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MEMORANDUM

Date: **June 30, 2016**

To: **Tom Devine, City of Salem**
Department of Planning & Community Development

From: **Sean W. Kelley, P.E.**

Subject: **City of Salem, MA, Essex County FEMA Flood Map Revisions**

A. INTRODUCTION

This Letter of Map Revision (LOMR) submittal is made to request that revisions to FIRM panels 25009C0417G, 25009C0419G, 25009C0436G, 25009C0438G and 25009C0532G (City of Salem, Massachusetts, Essex County) be made based on a site-specific analysis of waves and water levels. The changes are based on a **1) re-evaluation of wave setup** along the City's shoreline and in Salem Sound, and also on **2) a re-evaluation of 1% water levels offshore of Salem Sound** in Massachusetts Bay. The recent successful appeal of the flood maps for Suffolk County (Boston Harbor and vicinity) resulted in a drop in 1% water levels of 0.6 feet by recomputing extreme water levels based on the multi-decade tide record from the Boston Harbor gauge station. Based on the successful Suffolk County appeal, a re-evaluation of 1% water levels along the Essex County shoreline was made.

All requested changes are within the City of Salem, which is situated along the western shoreline of Salem Sound, an inlet of Massachusetts Bay (Figure 1). The southeastern extent of the Sound is defined by a chain of islands, ledges and shoals. These revisions are based on the site specific re-evaluation of storm waves and water levels at three existing analysis transects (Essex County transects 27, 29 and 30, shown in Figure 2) and one new analysis transect identified as 27B.

An extremal analysis of US Army Corps of Engineers (USACE) Wave Information Study (WIS) offshore wave hindcast data was used together with the FEMA-approved wave model SWAN was used to determine wave conditions within Salem Sound. SWAN is capable of being run in either full 2-dimentional (2D) or 1-dimensional (1D) modes. SWAN was run in 2D mode to propagate waves from offshore into Salem Sound, through the many channels that exist between the islands and ledge areas of the Sound. The same SWAN wave model was run in 1D mode for the four separate cross-shore analysis transects used in this study. The main purpose of the additional 1D analysis was to determine wave setup magnitude at each transect, using a FEMA approved methodology (based on the results of the appeal of the Rockport, MA preliminary flood maps in 2014).

An extreme water level analysis was performed using 1% water levels computed for the Boston Harbor and Portsmouth (Seavey Is.), NH NOAA tide gauges. The re-evaluation of offshore 1% flood levels was done for this analysis in order to incorporate the results of the recent successful appeal of the Suffolk County, MA flood maps, that was based in part in an updated evaluation of the Boston Harbor tide gauge record. Based on this analysis, the 1% still water level offshore of Salem Sound was determined to be 9.4 feet NAVD, which is 0.6 feet lower than the level used in the 2014 Essex County FIS, and equal to the 1% SWEL used in the effective Suffolk County FIS.

Transect 27, at the head of Salem Harbor was used to determine the 1% flood level in the inland area of South Salem based on wave setup levels computed at the entrance of the Forest River using the wave model SWAN.

Analyses for transects 29 (Winter Island) and 30 (Juniper Point) also used the results of the SWAN wave model to determine setup levels at the shoreline, but also included a re-evaluation of run up and overtopping levels, as appropriate.

The new analysis transect 27B (Hemenway Road) was added to determine setup and wave levels in a sheltered area in the sheltered inner reaches of Salem Harbor (Figure 2).

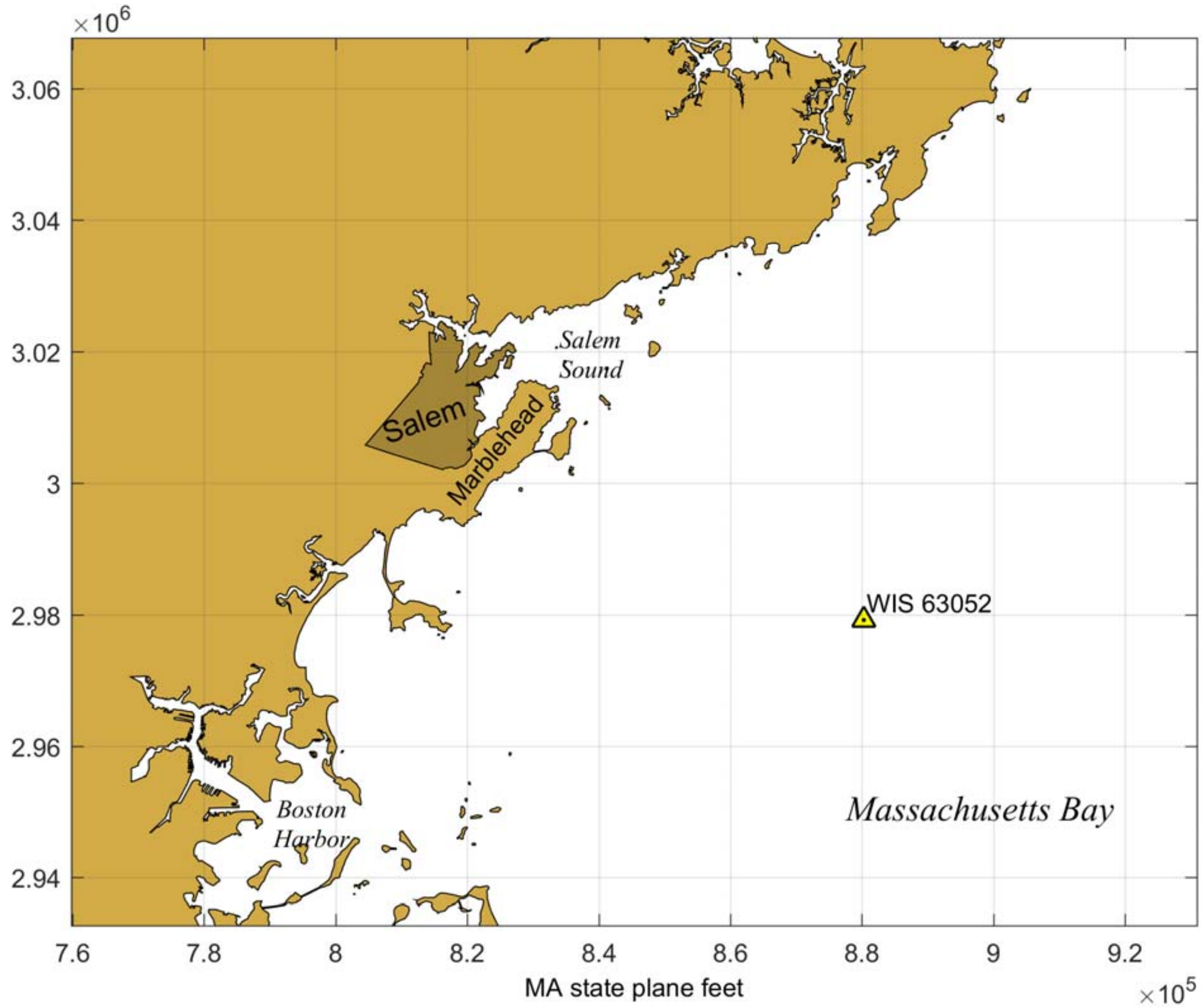

Figure 1. Map of the northern Massachusetts Bay coastline, showing the location of the study area along the shoreline of Salem in Salem Sound. The triangle marker indicates the location of the WIS wave hindcast station used as the source of offshore wave data.

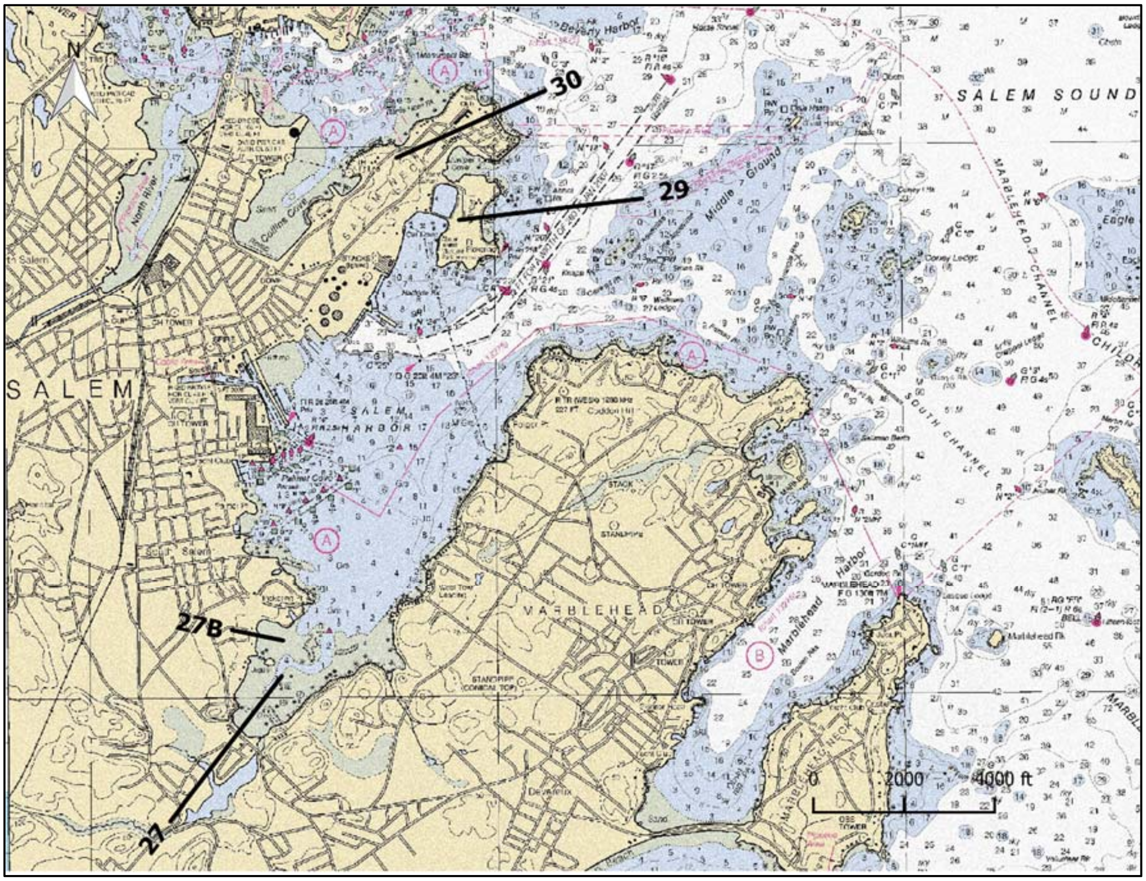

Figure 2. Salem Sound vicinity (NOAA chart 13075) with analysis transects (black lines) used to determine BFEs along the Salem coastline.

B. ELEVATION DATA

Elevation data from four sources were used to specify elevations along the length of the transect: 1) the NOAA GEODAS offshore bathymetry archive, 2) USACE 2010 LiDAR in the nearshore region, 3) the 2013 USGS LiDAR flight for upland topography. All elevation data were combined into a single dataset, referenced to the NAVD vertical datum, and to the Massachusetts State Plane mainland coordinate system.

C. OFFSHORE STILL WATER FLOOD ELEVATION ANALYSIS

The recent successful appeal of flood maps in Suffolk County, MA brough to light issues with the extreme stilwater elevation (SWEL) analysis that was the bases for water levels also used in the 2014 updated Essex County, MA flood maps. The SWEL analysis performed for the Suffolk County appeal (WHG, 2014) demonstrated that the results presented in the 2012 STARR report "Updated Tidal Profiles for the New England Coastline" were an overestimate of the 1% SWEL at Boston Harbor. The appeal analysis computed a 1% SWEL of 9.4 ft NAVD for the Boston tide gauge, which is 0.6 feet lower than the level from the STARR report, and equal to the level in the original Boston FIS. Communications with AECOM indicated that similar issues were encountered with the Rockingham County, NH preliminary FIS (2014), where the SWEL for Portsmouth, NH in the 2012 STARR report was found also to be too high. As a result, the SWEL used in the Rockingham Co., NH preliminary FIS end up being set at the same level used in the historic version of the FIS.

Understanding that corrections have been made to SWELs used in both the effective 2016 Boston and preliminary 2014 Portsmouth flood insurance studies, and understanding that the SWEL determined for the Salem coastline is based on a linear interpolation of the extreme water levels determined for Boston and Portsmouth (as described in the 2012 STARR report), it follows that Essex County SWELs also should be adjusted.

NOAA provides extreme water level analyses of their tide gauge data as part of the NOAA Tides and Currents website (tidesandcurrects.noaa.gov). The results of this analysis are provided in Figures 1 and 2, taken from the NOAA website. Data from these gauges was used to determine extreme water levels in the 2012 STARR report, and the original USACE New England flood profiles, at Boston and Portsmouth, respectively.

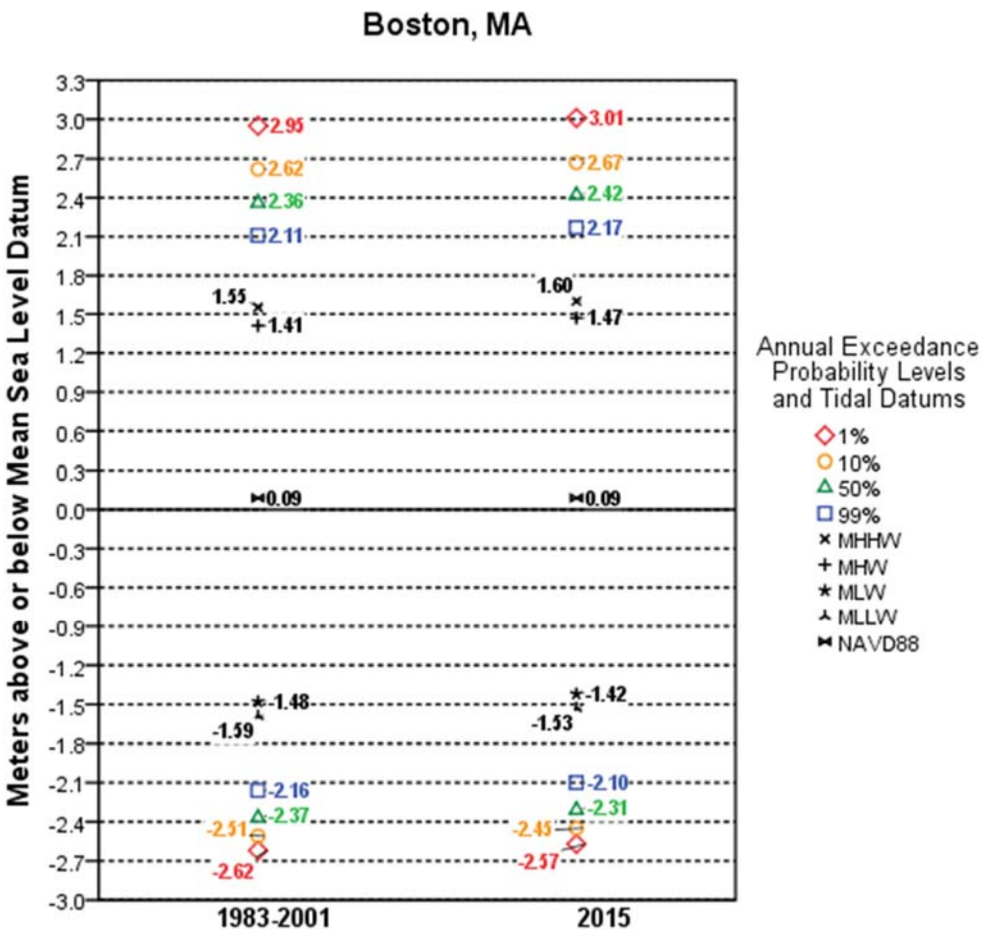

Figure 3. Extreme water level analysis results for the long-term Boston NOAA tide gauge, performed by NOAA (available from http://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8443970) .

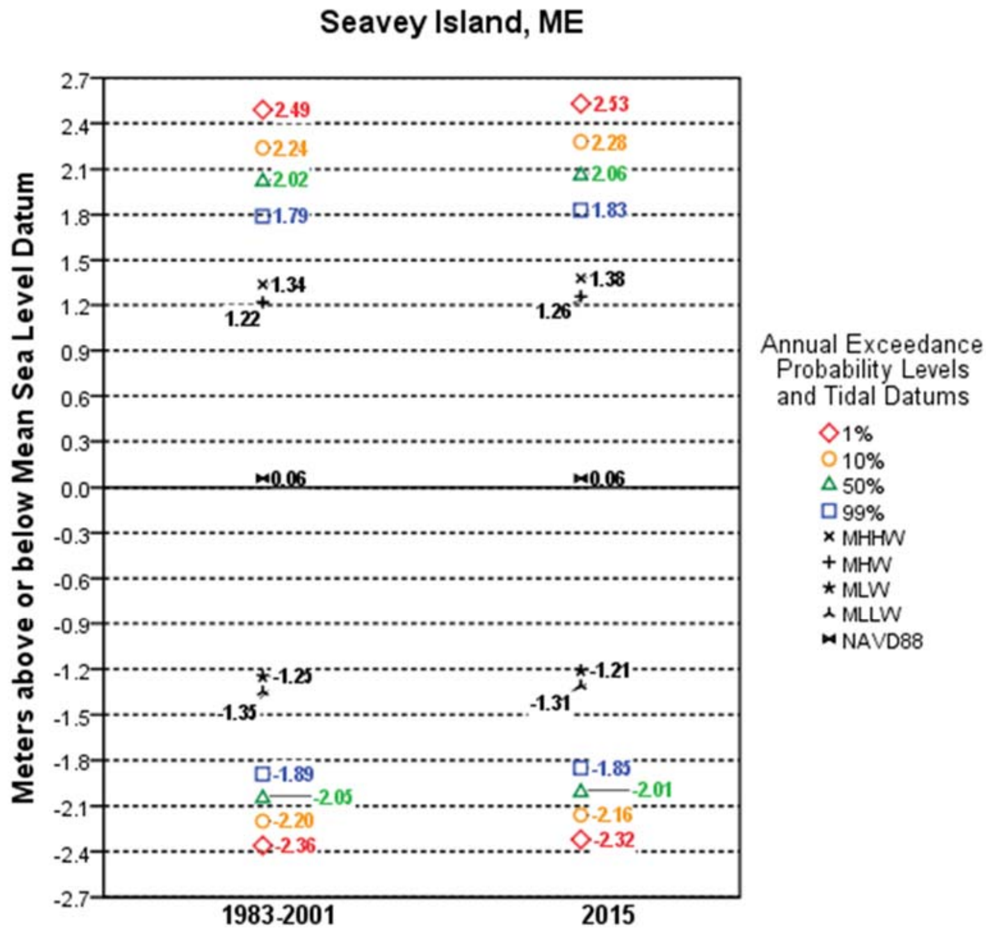

Figure 4. Extreme water level analysis results for the long-term Seavey Is., ME NOAA tide gauge, performed by NOAA (available from http://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8443970) .

The results of these NOAA analyses was used to estimate the 1% SWEL offshore of Salem, since they provide a consistent analysis of the real tide data at both stations, that has been updated for 2015 estimated levels of sea level rise (SLR). Using a linear interpolation of the NOAA extreme water levels, as was done in the 2012 STARR report, gives a 1% SWEL of 9.4 feet NAVD and a 10% SWEL of 8.3 feet at the location of Salem Sound along the northern Massachusetts Bay coastline. Therefore, the 1% SWEL level determined for Salem using the levels determined by NOAA ends up being equal to the 1% level determined for Boston Harbor in the successful Suffolk County appeal.

SWEL values from past and preliminary FISs and the 2012 STARR report presented in Table 1 show that historically SWELs determined for Salem have been between the Boston and Portsmouth levels, with the level at Boston being the higher end of the range. The 9.4 ft NAVD 1% SWEL level determined for Salem using the NOAA analysis results is therefore conservative, since it is equal to the preliminary 1% level set for Boston. The 1% SWEL at Salem was also the same as Boston's in the 2012 STARR report. The linear interpolation used to determine the Salem SWEL is provided on the data CD (interpolate_flood_levels.xls). At the very least, in light of the changes made for both Boston and Portsmouth (Suffolk and Rockingham Counties), the SWEL for Salem should be set to be equal to the Boston SWEL, as was the case in the 2012 STARR report.

Table 1. Comparison of 1% water levels. SWELs in feet, NAVD. Historic FIS levels are the past studies, with indicated effective dates. STARR 2012 was the source for SWELs in the recent remapping effort in FEMA Region 1, "Updated Tidal Profiles for the New England Coastline". Latest effective and preliminary levels are from the 2016 Suffolk Co., MA FIS appeal (Boston), and the 2014 Rockingham Co., NH preliminary FIS. 1% SWEL determined by NOAA for the Boston and Seavey Is., ME gauge records is also provided.

Location	historic FIS (date)	STARR 2012	Effective and Preliminary (date)	NOAA Tides and Currents
Boston, MA	9.4 ft (2009)	10.0 ft	9.4 ft (2016)	9.6 ft
Portsmouth, NH	8.4 ft (2005)	9.5 ft	8.4 ft (2014)	8.1 ft
Salemy, MA	8.8 ft (1985, 2012)	10.0 ft	N/A	N/A

D. EXTEMAL ANALYSIS OF WAVES

Wave conditions used as boundary conditions for the SWAN wave model of Salem Sound and the Salem coastline were developed using the same source of data used in the FIS, namely the USACE WIS hindcast from station 63052. The latest version of the WIS hindcast was used, and includes 33-years of wave data from January 1980 through December 2012. Waves roses that show the percent occurrence of wave height and period from the different compass sectors is presented in Figure 5.

Using a standard method outline in the ACES manual (CERC, 1992), and in the USACE Coastal Engineering Manual (USACE, 2002), the extremal analysis was performed using waves from the complete 33-year WIS record, binned according to wave direction into sixteen separate 22.5 degree sectors. The largest waves in each bin were determined for each separate year in the hindcast. The Fisher–Tippett distribution function was then used to determine the 100-year (1-percent) wave height for each of seven compass sectors between NE and S. An example of the resulting return period wave height from this analysis is presented in Figure 6, for the SE sector.

Corresponding peak wave periods were then determined for each wave by interpolating values provided in Table D.2.8-2 of the Guidelines and Specifications for Flood Hazard Mapping Partners (FEMA, 2007). The final results of the extremal analysis are presented in Table 2.

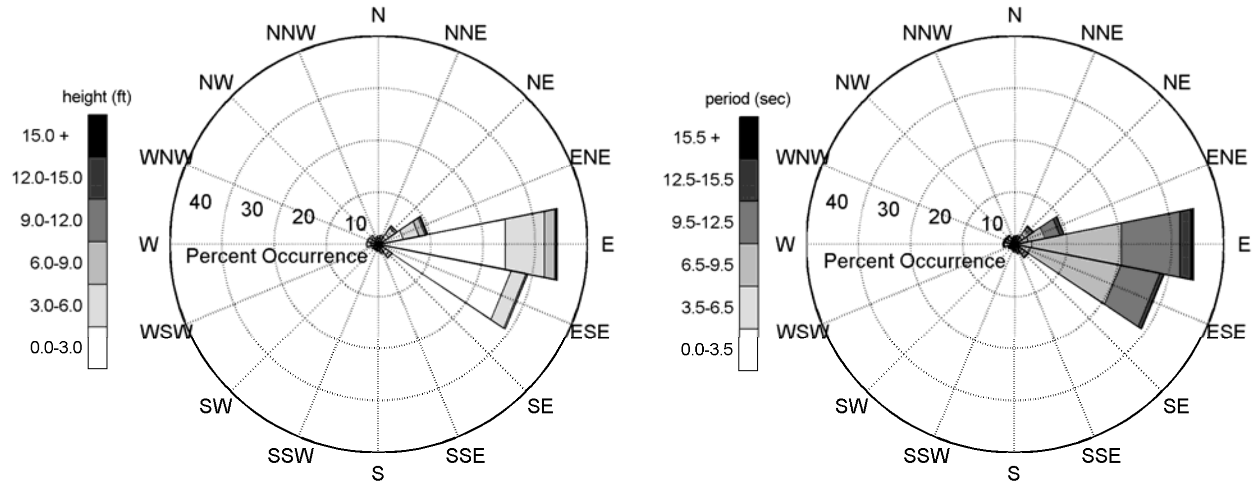

Figure 5. Wave height and period for hindcast data from WIS station 63052 (SE of Salem Sound) for the 33-year period between January 1980 and December 2012. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction.

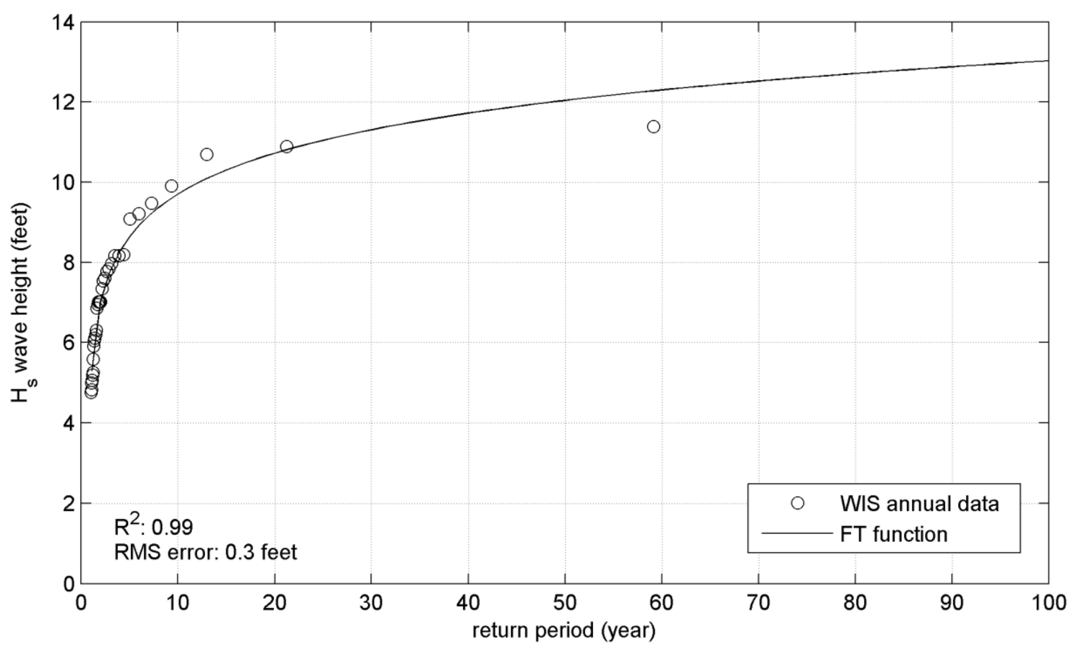

Figure 6. Return period vs. significant wave height (black line) for the SE compass sector, and annual largest wave heights from WIS hindcast station 63052 (black circles). R^2 correlation between data and FT distribution function is 0.99 with standard error of 0.3 feet.

Table 2. Results of extremal analysis of 33-year WIS hindcast data for station 63052, offshore Salem Sound.

Compass Sector	H_s Wave Height (feet)	T Mean Period (sec)
NNE	12.8	8.2
NE	19.0	10.2
ENE	25.6	12.3
E	25.2	12.1
ESE	15.4	9.0
SE	13.0	8.3
SSE	9.6	7.2
S	8.1	6.7

E. 2D WAVE MODEL DEVELOPMENT AND RESULTS

A wave model grid was developed to run the seven extreme wave cases listed in Table 1. The 2D model was used to propagate waves into Salem Sound from offshore, through in the many inlets and channels that exist between islands and ledges along the seaward boundary of the Sound. Model output was used to develop boundary conditions for the separate 1D cross-shore SWAN transects that correspond to each separate analysis transect. Sources of bathymetry interpolated to the SWAN grid are the NOAA GEODAS archive and recent USACE 2010 LiDAR in the nearshore region. Topography data from the 2013 LiDAR flight of the USGS were also used in the specification of elevations in the model grid. Elevations range between 46.6 and -174.2 feet NAVD. Grid cells in the model domain that have elevations higher than the water level (including setup) are automatically removed from the simulation in the course of each model run. The final regular Cartesian grid (Figure 7) is has 448,950 cells with a 20 meter spacing. The eastern boundary is 6.6 nautical miles (NM) long, while the northern boundary is 7.9 NM long.

Each model run was parametrized by specifying the wave conditions listed in Table 1 along the complete length of the ocean boundary of the grid. Since the grid elevations are specified in feet NAVD, a storm surge still water elevation (SWEL) of 9.4 feet was specified for each model run. This SWEL for Salem Sound is taken from the extreme water level analysis presented in Section C. Finally, a wind speed of 80 mph was included in the simulations, using a direction that is the same as the wave direction of each case. 2D model wave height output at the seaward end of each analysis transect is presented in Table 3.

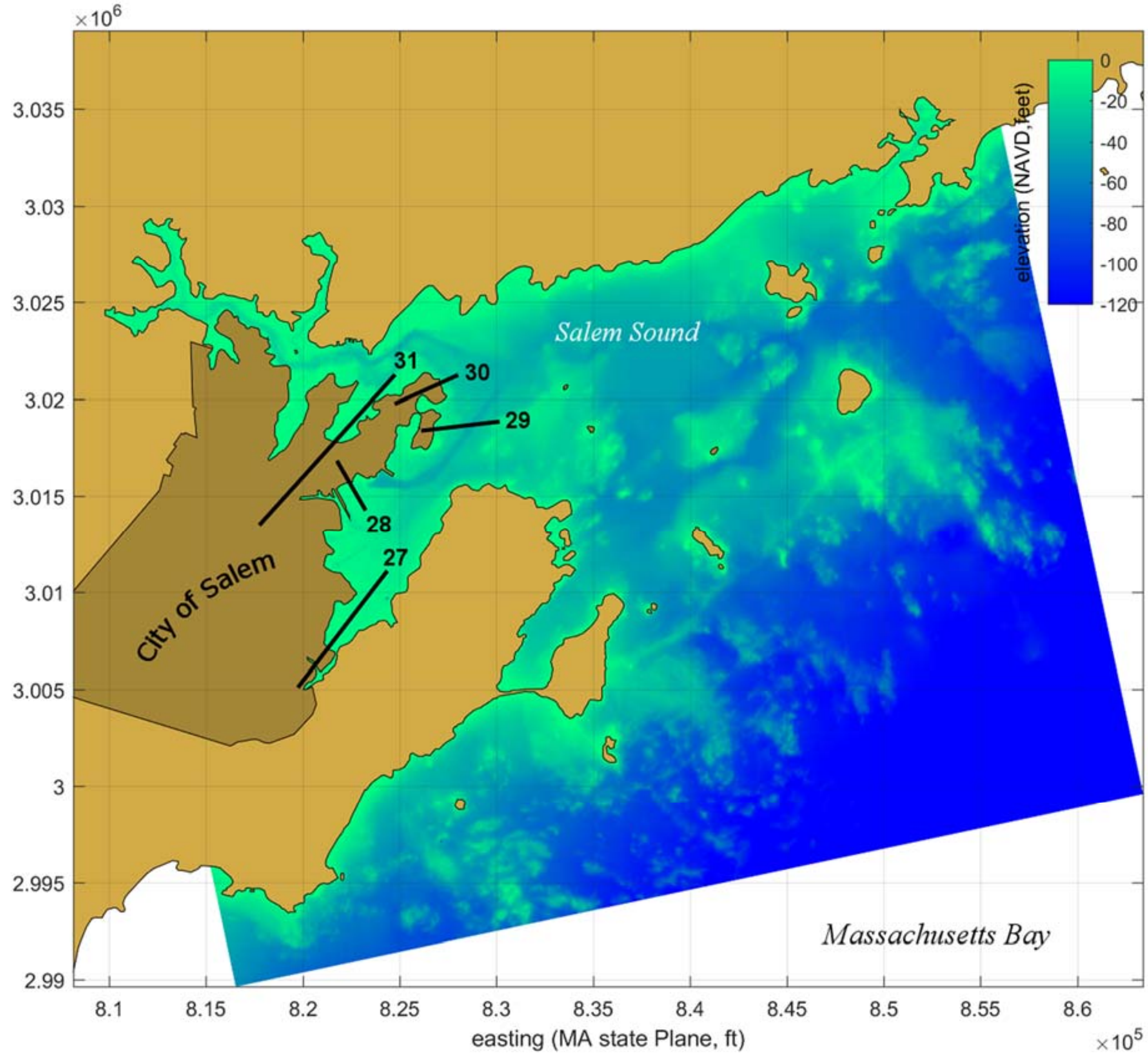

Figure 7. Extent of 2D SWAN wave model grid used to determine wave conditions in Salem Sound. Existing Essex County FIS analysis transects (27 through 31) in Salem are shown.

Table 3. 2D wave model output H_s wave height (feet) at offshore end of cross-shore analysis transects (Figure 2).

Compass Sector	Transect 27	Transect 27B	Transect 29	Transect 30
NNE	2.6	2.0	5.6	4.6
NE	2.3	2.0	6.9	5.9
ENE	2.3	2.0	8.2	7.2
E	2.0	2.3	8.5	7.9
ESE	1.0	1.6	7.9	7.2
SE	0.3	0.7	6.9	6.6

F. 1D WAVE MODEL DEVELOPMENT AT SHORELINE TRANSECTS

Individual cross-shore SWAN models (1D transects) at each analysis transect were run using the wave data output from the 2D simulation. The 1D simulations were used to compute wave setup at the shoreline for each transect. Setup is an increase in water level against a coastline that results from wave breaking in the surf zone. In the 1D mode, the setup formulation is exact, and is therefore computes the true magnitude of setup. The use of the 1D mode of the SWAN wave model to compute wave setup has been made in the successful appeal of the Rockport, MA preliminary flood maps (2014) and a recent LOMR in Barnstable, MA (Case No. 15-01-0831P)

The cross-shore elevation profile of each transect was developed using the same data set used to parameterize the 2D model grid. Each model grid has a 3.3-foot (1.0 meter) grid spacing. This very fine grid resolution ensures that the grid resolution does not influence the computed wave parameters (Sasaki and Iizuka, 2007). The elevation profiles of each transect is presented in Figures 8 through 11.

A wind speed of 80 mph was applied in the simulation, similar to the 2D SWAN runs. The wave and wind direction was set to correspond to the orientation of the model transect to maximize the computed wave setup, which is the most conservative assumption.

Wave setup generated in Salem Sound due to wave breaking across the island and ledge boundary of the sound was also included as an input for each transect simulation. Table 4 presents the boundary condition still water levels specified at the offshore end of each analysis transect. This water level is the sum of the offshore (Massachusetts Bay) 1% still water level and the magnitude of setup determined by the 2D wave model of the Sound, for each separate wave case at a point corresponding to the offshore start of the 1D transect.

The resulting maximum water levels at the shoreline for each transect and each separate wave case are presented in Table 5. The smallest total water level values are computed for the transect at the southwestern reach of Salem Harbor, at the inlet to the Forest River (**Transect 27**), where total 2D plus 1D wave setup varies between 0.2 and 0.6 feet for all modeled sectors. The largest values occur at Winter Island Park (**Transect 29**) where total wave setup level values range between 0.9 and 1.5 feet.

Table 4. Still water level (feet, NAVD) at offshore end of cross-shore analysis transects (Figure 2). This level is the sum of the 1% SWEL offshore in Massachusetts Bay, and the local setup generated in Salem Sound by waves breaking across its island and ledge perimeter.

Compass Sector	Transect 27	Transect 27B	Transect 29	Transect 30
NE	9.5	9.5	9.5	9.5
ENE	9.8	9.8	9.7	9.8
E	10.0	10.0	9.9	9.9
ESE	9.6	9.6	9.6	9.6
SE	9.6	9.6	9.5	9.5

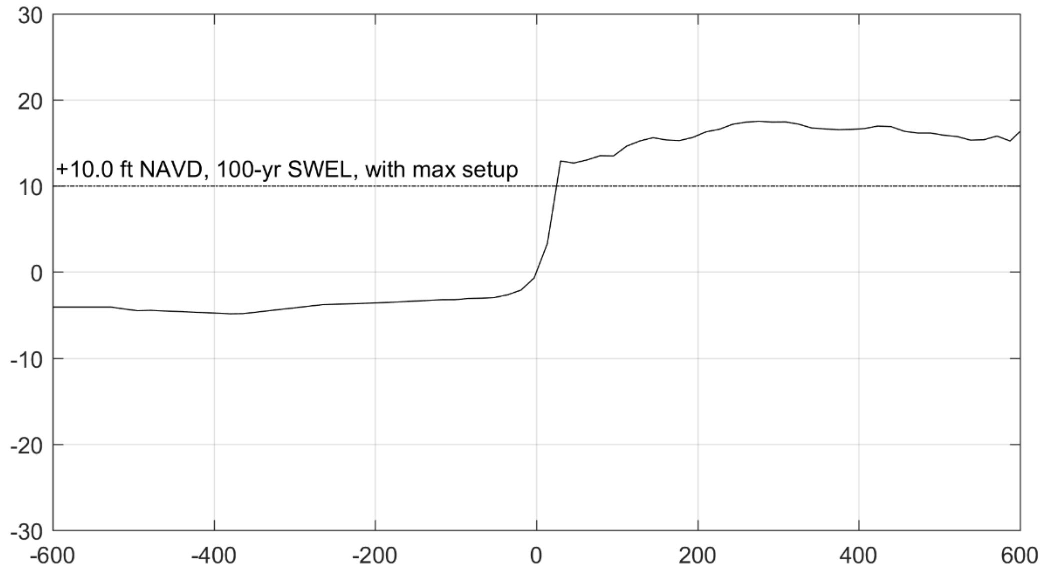

Figure 8. Cross-shore profile of Transect 27 at Lafayette Street.

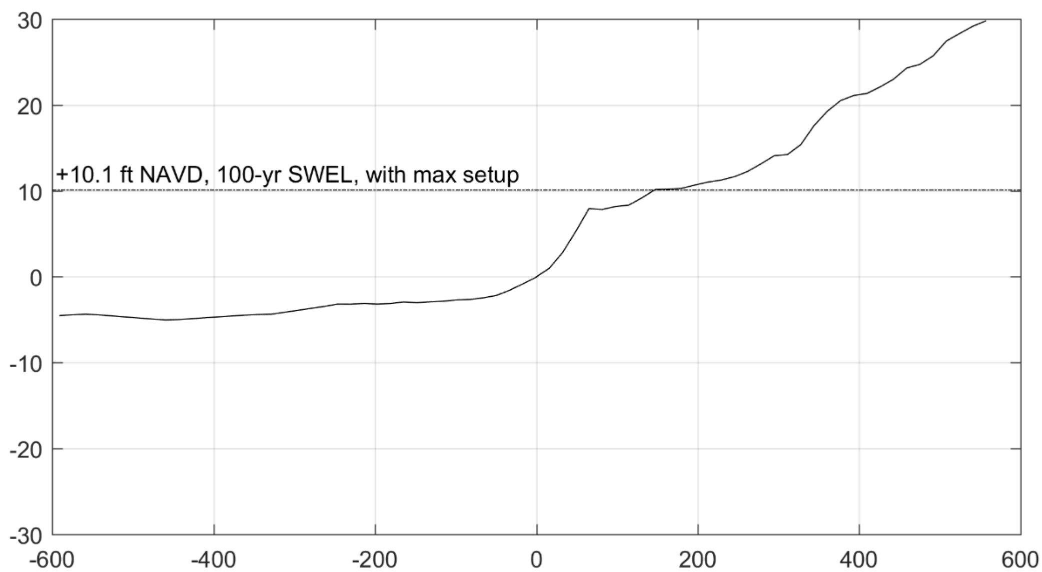

Figure 9. Cross-shore profile of Transect 27B at Hemenway Road.

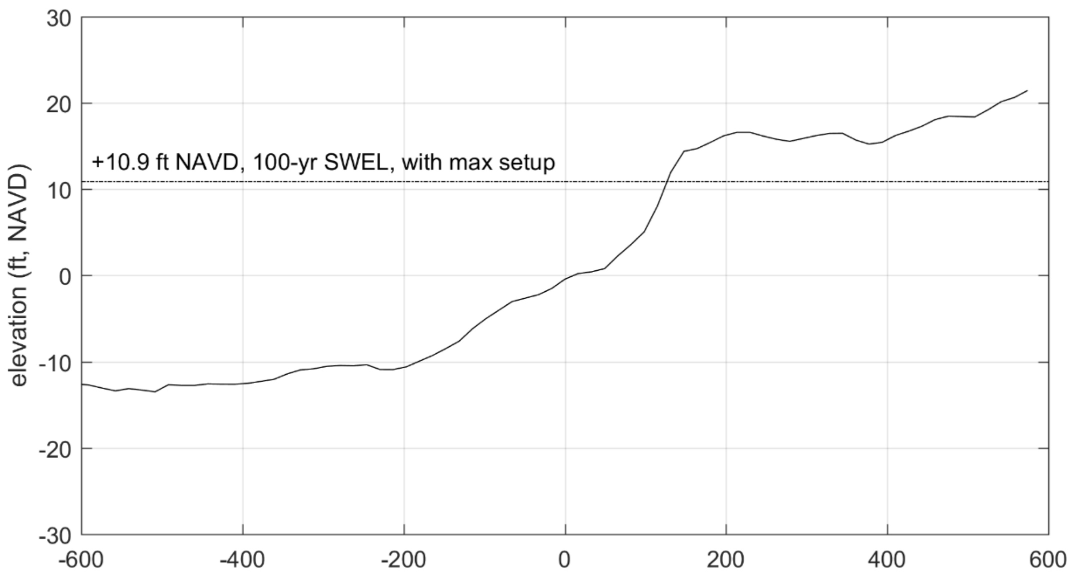

Figure 10. Cross-shore profile of Transect 29 at Winter Island Park.

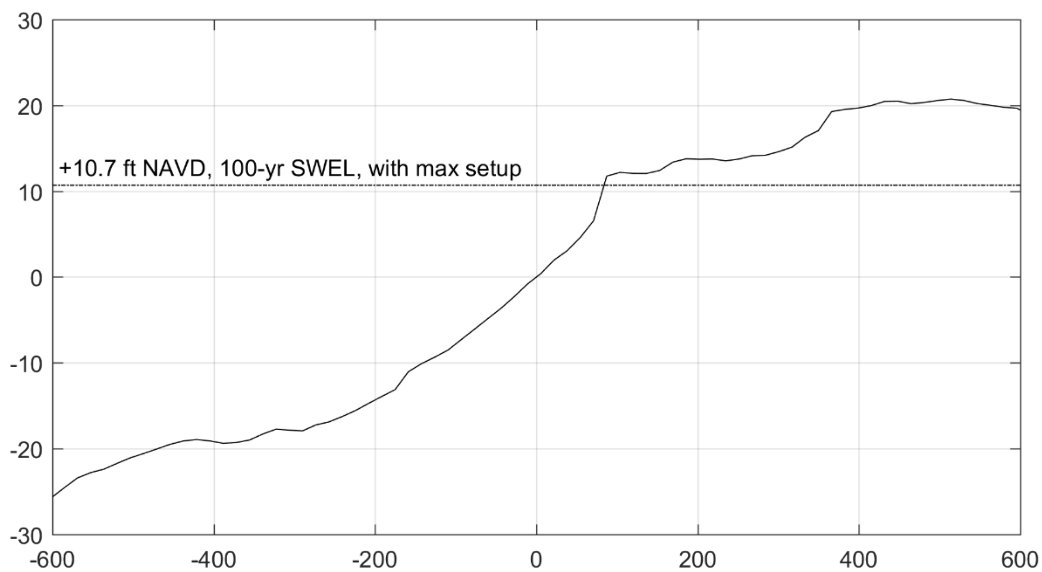

Figure 11. Cross-shore profile of Transect 30 at Juniper Point.

Table 5. Maximum total water level (in feet, NAVD) at the shoreline of each analysis transect (Figure 2), determined as the combination of offshore 1% SWEL (for Massachusetts Bay), local 2D in Salem Sound and maximum 1D SWAN model setup at each transect.

Compass Sector	Transect 27	Transect 27B	Transect 29	Transect 30
NE	9.6	9.6	10.3	9.8
ENE	9.8	9.9	10.7	10.5
E	10.0	10.1	10.9	10.7
ESE	9.7	9.7	10.5	10.4
SE	9.6	9.6	10.5	10.3

G. BASE FLOOD ELEVATION DETERMINATION

With the completion of the wave analysis to determine 100-year wave conditions, including wave setup at each transect, it is necessary to compute base flood elevations (BFEs) used to delineate the flood zones of the proposed map revisions. At Transects 27B, 29 and 30, computations of WHAFIS wave envelopes, 2% wave run up elevation and overtopping volume discharge rate (when appropriate) where made for existing grades and failed wall profiles. The results of the SWAN modeling at Transect 27 were used to determine the maximum SWEL at the entrance to the Forest River, and therefore the flood level in South Salem.

G.1. Transect 27 – Forest River

The maximum water level that is computed for Transect 27 at the inlet of the Forest River is 10.0 feet, NAVD. This is the sum of the SWEL offshore of Salem Sound (9.4 feet NAVD determined from the 1% water level analysis of Section C) and the sum of wave setup generated in the 2D Salem Sound and 1D SWAN transect models (0.6 feet total setup). The total 1% water level at the inlet to the Forest River is therefore 10.0 feet NAVD. Based on this result, the AE zone in South Salem was re-delineated along the 10 ft NAVD contour. This re-delineation results in a lowering of the BFE in South Salem from 11 feet to 10 feet, and a reduction in the area inundated during the 1% flood event.

G.2. Transect 27B – Hemenway Road

The new analysis transect at Hemenway Road was used to delineate flood zones in this sheltered area located in the upper reaches of Salem Harbor. The 1% SWEL determined for this transect is 10.1 feet NAVD, based on the offshore 1% flood level and the combined 2D and 1D wave model setup. Wave run up was computed using RUNUP 2.0. WHAFIS output determined the flood zone in the Harbor is an AE zone with an elevation of 12 feet. The 2% run up elevation on the upland slope is 11 feet NAVD. Therefore, the area is mapped with a 12 ft AE zone in the Harbor that transitions into a 11 foot AE zone with a landward limit along the 11 foot NAVD contour. The re-delineation results In a lowering of the maximum BFE in the Harbor from 16 feet to 12 feet, and a change in the designation of the area from Zone VE to Zone AE.

G.3 Transect 29 – Winter Island Park

The maximum SWEL at the existing Winter Island Park transect (Transect 29) is determined to be 10.9 feet based on the combined 2D and 1D setup computed by SWAN. This transect is across a natural rocky headland. Using the updated water levels, RUNUP 2.0 was run to determine the wave run up elevation. The final 2% run up elevation was adjusted using the Low Coastal Bluff Assumption, found in the FEMA Guidelines and Specifications (2007) in Section 2.8.1.7. Overtopping rates computed for this transect indicate that an AO zone with a depth of 2 feet would be specified. The method of Cox and Machemehl (FEMA, 2007, Section 2.8.1.7 and Allen, *et al*., 2012, Section 6.4.2) is used to show that the flow would quickly transition to the water elevation determined using the Low Bluff Assumption analysis (i.e, within 2 feet landward of the slope crest)). Therefore, landward of the slope crest, the area is mapped as Zone AE, elevation 16 feet NAVD.

The final BFEs determined for this transect are 17 ft NAVD offshore the slope face, based on WHAFIS results, and Zone AE elevation 16 ft landward of the slope crest. This is a reduction in the BFEs of the effective map, where a VE zone with a 21 ft elevation is mapped offshore of the slope crest, a 19 ft VE zone is in place landward of the crest, followed by an AE zone with an elevation of 19 feet NAVD. Areas currently mapped as Zone AE with an elevation of 14 feet in the vicinity of this transect would have the BFE lowered to 11 feet. This is due to the reduction in the total SWEL and setup magnitude determined in this analysis, compared to the effective FIS.

G.4. Transect 30 – Juniper Point

At the existing FEMA transect 30, the maximum SWEL is determined to be 10.7 feet NAVD, using the results of the computations of setup output from the 2D Salem Sound and 1D transect models. This transect has a vertical masonry wall with a cap elevation of 11.4 feet NAVD, which is characteristic of the area of Juniper Point facing Salem Sound. The shoreline is rocky with sand in the upper elevations of the profile near the wall.

Run up calculations were made for both the intact wall and failed structure profile, according to the method outlines in the FEMA guidelines and Specifications (2007, Section D.2.10.3.2). The run up on the intact wall reaches an elevation of 24 feet NAVD. The run up on the failed wall profile is determined to be 14.5 feet NAVD, based on RUNUP 2.0 results modified based on FEMA (2007), Figure D.2.8-9. The overtopping rate of the failed wall is in excess of 1.0 ft^3/sec/ft, and therefore a VE splash zone that is 30 feet wide is specified, based on the guidance of FEMA (2007), Table D.2.8-6. The method of Cox and Machemehl (FEMA, 2007, Section 2.8.1.7 and Allen, *et al*., 2012, Section 6.4.2) is used to show that the flow depth over land would quickly reduce to less than one foot, well within 10 feet landward of the crest of the wall, so no further AO is needed landward of the VE splash zone.

The proposed changes would increase the BFE in the area offshore of the wall to 24 feet from 21 feet. Landward of the crest of the wall's failed profile, the BFE would decrease to 15 feet NAVD from the existing 21 feet. Similar to Transect 29, areas currently mapped as Zone AE with an elevation of 14 feet in the vicinity of this transect would have the BFE lowered to 11 feet. Again, this is due to the reduction in the total SWEL and setup magnitude determined in this analysis, compared to the effective FIS.

G. PROPOSED BFE DELINEATIONS

Based on the results of the analyses at the four different transects, flood zone delineations were redrawn for the affected areas the City. Both the effective delineations and the proposed changes are presented in the five map panels accompanying this memo.

H. REFERENCES

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