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August 18, 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: Duxbury Maritime School design water levels and wave conditions

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Storm generated flood inundation is not a new challenge for South Shore communities. 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. 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 Duxbury Beach barrier complex, the properties along the mainland shoreline of Duxbury Bay are protected from storm wave conditions often associated with the open Atlantic Ocean, providing relatively safe conditions for development of communities along the bay 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 Duxbury Maritime School, much of the site is presently between 7 and 9 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), which aligns more accurately with observed flooding patterns at the site than the Massachusetts Coastal Flood Risk Model (MC-FRM).

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 do not propagate into the developed areas.

Figure 1. Portion of updated FEMA Flood Insurance Rate Map (FIRM) for Duxbury, last updated on July 6, 2021.

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 evaluate the level of shore protection needed.

A. Updated Sea Level Rise Analysis

The exposure of population and infrastructure to flooding on the South Shore 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).

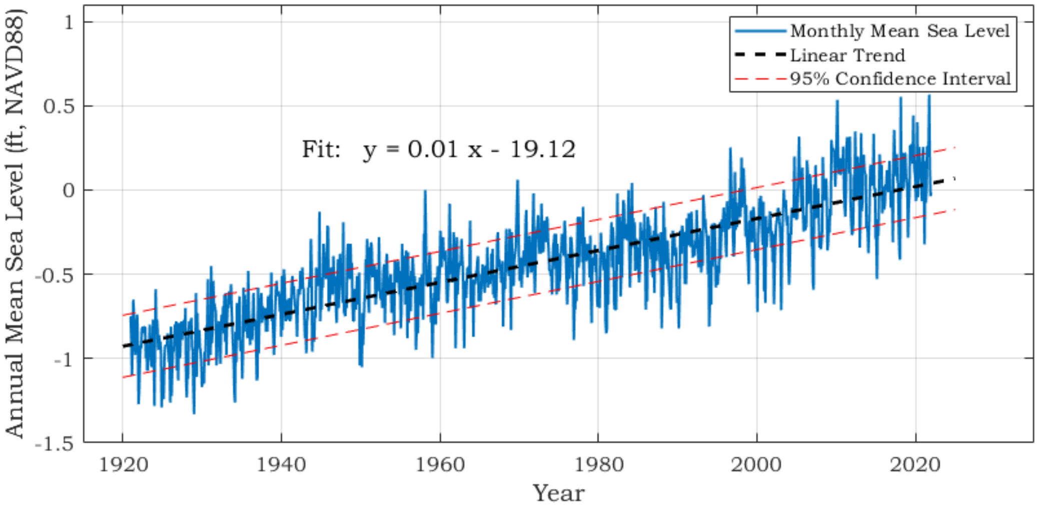

Figure 2. Monthly mean water levels recorded in Boston Harbor between 1921 and 2021 indicate a linear trend in sea level rise over the past 100 years of approximately 0.01 feet per year (*Source: NOAA*)

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 datasets 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.

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

The above 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.

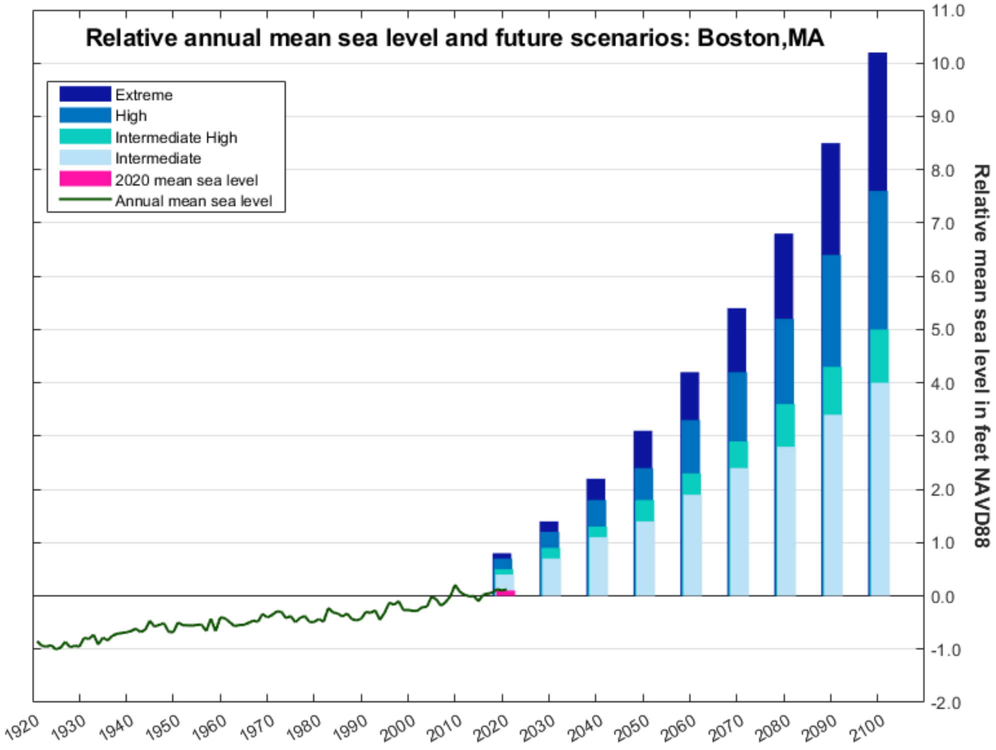

Figure 3. Relative mean sea level projections for the Boston, MA tide station based on four National Climate Assessment global scenarios with associated probabilistic model outputs from the Northeast Climate Science Center. The probabilistic projections are listed in Table 1. The pink bar denotes the 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.

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 developing future coastal hazard mitigation and improvement alternatives. 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.

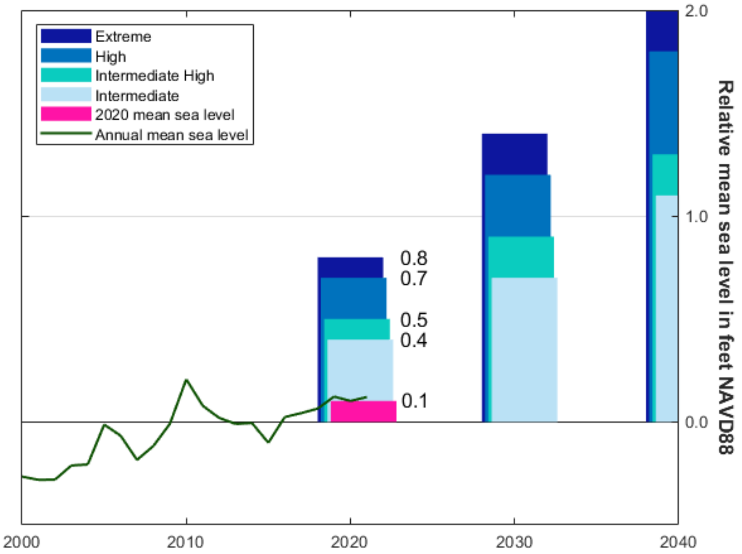

Figure 4. Comparison of probabilistic sea level rise projections from Resilient MA (DeConto and Kopp, 2017) and measured annual mean sea level for Boston Harbor, Massachusetts.

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.

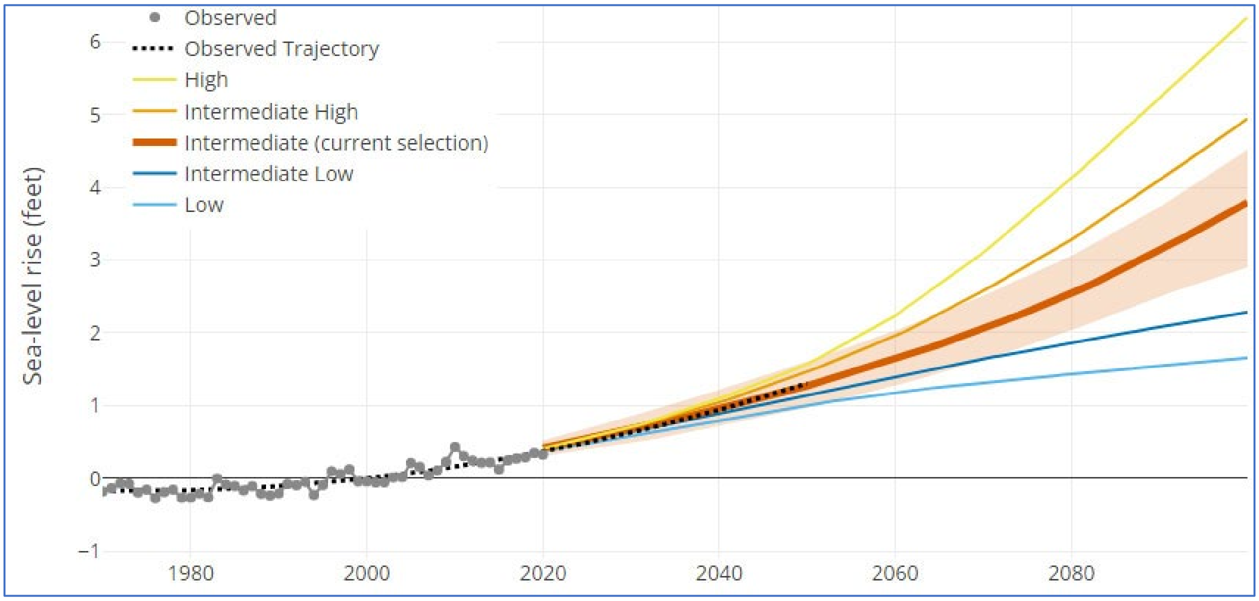

Figure 5. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding?

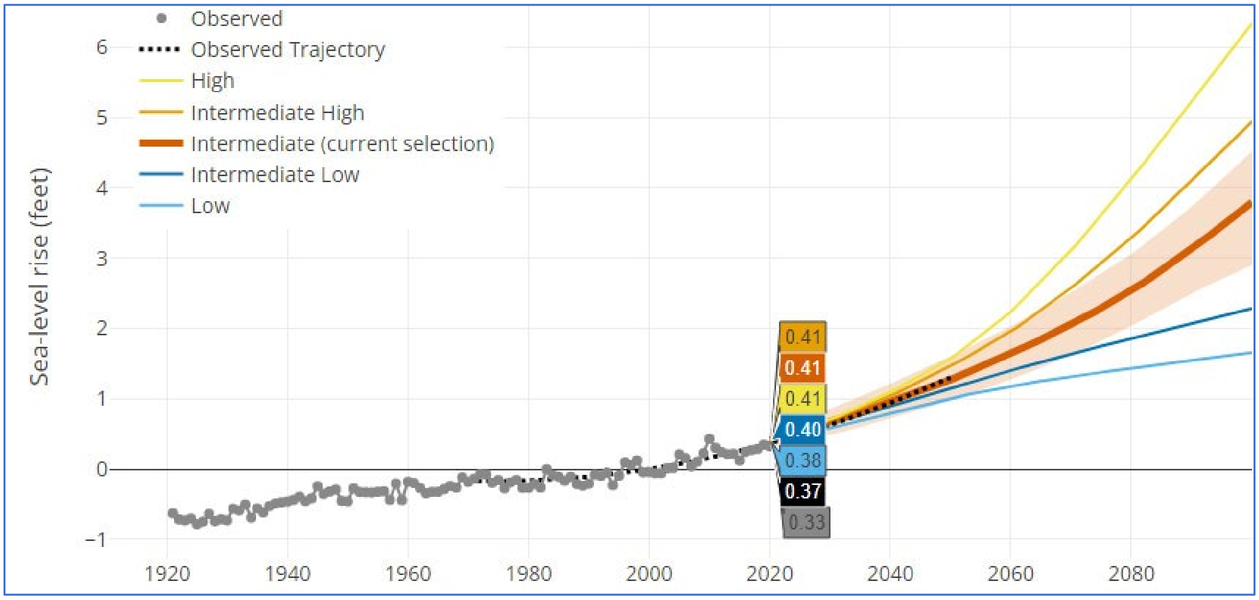

Figure 6. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). The colored numbers represent the modeling results for the various scenarios for 2020, as well as the observed mean sea level. Results for a full range of scenarios 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).*

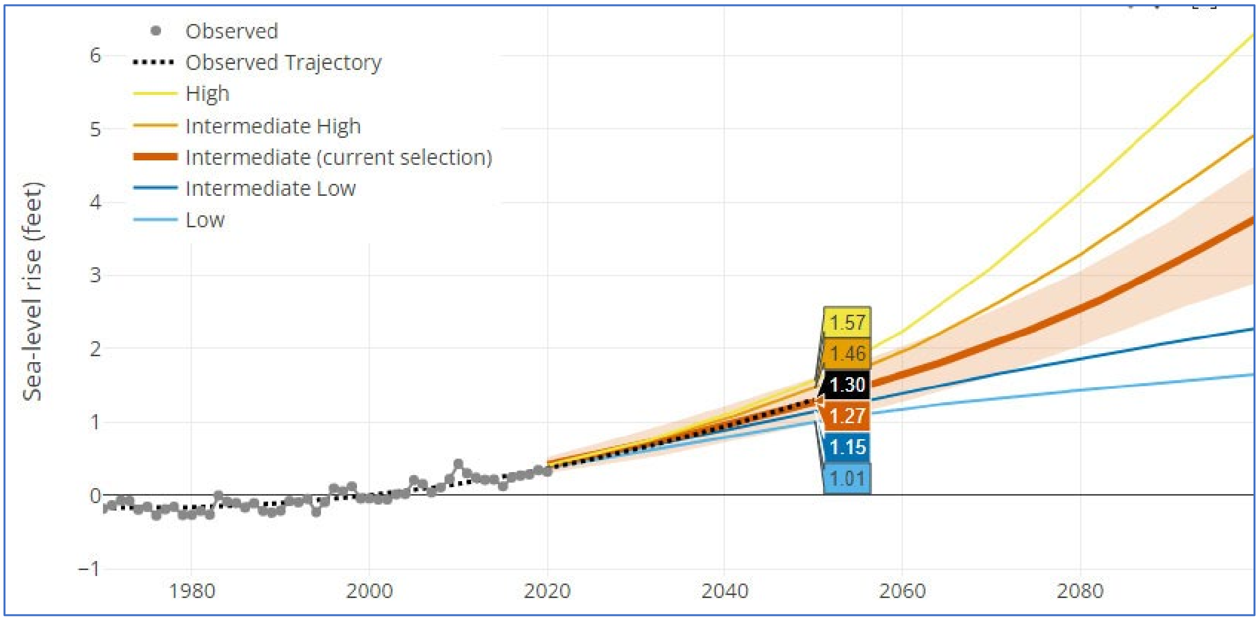

Figure 7. Projected sea level rise for Boston Harbor, Massachusetts based upon modeling analyses performed by NOAA (Sweet, et. al., 2022). The colored numbers represent the modeling results for the various scenarios for 2050. Results for a full range of scenarios can be found at: https://sealevel.nasa.gov/flooding-analysis-tool/projected-flooding?

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 mainland shoreline of Duxbury Bay, 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 bulkheads and/or surface elevation of parking/storage areas, 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, 2nd 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 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

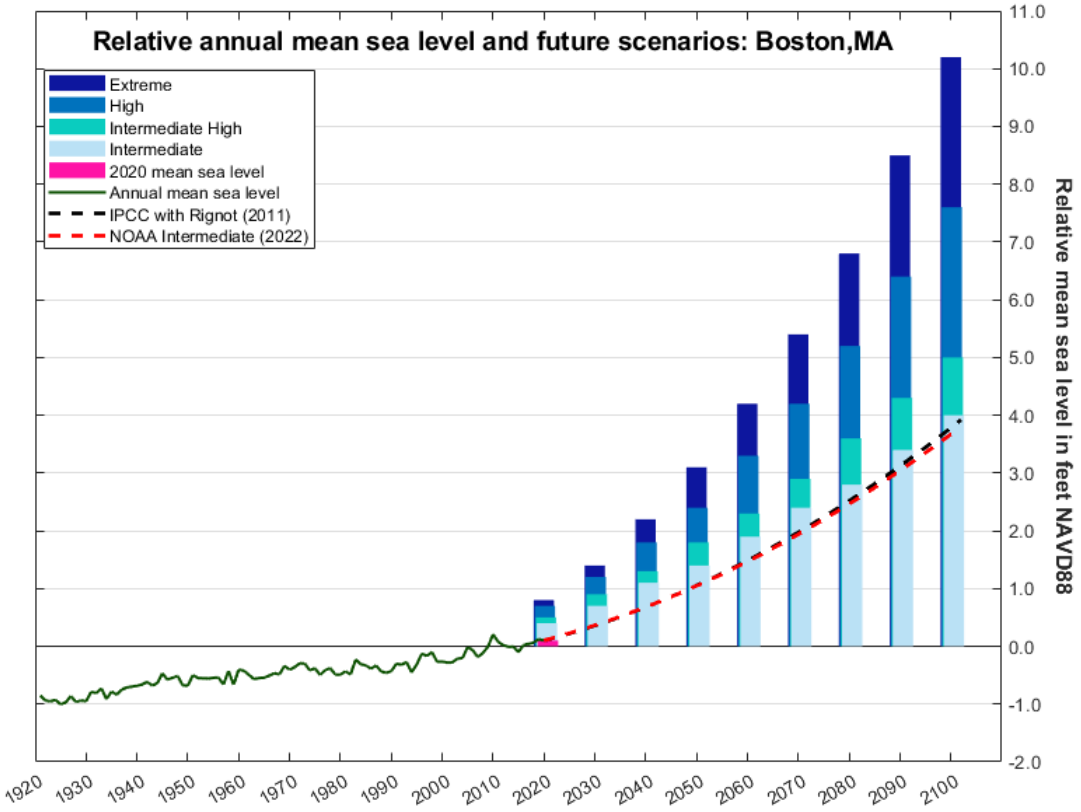

Figure 8. Sea level rise projections with the latest NOAA projections (adjusted to account for current mean sea level; dashed red line) and a curve representing flood projections from the IPCC augmented by sheet ice contributions determined by Rignot et al. (2011; dashed black line). The bar plot represents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

B. Design Wave and Overtopping Analysis

Design wave conditions were developed for the waterfront area of the Duxbury Maritime School. As part of this analysis, design wave conditions were computed using the SWAN 2D wave model (Booij, 1999). Wave model outputs were then 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 Model Input Data

Several data sets were compiled as part of the effort to create the SWAN wave model for the Duxbury Harbor project area. Data used in this analysis are intended to represent the present, site-specific physical conditions in the Harbor and within the school property. Most data used in this analysis were retrieved from public sources of quality-controlled data (for example, bathymetry, wind, and wave data). Some data used in this analysis were collected as part of this project (for example, the land survey of the school site).

Elevation Data. The 2016 US Army Corps of Engineers (USACE) topography/bathymetry digital elevation model (DEM) provides the best coverage in Duxbury Bay in the project vicinity. The DEM was developed by USACE using several sources including LiDAR flights and NOAA fathometer surveys, in order to create a continuous, gridded terrain/bathymetric surface. A 2019 fathometer survey of the USACE-maintained Duxbury anchorage basin and navigation channel was used to specify bay depths within the area that was surveyed. In areas beyond Duxbury Bay elevation data were accessed from NOAA's National Centers for Environmental Information bathymetric data viewer (https://www.ncei.noaa.gov/maps/bathymetry).

A contour plot of topography and bathymetry for the sources used in this analysis is shown in Figure 9, in the Duxbury Harbor vicinity.

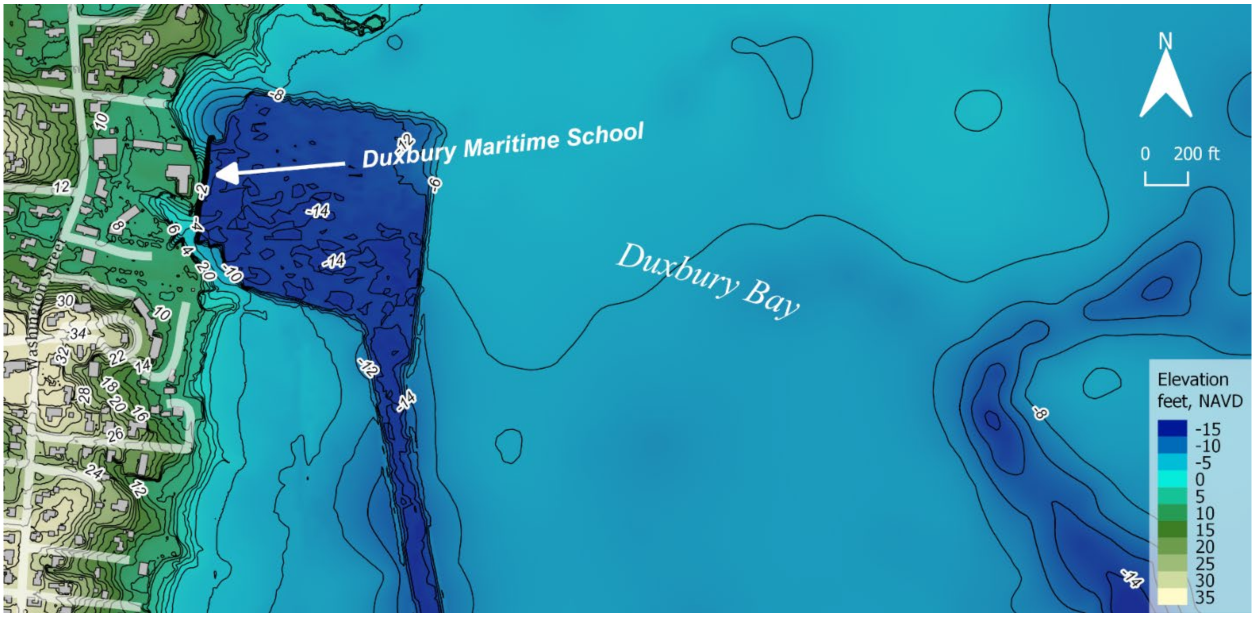

Figure 9. Map of topography in the vicinity of Duxbury Maritime School, including 2019 US Army Corps elevation data within the federal navigation project area. Contours lines are provided at 2-foot intervals.

Wave and Wind Data. The USACE Wave Information Study (WIS) hindcast provides wave and wind data time series at dozens of stations along the US coastline. Wind and 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 used in this analysis.

The hindcast record from WIS station 63060 (mapped in Figure 10) was used for this study. This station is about 17 miles northeast east of Duxbury, in Massachusetts Bay, in an area with ocean depths of about 190 feet. 63060 is the closest WIS station to Duxbury.

An extremal analysis of wave heights and wind speeds was performed to develop wave model input conditions that represent the 100-year storm event for every compass sector. The wave and wind conditions that result from this analysis are listed in Table 3 for compass sectors that would develop waves in Duxbury Bay that would be directed toward the project site.

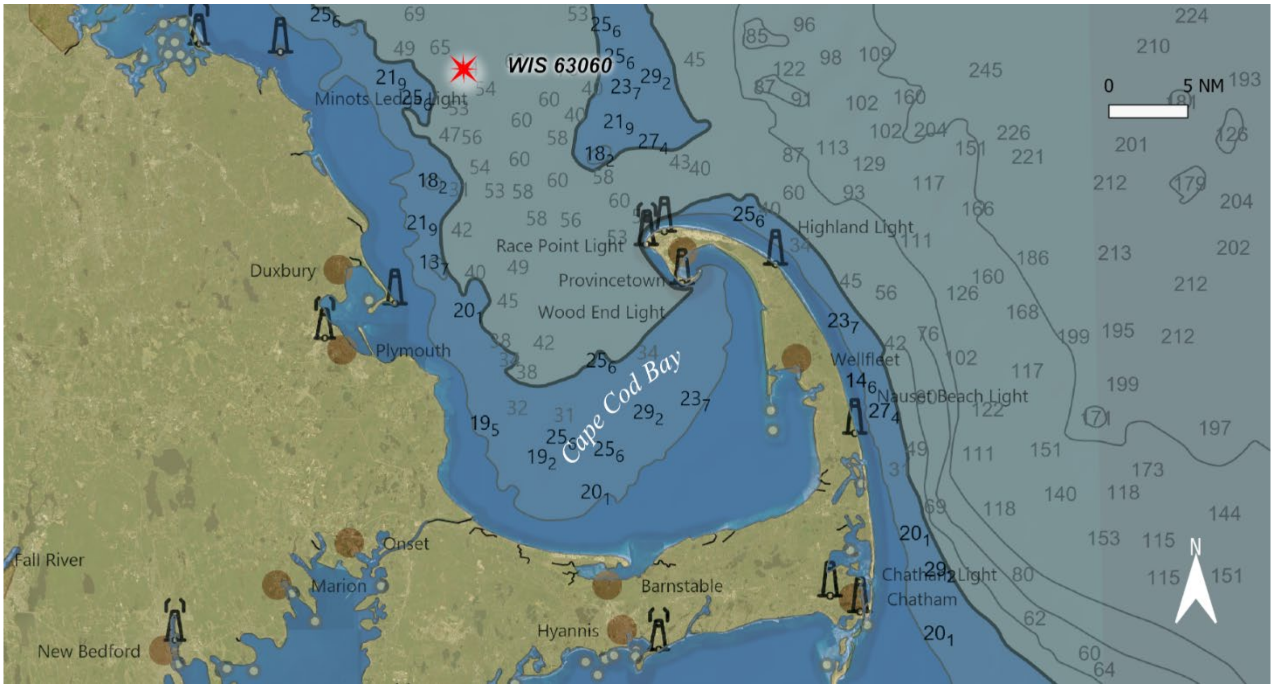

Figure 10. Location of WIS hindcast station 63060 in Massachusetts Bay, overlain on NOAA ENC chart of Massachusetts Bay (depths in meters and tenths).

Table 3. Storm wind and wave characteristics (1% return frequency) used in the runs of the Duxbury SWAN wave model.

Storm parameter	Compass sector						
	NNE	NE	ENE	E	ESE	SE	SSE
Sustained wind speed (kts)	52.0	48.6	47.7	45.3	46.7	44.4	49.8
Offshore wave height (ft)	21.2	25.2	26.6	21.6	15.4	15.2	14.1
Offshore wave mean period (sec)	9.9	11.0	11.4	10.0	8.2	8.2	7.9
Still water level (ft, NAVD)	9.5	9.5	9.5	9.5	9.5	9.5	9.5

SWAN Model Development

Development of the Duxbury 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 wave from the WIS hindcast record in Massachusetts Bay, at station 63060. The SWAN model for Duxbury Bay consists of three cartesian grid meshes. They range from a coarse mesh with a 492-foot (150-meter) mesh that covers Cape Cod Bay, a 66-foot (20-meter) mesh intermediate mesh that covers the whole Plymouth Bay estuary, and finally a 2.2-foot (2-meter) fine-scale mesh in the area of the Duxbury Harbor waterfront. The bathymetry and extents of these three grids is shown in Figure 11. 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 only in the particular area of interest. In this case the Duxbury Harbor grid is nested within the Plymouth Bay grid, which in turn is nested within the Cape Cod Bay grid.

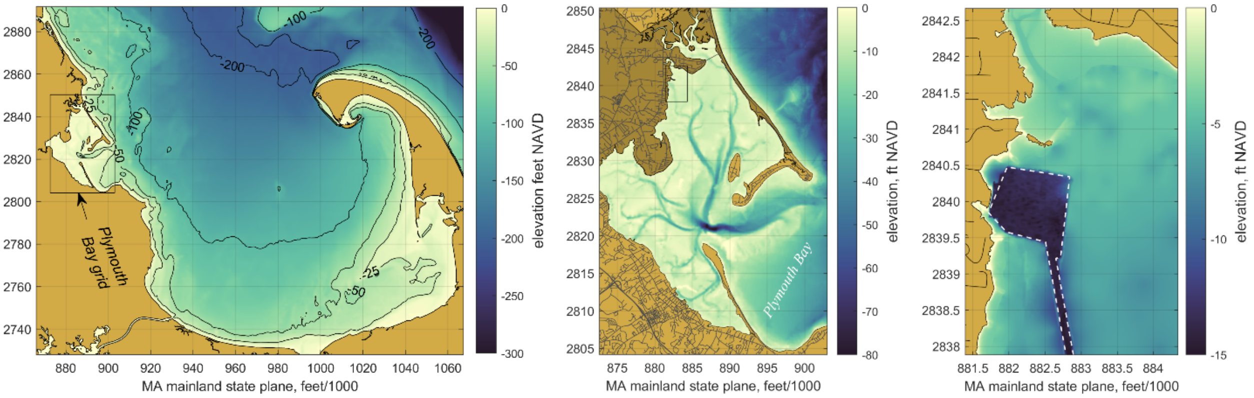

Figure 11. Contour plots of bathymetry used in the wave model coarse 150-meter grid of Cape Cod Bay, the intermediate 20-meter grid of Plymouth Bay, and the fine nested 2-meter grid of the Duxbury Harbor shoreline project area.

Winds blowing from the SSE compass sector generate the largest waves in the Duxbury Harbor anchorage basin. For this wase case, the Hs wave height is 3.7 feet just offshore of the Maritime school property, while the peak wave period is 3.7 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 anchorage basin do increase slightly for these projected future conditions, but by only about 6% even for 2070 water levels.

Shaded contour plots of wave heights in Salem Sound and offshore of Endicott Beach are presented in Figure 12 for 100-year storm conditions with winds blowing from the SSE, and with present mean sea level.

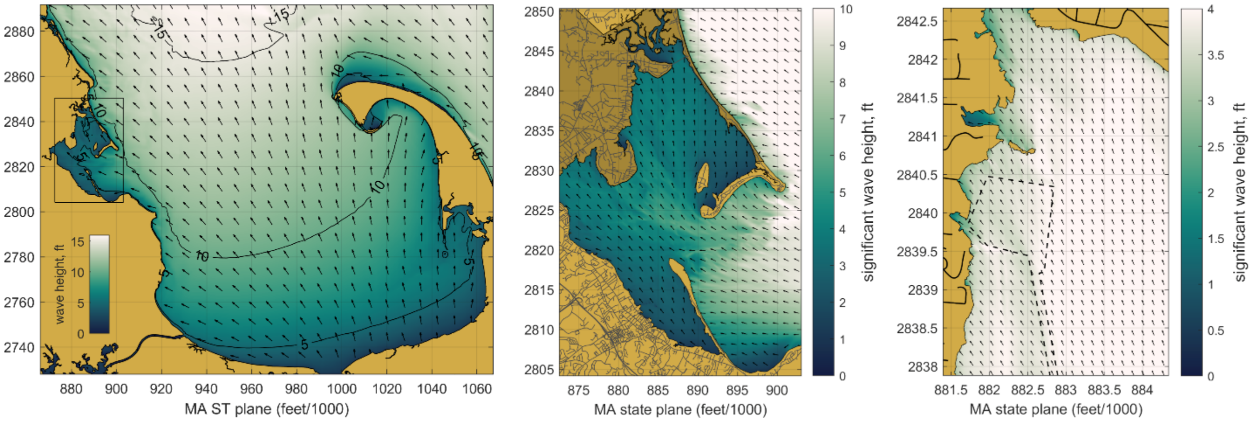

Figure 12. Contour plots of wave height (Hs) and direction (arrows) for the modeled 100-year storm conditions from the SSE, for the Cape Cod Bay grid (left), Plymouth Bay grid (center), and the Duxbury Harbor fine grid (right).

Wave Overtopping and Seawall Height Determination

Output from the SWAN wave model was used to calculate wave reflection, wave overtopping rates, and wave forces for different wall configuration scenarios. For these calculations, the SE model case was used with the 100-year SWEL plus wave setup (9.6 feet NAVD)

Wave overtopping. 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 the maritime school waterfront. The overtopping rate calculations were used to find the minimum wall height that would be required to reduce wave overtopping to a point that would limit damage to pavement in the vicinity of the wall. According to Table VI-5-6 of the USACE Coastal Engineering Manual (2011), overtopping discharges greater than 50 liters/sec per linear meter of wall (0.54 cfs/foot) will cause dame to paved surfaces.

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

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

where R_c is the structure freeboard

H_{mo} is the offshore significant wave height

Using this method, the wall height was iterated in order to achieve an overtopping rate of 50 liters/sec per meter. For present mean sea level conditions, a vertical wall crest would need to be at elevation +11.6 feet NAVD in order to reduce overtopping to 50 liters/sec per meter. This is a 1.7-foot increase over the height of the existing wall. In in order to achieve the same performance for projected 2050 and 2070 mean sea levels, the wall crest would need to be +12.6 and +13.6 feet NAVD respectively. Results of the overtopping analysis are summarized in Table 4.

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

Year	Present	2050	2070
Sea Level Rise from present, feet	0.0	1.0	1.8
Present 1% water level, ft NAVD	9.5	9.5	9.5
Total water level, ft NAVD	9.5	10.5	11.3
DH anchorage wave height, ft	3.5	3.6	3.7
DH anchorage peak wave period, sec	3.7	3.7	3.7
Wall toe elevation, feet NAVD	-13.1	-13.1	-13.1
Wall crest elevation, feet NAVD	11.6	12.6	13.6

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