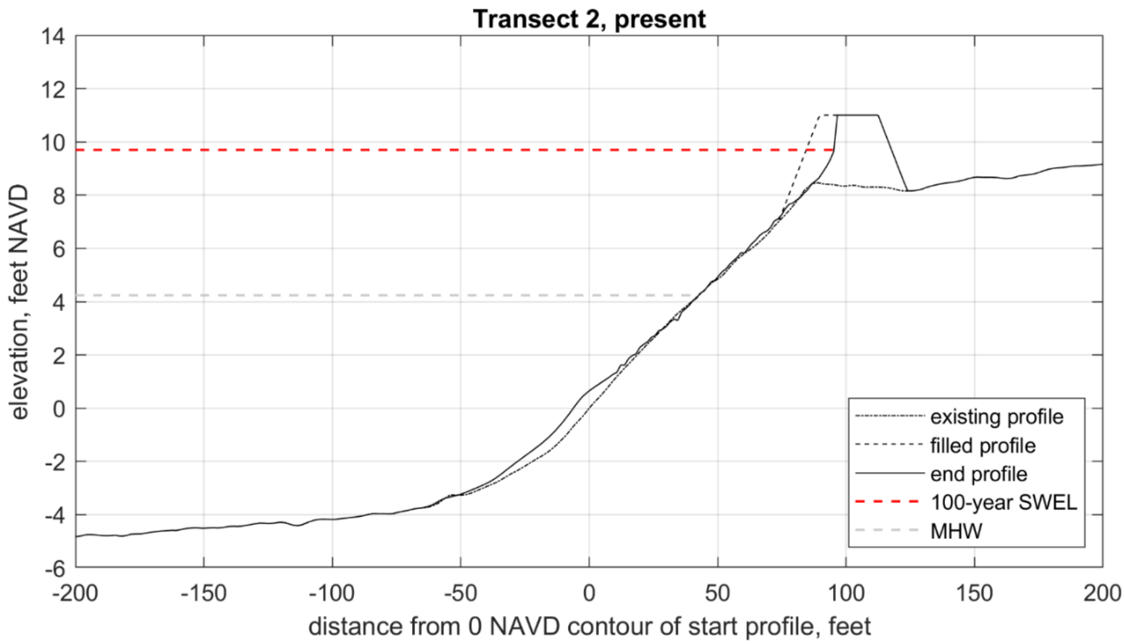

Figure 21. Xbeach model output for the modeled 1-percent (100-year) storm for Transect 1 at Bathing Beach, with existing topography, for present MSL. The start profile is indicated by the dashed black line, and the shoreline at the end of the simulation is indicated by the solid black line. Present MHW and the present 1-percent SWEL are also indicated.

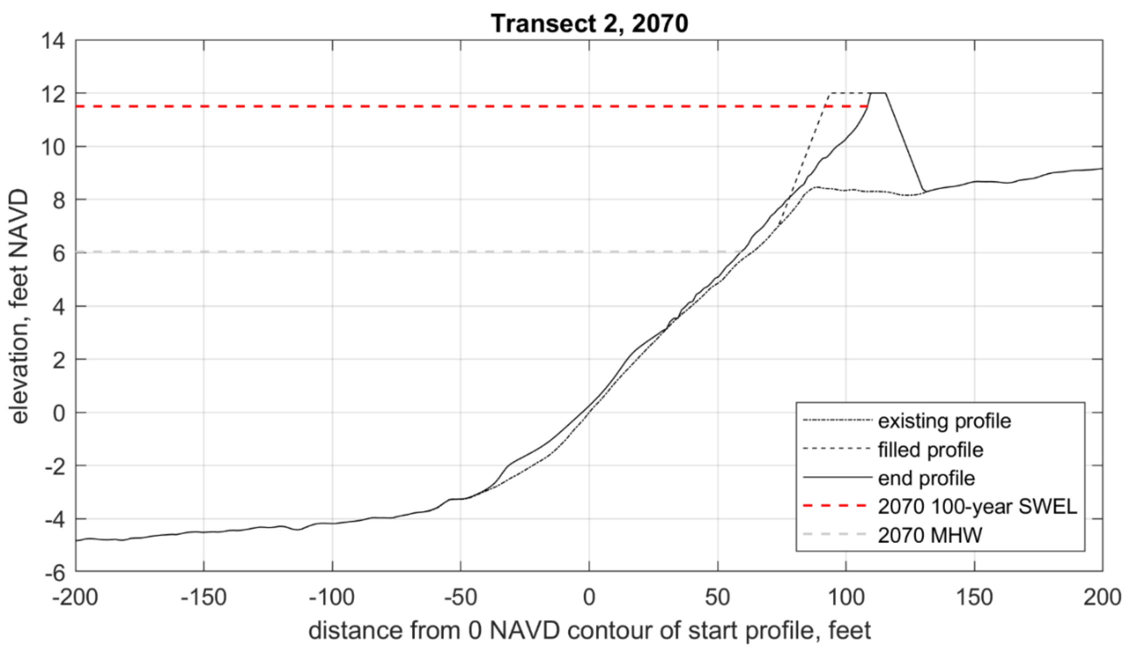

Figure 22. Xbeach model output for the modeled 1-percent (100-year) storm for Transect 1 at Bathing Beach, with existing topography, for projected 2070 MSL. The start profile is indicated by the dashed black line, and the shoreline at the end of the simulation is indicated by the solid black line. 2070 MHW and the 2070 1-percent SWEL are also indicated.

Table 7. Dune crest elevations and crest widths, in feet NAVD88, to prevent wave overtopping and erosion during 100-year storm event; for present, 2050, and 2070 sea level scenarios.

	Sea level scenario					
	present		2050		2070	
	elevation	crest width (ft)	elevation	crest width (ft)	elevation	crest width (ft)
Transect 1	10.7	22	11.0	22	12.0	22
Transect 2	10.7	22	11.0	22	12.0	22

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