MEMORANDUM

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Task 1.0 - Develop Design Flood Elevations

Asset specific Design Flood Elevations (DFEs) were developed to provide target elevations for both protection of critical assets and to provide criteria for future planning of the Steamship Authority Woods Hole Ferry Terminal Reconstruction project. The DFEs were developed to protect specific assets against future storms and sea level rise under a changing climate. The DFEs provide a recommended elevation to be applied in the design of important assets. A specific target DFE has been developed for important infrastructure components of the project. This includes the terminal building, the equipment storage building, the outdoor electrical equipment, and fixed portions of the north and south piers.

Typically, a DFE represents the highest flood elevation under current day conditions, and is generally prepared for the 100-yr return period storm level, or base flood elevation, plus freeboard. For this project, the DFEs represent an elevation that flood water is expected to reach over the service life of the asset, while also including the acceptable risk tolerance for that asset type. For example, the terminal building should be designed to remain dry under all reasonable storm conditions over the service life of the structure. As such, a DFE for the terminal building has been developed to protect the facility during a 100-yr return period flood over the 50-year service life of the facility. The fixed pier sections however, can be designed to get wet under storm conditions, but need to remain dry during all normal and elevated tidal conditions such that day to day operations are not interrupted. Therefore, DFEs for the fixed piers have been developed to ensure that the piers remain above annual high water and small to moderate storm events (i.e., less than 10-yr events) for all projected sea level rise scenarios over the 50-year service life of the project. This will allow operations at the fixed piers to continue without interruptions through the desired design life, except during extreme storm events when operations would be suspended.

Since the recommended DFEs incorporate the effects of sea level rise and changing climate conditions, they exceed the design flood elevations required by code and current best practices. As such, these DFEs will meet any active building code or design guidance. The DFEs for the Ferry Terminal assets were established by evaluating previous work conducted by Woods Hole Group for the area, including the Evaluation of Federal Emergency Management Agency Flood Insurance Study for the Woods Hole Oceanographic Institution (WHOI)

Facilities in Woods Hole, MA (Woods Hole Group, 2016), development of design parameters for the WHOI Iselin Dock, and results from the Massachusetts Coast Flood Risk Model (MC-FRM) (Bosma et al., in production). Woods Hole Group has conducted an extensive coastal processes analysis for the Massachusetts coastline including modeling flooding and inundation under future climate conditions. These results are being applied as a standard across the Commonwealth and results presented herein are based on the Massachusetts Coast Flood Risk Model developed by Woods Hole Group.

Sea level rise projections utilized in MC-FRM were based on the Representative Concentration Pathways (RCP) greenhouse gas concentration trajectories developed as part of the Intergovernmental Panel on Climate Change (IPCC). These pathways describe a wide range of possible scenarios that may occur due to future anthropogenic greenhouse gas emissions. The RCP pathway utilized in this assessment (RCP 8.5) assumes that no changes are made to human based emissions. For Woods Hole, this scenario assumes a sea level rise of 4.3 ft over the next 50-years. The sea level rise scenario was developed specifically for the Commonwealth of Massachusetts (DeConto and Kopp, 2017) and is consistent with the projections being implemented for the statewide hazard mitigation assessments and by MassDOT in the development of the Massachusetts Coast Flood Risk Model (MC-FRM). Therefore, the Steamship Authority can be confident that the DFE development aligns with the recommended projection values used for the coastlines in Massachusetts. Projections were developed for the Commonwealth of Massachusetts and take into account regional considerations for the Northeast.

DFEs were developed for each asset using results from MC-FRM based on the risk tolerance estimated for the asset and the designed 50-year service life. Standards published in the American Society of Civil Engineers (ASCE) Flood Resistant Design and Construction Manual 24-14 were also incorporated. For Class 3 structures located in FEMA Coastal AE flood zones (see discussion in Task 3.0 for FEMA flood zones now and with future sea level rise), these standards call for 2 feet of freeboard to be added to the DFE, or the 500-year flood elevation whichever is higher, so that buildings and structures are better able to resist flood loads and flood damages. These standards define the minimum elevation of the lowest floor, the minimum elevation of utilities and equipment, and the minimum elevation of dry floodproofing for non-residential structures. The recommended asset specific DFEs developed using the MC-FRM results for a 100-year flood event, over the 50-year service life of the project, coupled with the ASCE 24-14 standards are presented in Table 1.

Table 1: Design Flood Elevations for Critical Infrastructure Planned for the Woods Hole Ferry Terminal Reconstruction Project.

Asset	Service Life	Level of Protection	Recommended Design Flood Elevation (ft, NAVD88)
Terminal Building	~50 years	No flooding up to 100-year return period level	17
Equipment Storage Building	~50 years	No flooding up to 50-year return period level	15.3
Electrical Equipment (located at the southwest corner of the employee parking lot)	~50 years	No flooding up to 200-year return period level	16.6
North Fixed Pier	~50 years	Flooding allowed during moderate or greater events (>=10-yr) on fixed pier	14.5
South Fixed Pier	~50 years	Flooding allowed during moderate or greater events (>=10-yr) on fixed pier	14.5

As described in supplemental information filed with the Massachusetts Environmental Protection Act (MEPA) Environmental Notification Form (ENF) for the proposed Ferry Terminal project, a number of design considerations have been incorporated to address resiliency to sea level rise, both in the short-term and long-term. Specifically, the apron along the bulkhead will be raised to an elevation of 9.0 ft NAVD88 and the first floor of the ferry terminal building will be raised to an elevation of 13.0 ft NAVD88. Flood protection for the ferry terminal building up to elevation 17 ft NAVD88 will also be provided through the design of dry and/or wet floodproofing techniques. Dry floodproofing is planned around three sides of the ferry terminal building and deployable floodproofing along the fourth side. The platforms of the fixed piers will range in elevation from 12.8 to 13.9 ft NAVD88, with the possibility of "adding height" in the future by installing ramps and/or platforms on the pier deck to accommodate increases in sea level. Designs for the electrical equipment are not yet complete, but are planned to be installed in an area with existing elevations of 15.5 to 16.5 ft NAVD88.

Comparisons between the recommended DFEs and the proposed elevations for the key assets indicates that the target elevations have largely been met:

- Terminal building – Assuming that 4 ft of dry floodproofing and deployable floodproofing are incorporated into the building design, the recommended DFE of 17 ft NAVD88 will be met. The floodproofing design components are critical to ensure resiliency and continued operation of the building over the 50-yr design life. It is recommended that an Operations and Maintenance plan be developed and implemented for the floodproofing to ensure smooth and effective operation when it is needed. Woods Hole Group can provide assistance with selection of floodproofing methods and development of the Operations and Maintenance plan, if desired.

- Equipment Storage and Electrical Equipment – Based on existing elevations in the areas where the equipment storage and electrical equipment are to be installed, the recommended DFEs of 15.3 and 16.6 ft NAVD88 can be met through on site designs that include an elevated concrete pad.

- Fixed Piers – The fixed portions of the piers do not currently meet the recommended DFE of 14.5 ft NAVD88; however, they have been designed in anticipation of "adding height" in the future by installing ramps and/or platforms on the pier deck to accommodate increases in sea level. This should ensure functionality during low to moderate storms (i.e., 10-yr event) over the design life of the piers. The more seaward floating platforms will be connected to the fixed piers via a 70-ft long hinged gangway capable of accommodating a rise in sea level of 2.0 ft. Assuming a sea level rise of 4.3 ft over the next 50-years, the floating pier platforms should provide accessibility during low to moderate storms over the design life of the project.

  Of greater concern, however, is inundation of the area between the bulkhead and the ferry terminal, making access to/from the elevated fixed piers impossible. As proposed, raising the bulkhead to elevation 9.0 ft NAVD88 will provide increased flood protection over existing conditions, however; as shown in Task 2.0, the bulkhead can be expected to be overtopped with increasing frequency over the lifetime of the project. For example, in 2050 there will be a 5% chance that storm water levels will overtop the bulkhead. As such, recommendations for increased flood protection along the bulkhead will be provided in Task 2.0. Given the potential for future flooding in the area between the bulkhead and the ferry terminal, and the likelihood that SSA operations will be shut down during moderate storm events, the proposed elevations of the fixed portions of the piers are adequate.

Task 2.0 - Flood Pathway Assessment and Conceptual Nature Based Adaptation

To develop potential resiliency adaptation options for the Steamship Authority Ferry Terminal site in Woods Hole, a detailed analysis of potential flood pathways for present day conditions, as well as future conditions, was conducted. Figure 1 shows the proposed structures that were included in the flood pathway analysis. The analysis utilized the detailed, probabilistic, hydrodynamic flood results from the MC-FRM described in Task 1.0 to identify the flooding dynamics that are expected to occur under present day and future climate conditions. Specifically, the MC-FRM results were used to determine the progression of flooding that will occur at the Woods Hole Ferry Terminal property during increasing levels of return period storm events. This flood pathway analysis was conducted for present day climate conditions, as well as climate conditions expected in 2030, 2050 and 2070 (Figures 2-5). The flood pathway analysis identified, spatially, sources of flooding waters which could have impacts on proposed structures within the Woods Hole Ferry Terminal footprint.

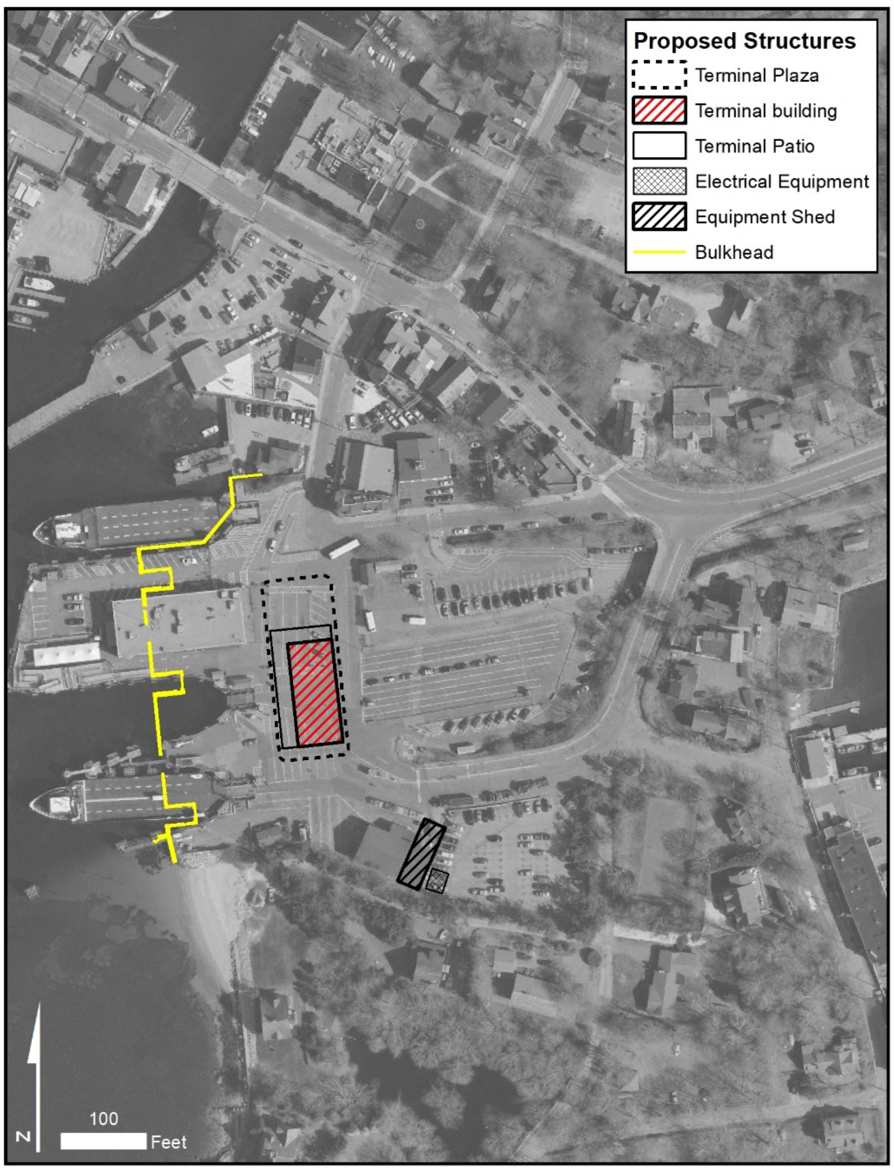

Figure 1. Study area with the proposed structures considered in the flood pathway analysis.

Figures 2-5 present the flood pathway results for present day and future climate conditions. The panels show the progression of flooding (sequentially from panel 1 to 6) during increasing storm levels and water flow expected to enter the Woods Hole Ferry Terminal property. The blue colors represent the areas expected to be flooded with coastal storm-based flood waters, the black solid arrows indicate entry points for direct sheet flow of water and the black dashed areas indicate flooding of structures that are overtopped during a particular return period.

The flood pathway analysis identified two major flood pathways which will have significant impact on the Woods Hole Ferry Terminal in present day and also in future climate conditions. The first major flood pathway was identified just north of Little Harbor and shows water entering the Woods Hole Ferry Terminal via the Shining Sea Bikeway/SSA parking lot. The second major flood pathway was identified as sheet flow between the Steamship Authority and Naushon Trust properties, and overtopping of the northern portion of the proposed bulkhead. Sheet flow from this entry point will also enter the Woods Hole Ferry Terminal via Luscombe Ave. In present day, as seen in Figure 2, these two pathways do not produce significant flooding of the Woods Hole Ferry Terminal until a 20-50-year return period storm. However, in future conditions significant flooding from these two-flood pathways occur with smaller return period storms (5-10 year) as seen in Figures 3-5.

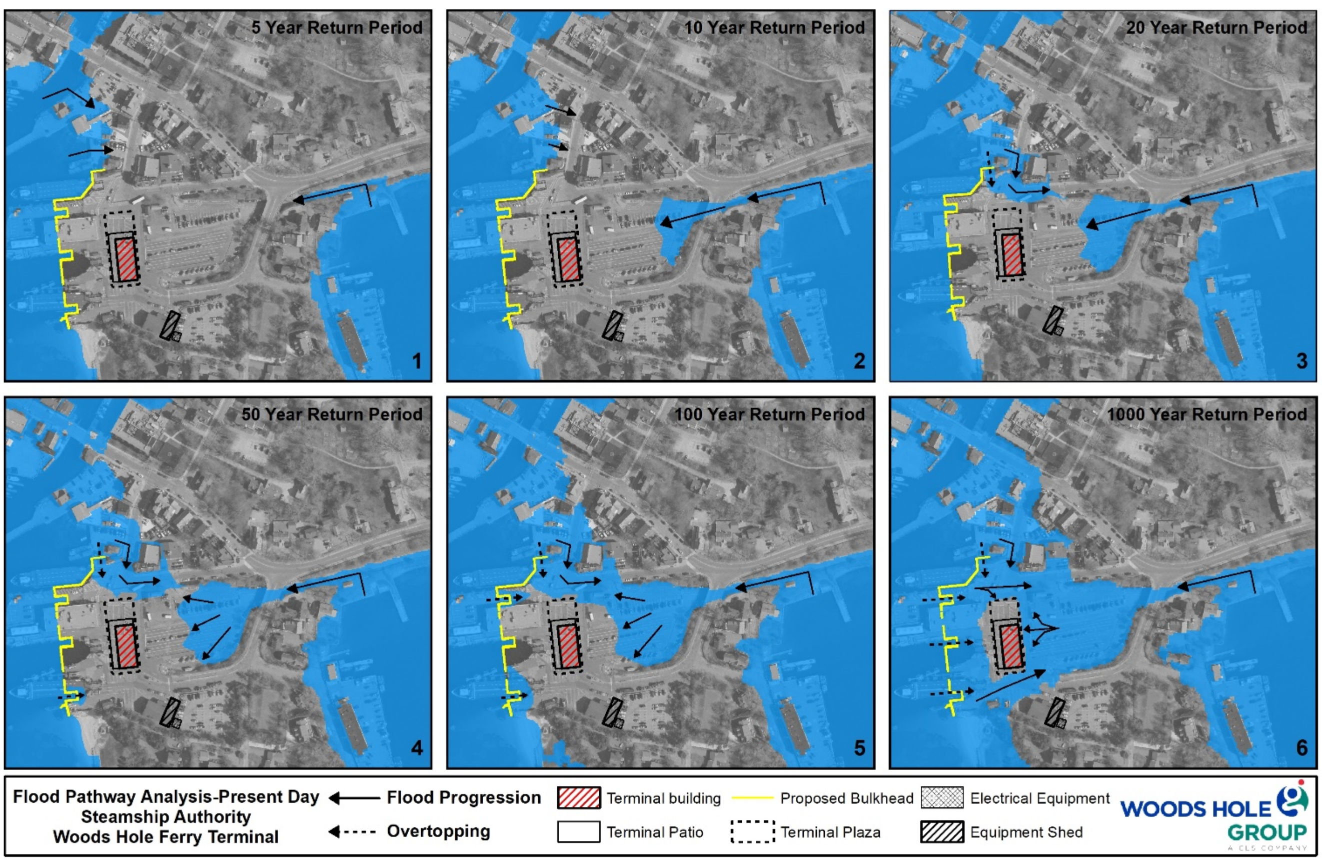

Figure 2. Flood pathways under present day water levels for storms with various return intervals.

As storms increase in intensity and climate changes in the future, a third potential flood pathway develops. This pathway shows flooding via overtopping of the southern portion of the Steamship Authority bulkhead, and sheet flow from south of the Woods Hole Ferry Terminal property. This potential pathway has implications for entering the Woods Hole Ferry Terminal property via Crane St and Cowdry Road. In Present Day (Figure 2), this entrance would be a pathway during a 1000-year return period storm. However, in future conditions, it will take smaller storms to overtop the same obstruction. As seen in Figures 3-5, access to the main Woods Hole Ferry Terminal area will be cut off by a 100-year in 2030, and by a 20-year return period storm in 2050. By 2070, access to the terminal building will be cut off by a storm with a 5-year return period (Figure 5).

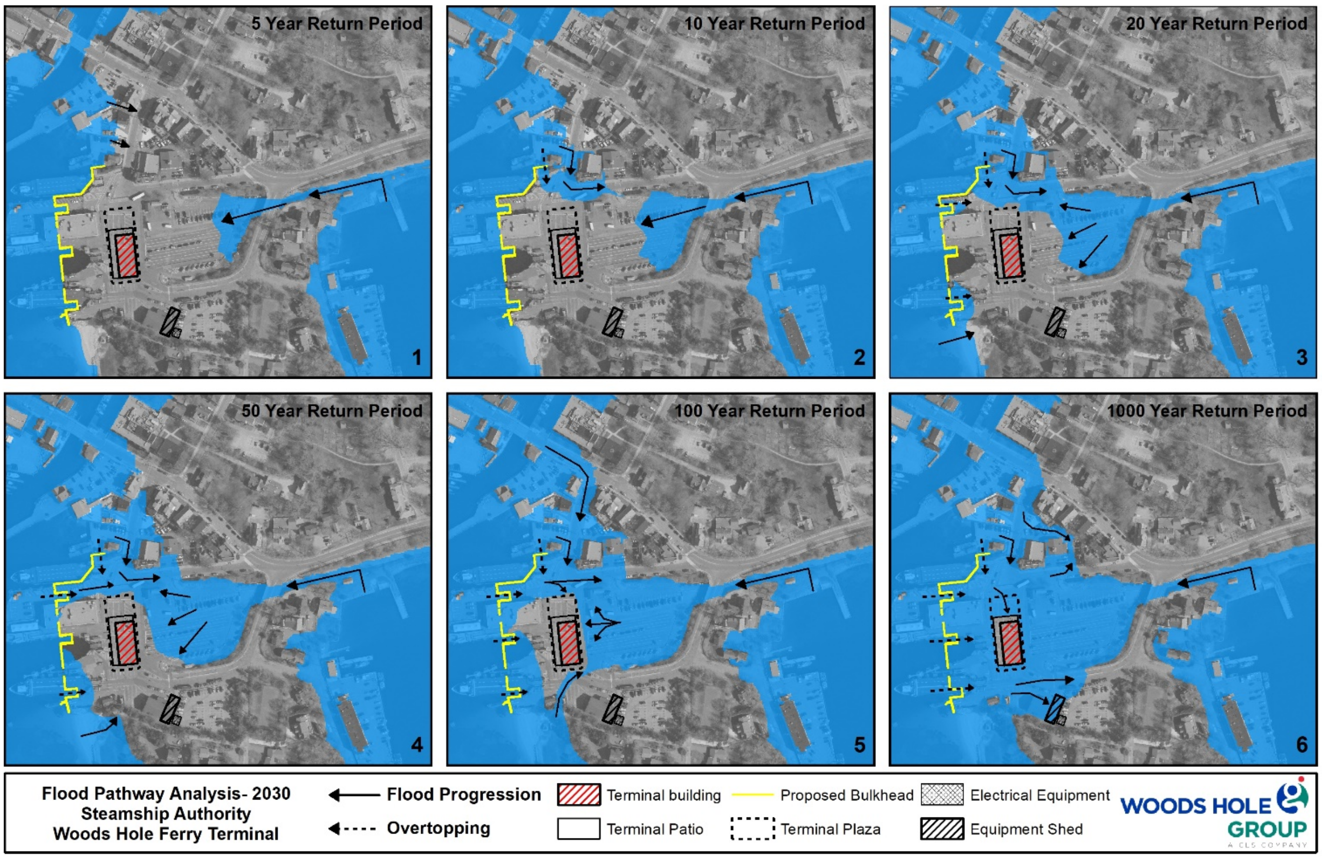

Figure 3. Flood pathways with 2030 water levels for storms with various return intervals.

Also, in the future, overtopping of the proposed bulkhead structures will add to the sheet flow already occurring at the identified pathways discussed above. In 2030, as seen in Figure 3, overtopping of the bulkhead structures will likely occur under 100-year and greater storm scenarios. Along with the sheet flow associated with the pathways, water from overtopping will begin to impede the access to the Terminal Plaza area.

By 2050, the implications of overtopping flooding within the Woods Hole Ferry Terminal footprint become increasingly severe (Figure 4). By this time horizon, the proposed bulkhead structures are overtopped by smaller storms (i.e. 20-year return period), further isolating the Terminal Plaza Building and preventing access to the Woods Hole Ferry Terminal facilities.

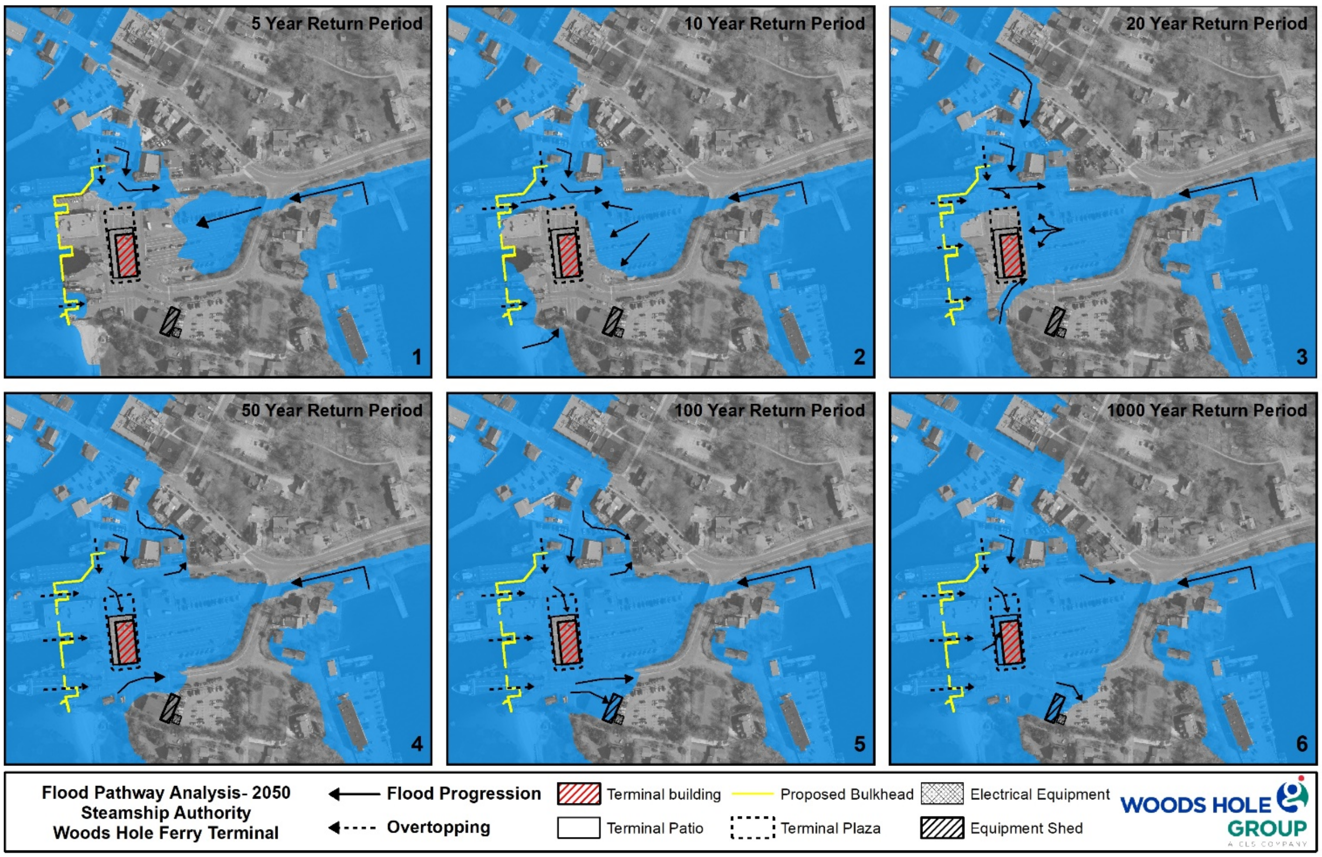

Figure 4. Flood pathways with 2050 water levels for storms with various return intervals.

The service life for the proposed structures at the Woods Hole Ferry terminal property is set for approximately 50 years. The flood pathways for 2070 visualized in Figure 5 can be utilized to understand the impacts that flooding will have on the proposed structures. The first floor of the ferry terminal building with floodproofing to 17 ft (NAVD88), will not be inundated by the 2070-time horizon. However, access to the property via Cowdry Road and access to the Terminal Plaza and Patio will be obstructed by the culmination of flood waters via the Shining Sea Bikeway/SSA parking lot, sheet flow from Luscombe Ave, and overtopping of the proposed bulkhead structures. The elevation surrounding the electrical equipment storage area is approximately 16.5 ft (NAVD88) and will become inundated by water under a 1000-year storm scenario, unless the components are elevated to the recommended DFE.

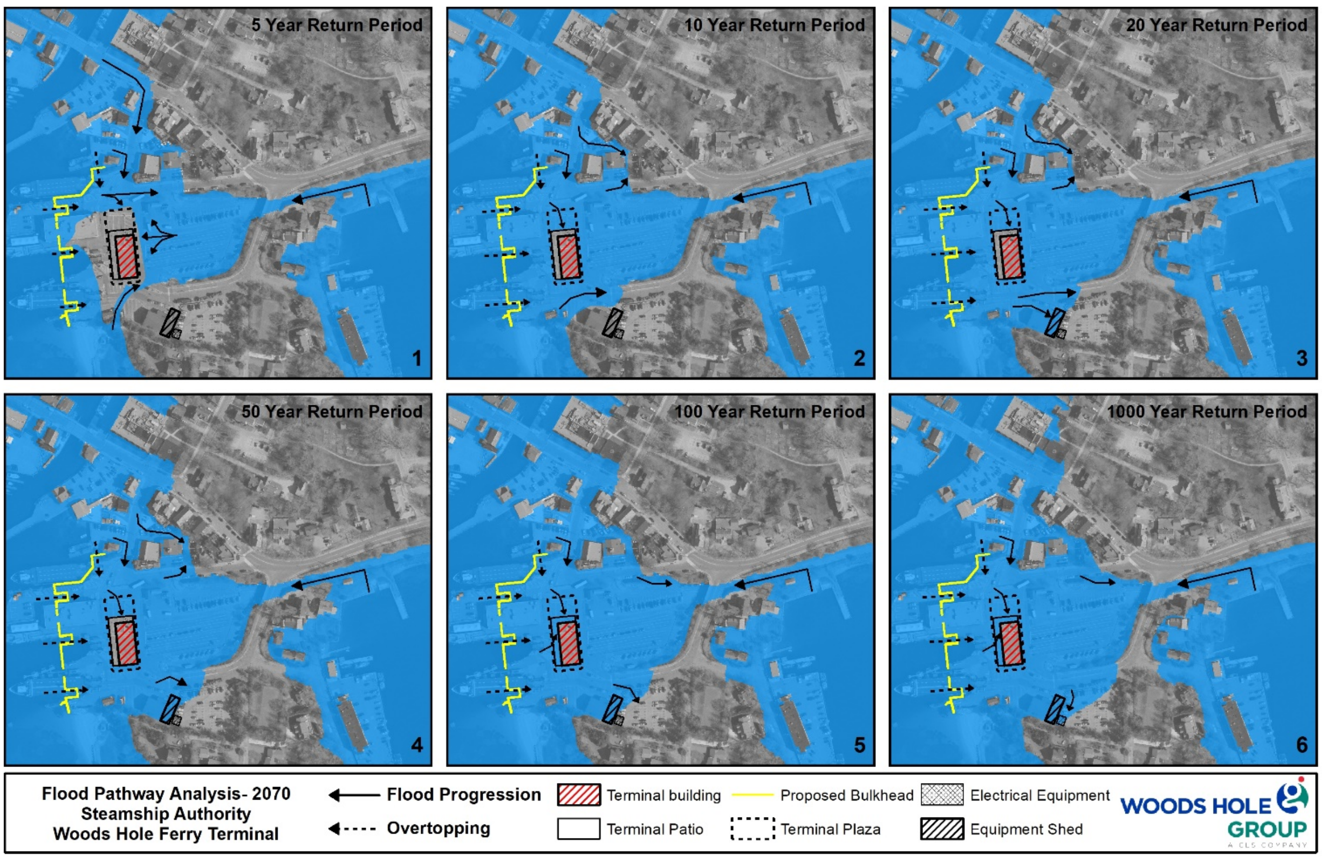

Figure 5. Flood pathways with 2070 water levels for storms with various return intervals.

The flood pathway analysis and results from the MC-FRM were utilized to develop a conceptual design approach for improving flood resilience at the Woods Hole Ferry Terminal. Rather than focusing on flood proofing individual assets and buildings, which can be accomplished through raising elevations, deployable flood barriers, or other asset specific flood proofing measures, these concepts are focused on keeping the entire facility dry and operational through a coastal storm event. Figure 6 presents potential adaptations for protection of the site. A self-rising tide gate is shown at the bridge that crosses the Shining Sea Bikeway/SSA parking lot to prevent water from flooding the property from Little Harbor. Extension of the bulkhead further inland on both sides of the terminal property and raising it to protect from future conditions is also a potential alternative. With this option it would also be necessary to regrade portions of the site to allow vehicle access to/from the ferries. Lastly deployable flood barriers along Luscombe Avenue are a potential adaptation that would help to prevent sheet flow flooding from the north. It is also clear from the flood pathway analysis that regional adaptations that consider flood pathways from Eel Pond via Water Street must also be considered. Implementation of these more regional approaches will require coordination with a broad group of stakeholders representing the Town of Falmouth, Village of Woods Hole, WHOI, National Oceanic and Atmospheric Administration (NOAA), and the Marine Biological Laboratory (MBL).

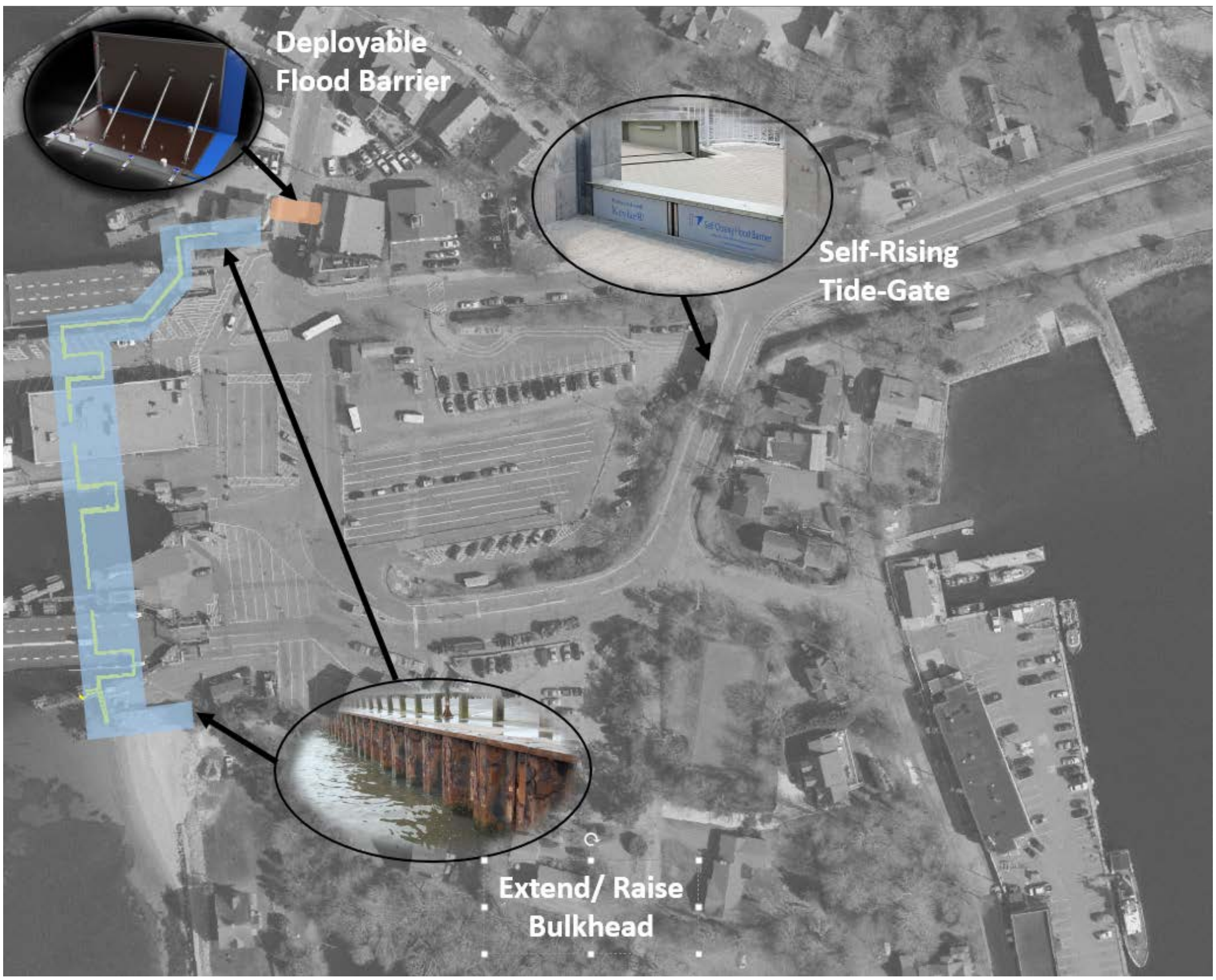

Figure 6. Conceptual design approaches to alleviate flooding in the study area.

Task 3.0 - Evaluate FEMA Flood Zones for Existing and Future Conditions

3.1 Introduction

For Task 3.0 Woods Hole Group performed an analysis of the FEMA flood zones in the area around the Woods Hole Ferry Terminal. FEMA backup information for the effective Flood Insurance Study and mapping in the vicinity of the Woods Hole Ferry Terminal was collected to determine the validity of the FEMA mapping and associated input parameters. Woods Hole Group obtained and reviewed the following FEMA documents as part of Task 3.0.

- FEMA Flood Insurance Rate Maps (FIRMs) effective July 16, 2014
- FEMA Flood Insurance Study (FIS) effective July 16, 2014
- FEMA modeling products including CHAMP, and WHAFIS

Figure 7 shows the flood zone mapping in the area of the Ferry Terminal as shown on the effective FEMA FIRM. The flood zones at the Ferry Terminal include a VE zone with a Base Flood Elevation (BFE) of 15 feet (pink), AE zones with BFEs of 12-13 feet (green), and X zones (clear), which are outside of the Special Flood Hazard Area. FEMA mapped the Woods Hole area using a single transect 175 (Blue line, Figure 7). This transect was modeled by FEMA using the Coastal Hazard Analysis Modeling Program (CHAMP) to determine the flood zone delineations along the transect, which were then extrapolated around the rest of the harbor using elevation information and engineering judgment.

To provide site specific information for the Ferry Terminal, Woods Hole Group established two additional transects as shown in Figure 8 (yellow and red lines). These transects were used to evaluate the flood zones following FEMA's methods for the following scenarios:

- Present day 1% annual chance water levels and flood conditions
- Proposed site elevations with an intact bulkhead and present day 1% annual chance water levels
- Proposed site elevations with a failed bulkhead and present day 1% annual chance water levels
- Proposed site elevations with an intact bulkhead and 1% annual chance water levels in 2070
- Proposed site elevations with a failed bulkhead and 1% annual chance water levels in 2070

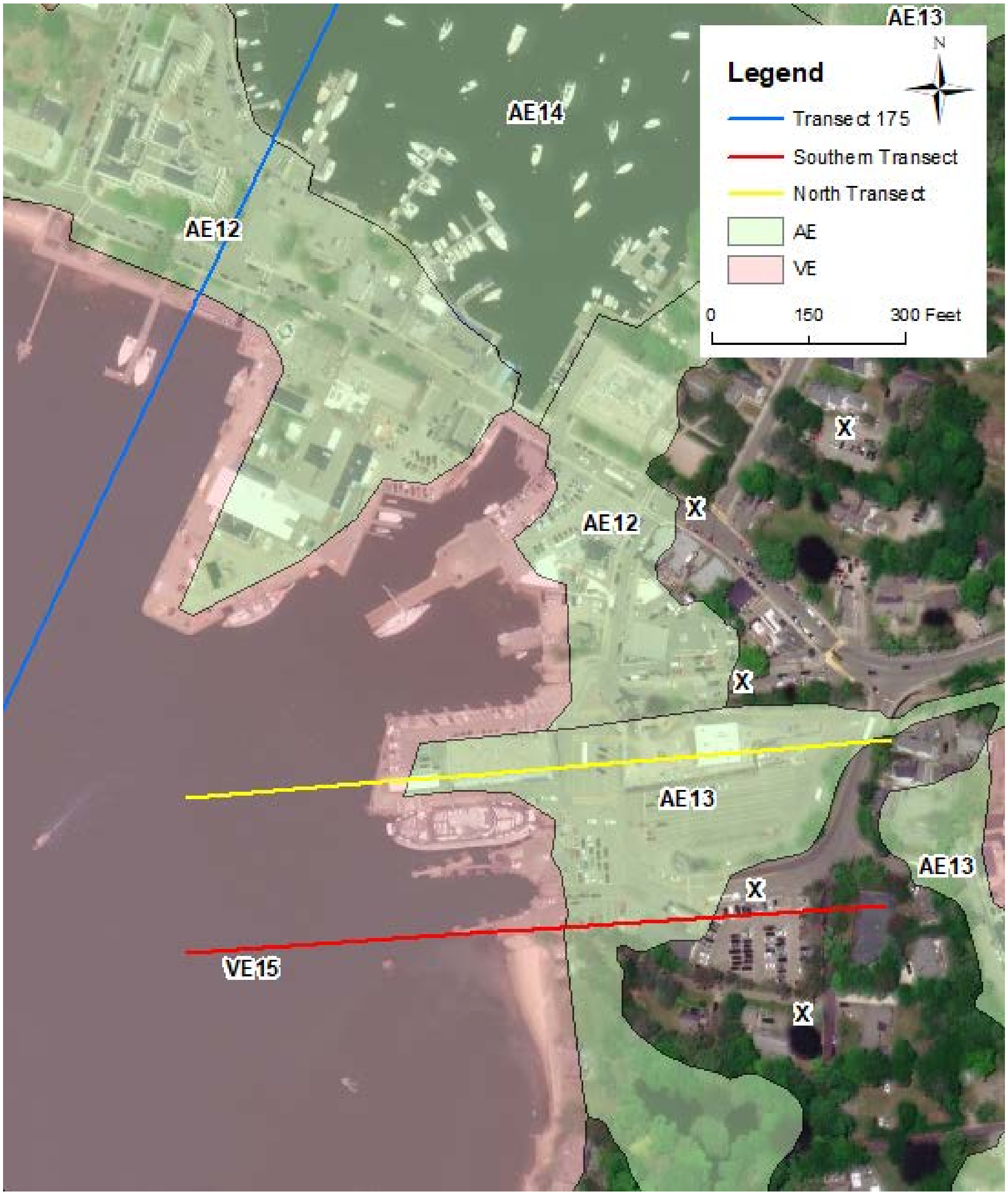

Figure 7: FEMA effective flood zones for Woods Hole with FEMA's transect 175 (blue line) and the two site specific transects developed for the Ferry Terminal (yellow and red lines).

3.2 Transect Creation

The elevations for each transect were taken from a combination of sources. Site specific bathymetric contours from the Woods Hole Ferry Terminal Reconstruction Plan were used for both present and proposed conditions. The elevations of the present day pier and terminal were taken from 2014 LiDAR (OCM Partners, 2019). The proposed site elevations were taken from the proposed site plan contours. Figure 8 and 9 show the difference between the present day conditions (blue) and the proposed conditions (red) for each transect.

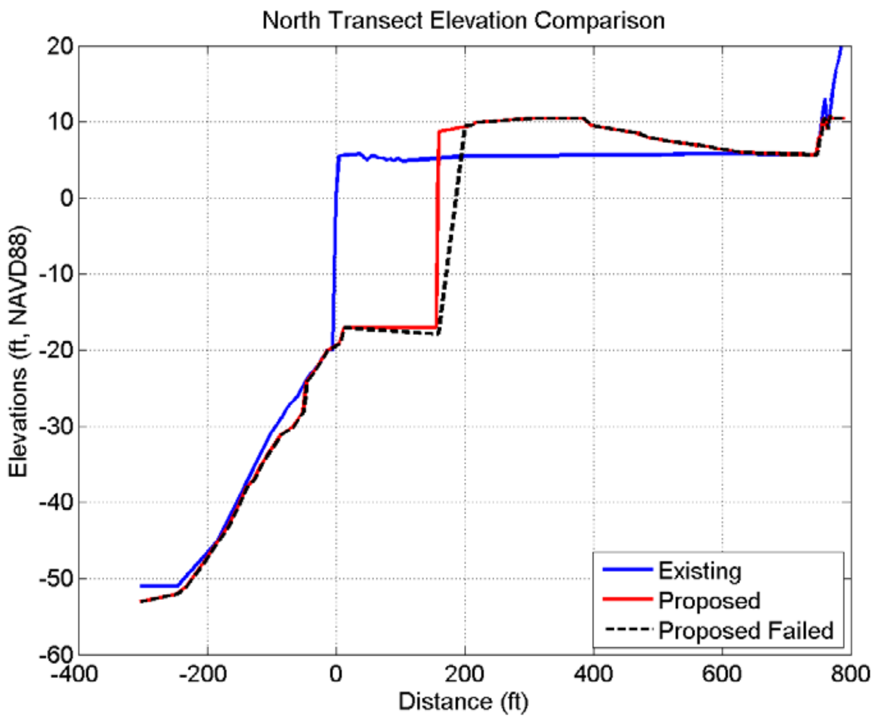

Figure 8: North site specific transect elevation comparison between existing conditions (blue), proposed conditions (red) and proposed conditions with a failed bulkhead (black dashed).

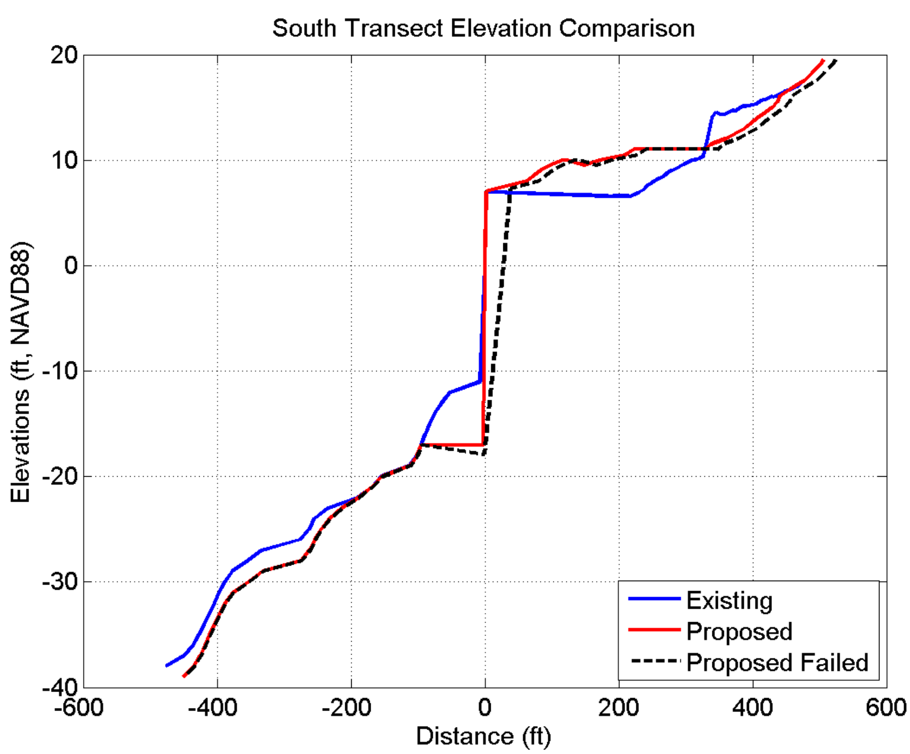

Figure 9: South site specific transect elevation comparison between existing conditions (blue), proposed conditions (red) and proposed conditions with a failed bulkhead (black dashed).

The bulkhead at each transect under proposed conditions was failed according to FEMA's guidelines as illustrated in Figure 10 (FEMA, 2015). This structure failure is required by FEMA in all cases, unless three is documentation showing that the structure was designed to withstand the %1 annual chance storm event. Scour was calculated using the coastal engineering manual equation (USACE, 2011) for non-breaking waves:

$$\frac{S_m}{H} = \frac{0.4}{[\sinh(kh)]^{1.35}} \qquad \text{Equation 1}$$

Where S_m is the maximum scour depth at the bulkhead, H is the wave height, h is the water depth at the toe, k is the incident wave number or $k = \frac{2\pi}{L}$ where L is the wavelength. Using this equation, scour was calculated to be 0.86 ft for each transect. Starting from the scoured elevation at the toe of the wall, the structure was assumed to fail on a slope of 1:1.5, until reaching the existing grade (Figure 10). The transects failed using this method are illustrated as black dashed lines in Figures 8 and 9.

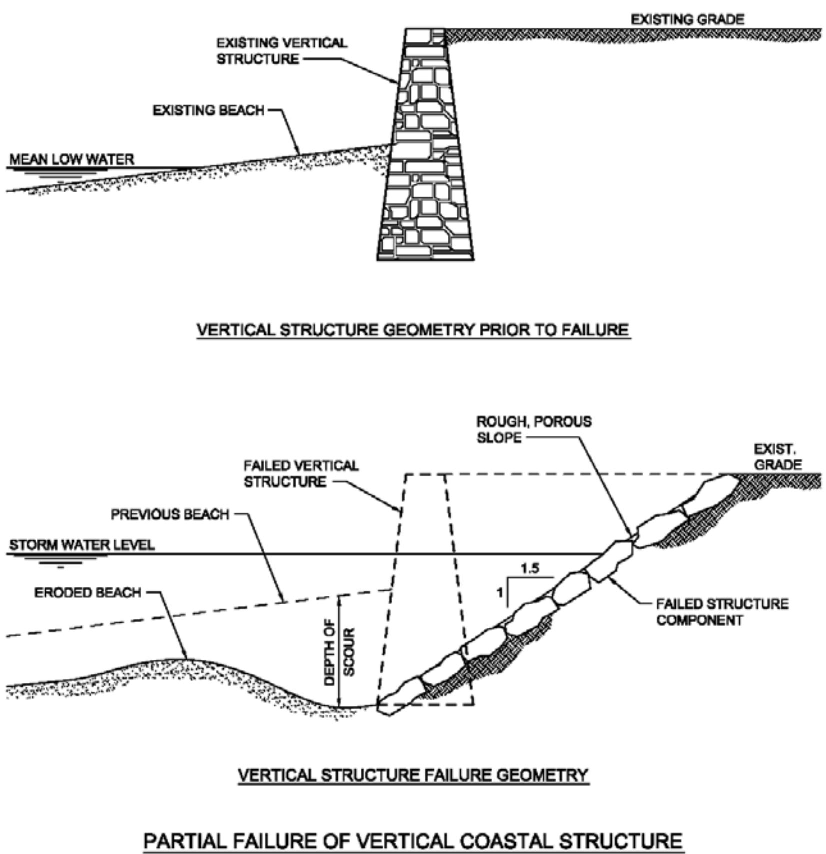

Figure 10: Structure failure guidelines from FEMA (FEMA, 2015) for failing a vertical structure.

3.3 Stillwater Elevations

A fundamental component of FEMA's detailed FIS process is the determination of the 1% annual chance stillwater level (SWEL). The SWEL is the elevation of the water due to the effects of astronomic tides and storm surge on the water surface. The SWL is integral in establishing the base inundation levels, determining the average slope for wave setup calculations, and determining water depths along transects for overland wave transformation.

For the current conditions, FEMA's SWEL for Transect 175 in Woods Hole was not revised, and was determined to be accurate for the nearby site specific transects. FEMA's 1% annual chance SWEL for Transect 175 was 10.1 ft NAVD88, which is consistent with the USACE Tidal Flood Profiles (USACE, 1988) for this area. Consequently, no changes were made to FEMA's SWEL for present day modeling.

For the 2070 projections, 1% annual chance return period SWEL conditions of 13.4 ft NAVD88 were extracted from the MC-FRM. This water level was then used with FEMA's analysis methods to determine the flood zones and BFEs that will affect the site in 2070.

3.4 Wind and Wave Climatology

Evaluation of 1% annual chance wave conditions is another fundamental component of FEMA's detailed FIS process. FEMA utilizes the energy-based significant wave height and peak wave period as the basis for coastal engineering analyses performed in support of mapping flood zones and associated water levels. Where the fetch is unlimited, deepwater wave conditions are generally taken from statistical analyses of measured buoy data or wave hindcast studies. In sheltered waters where the fetch length is limited due to the proximity of offshore landmasses or offshore engineered structures, a restricted fetch analysis is performed to develop the appropriate wave conditions. The waves are then transformed closer to the shoreline and inner harbor areas, and then used for calculations of wave setup and for overland wave transformation modeling.

FEMA utilized the restricted fetch method for generating significant wave conditions at Transect 175. The Automated Coastal Engineering System (ACES) software available through the Coastal Engineering and Design Analysis System (CEDAS, Version 4.0) was used by FEMA to generate the 1% annual chance wave conditions. The analysis assumes that wave conditions will be solely wind generated waves from storm winds. The geometry of the shoreline and landforms that surround Transect 175 were defined by establishing a series of radial fetches at 10 degree intervals. The fetch bands were used in the Wave Prediction – Wind Adjustment and Wave Growth (restricted fetch) module of ACES to define the distance and depth over water that storm winds can generate local waves. FEMA used a 1% annual chance wind speed of 78.74 miles per hour to simulate the storm wave conditions. The resulting 1% annual exceedance (100-year exceedance interval) significant wave height and period developed by FEMA were 4.01 ft and 3.57 seconds, respectively.

During evaluation of the wind and wave climatology data developed by FEMA, Woods Hole Group found justification for revising the 1% annual chance wind speed. Analysis of available nearby data indicated that FEMA's wind speed was higher than supported by the data. Woods Hole Group utilized the BUZM3 buoy in Buzzards Bay, which has a 30-year record of wind data to determine the 1% annual chance wind speed necessary for the fetch limited wave assessment. The winds from BUZM3 were binned by direction and averages were calculated every 3 hours for each year in the entire 30-yr dataset. The bin with the highest winds, that would create the largest waves, was found to approach from the SSW (160 to 180 degrees). The maximum of the binned 3 hour average wind speeds were found for each year, and an extremal analysis was used to determine a 1% annual chance wind speed of 63.5 miles per hour.

To develop revised wave conditions for the Ferry Terminal site, Woods Hole Group established a new set of radial fetches. A total of fourteen (14) radials were established at 10 degree intervals (Figure 11). The ACES Wave Prediction – Wind Adjustment and Wave Growth program was used with the revised 1% annual chance wind speed of 63.5 miles per hour to generate site specific waves for both transects (Figure 12). The resulting 1% annual chance wave height predicted by ACES was 6.07 ft. This is nearly 2 ft greater that the wave height used by FEMA for Transect 175, primarily because the site specific transects are more exposed to wind generated waves from the south and southeast. The larger waves were considered reasonable for this site, and were therefore used for the ensuing analyses, both for the existing and 2070 1% annual chance water level conditions.

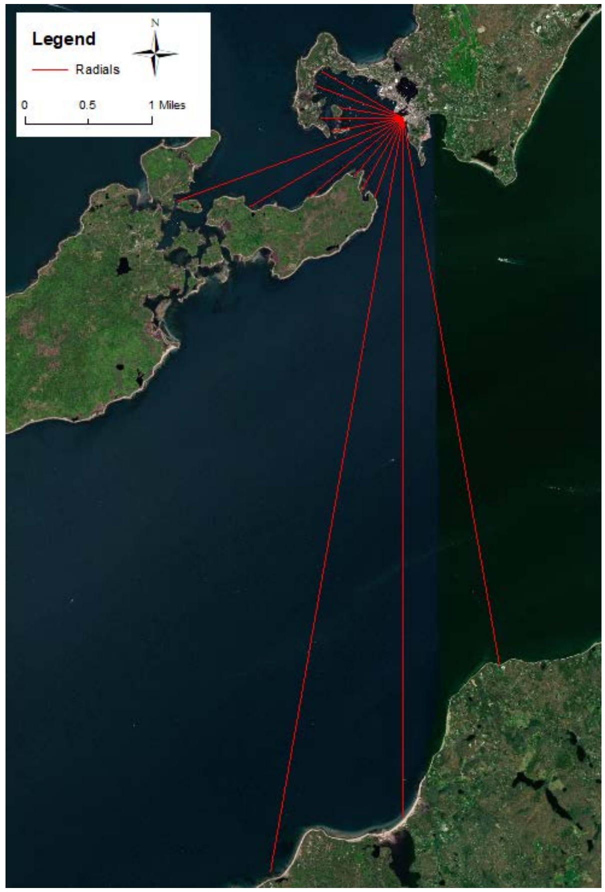

Figure 11: Radials used in ACES to determine the fetch limited wave height at the Woods Hole Ferry Terminal.

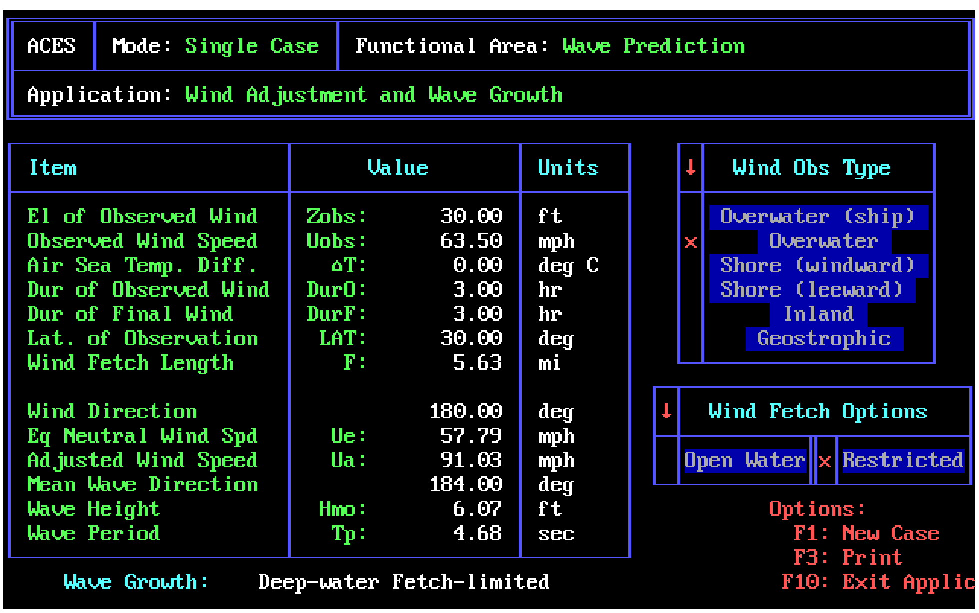

Figure 12: ACES analysis output for Woods Hole Ferry Terminal with a wind speed of 63.5 mph and a final wave height of 6.07 feet and a wave period of 4.68 seconds.

3.5 Wave Setup

The processes associated with wave setup have been recently incorporated into FEMA's detailed FIS evaluations. Wave setup refers to the increase in water level at the shoreline due to the breaking of waves and transfer of momentum to the water column. Wave setup is affected by the height of the waves, the speed at which waves approach the shore, and the slope of the ground near the shoreline. For the 2014 Barnstable County FIS, wave setup was computed by FEMA using the Direct Integration Method (DIM). At Transect 175 FEMA's wave setup value from DIM was 1.99 ft.

Recent studies on wave setup have demonstrated that the DIM over predicts the magnitude of wave setup when compared with physics based modeling approaches. As such, Woods Hole Group conducted an independent analysis of wave setup using the numerical model Simulating Waves Nearshore (SWAN). SWAN is a third-generation wave model, approved by FEMA, for obtaining realistic estimates of wave parameters in coastal areas from given wind, bottom, and current conditions. SWAN includes wave generation, dissipation, non-linear interactions, and transformations. It also includes bottom friction, currents, shoaling, refraction, diffraction, depth induced breaking, and wave setup. SWAN represents a model based approach that accounts for the physics of the waves, including the process of wave setup. The model was therefore selected as an improved alternate to the empirically based DIM utilized by FEMA for computing wave setup.

SWAN can be operated in both 1-D and 2-D modes. The 1-D model approach was considered to be more conservative for wave setup, since the 2-D model accounts for effects of the surrounding bathymetry and shoreline configuration on the wave form as it travels towards the coastline. The 1-D model is also consistent with FEMA's transect based analyses and readily allows representation of rapidly changing shoreline conditions at a high resolution.

SWAN 1-D was run for each site specific transect under current and proposed site elevations. Water levels were set to reflect the 1% annual chance SWEL of 10.1 ft NAVD88 for present day, and 13.4 ft NAVD88 for 2070 conditions. Incident wave heights of 6.07 ft with a period of 4.68 seconds were run for all conditions. Waves were assumed to conservatively approach normal to the shoreline (along the axis of the transects) and spectral spreading was turned off in the model (to ensure that the peak energy was not muted). This represents a conservative assumption where the model computed wave setup using peak wave conditions, rather than a spectral spread of the waves.

Results from the SWAN 1-D simulations were reviewed and the maximum wave setup along the transect for each condition was determined. The revised wave setup was then added to the SWEL to determine the total water level (TWL) for the site specific transects. Table 2 shows the SWEL, wave setup, and TWL for each of the six cases run with SWAN 1-D.

Table 2: Comparison of SWELs, wave setup, and TWLs used for each scenario modeled at the Woods Hole Ferry Terminal.

	North Transect			South Transect		
Parameter	**Current Conditions**	**Proposed Site Elevations – Present Day**	**Proposed Site Elevations - 2070**	**Current Conditions**	**Proposed Site Elevations – Present Day**	**Proposed Site Elevations - 2070**
SWEL (ft,NAVD88)	10.10	10.10	13.40	10.10	10.10	13.40
Wave Setup (ft)	0.42	0.50	0.49	0.54	0.81	0.48
TWL (ft,NAVD88)	10.52	10.60	13.89	10.64	10.91	13.88

3.6 Overland Wave Transformation and Flood Zone Mapping

Overland wave heights were calculated using the Wave Height Analysis for Flood Insurance Studies (WHAFIS) software within the Coastal Hazard Analysis for Mapping Program (CHAMP), following the methodology described in the FEMA Guidelines and Specifications. Corrected water levels and wave setup values from Table 2 were specified in CHAMP to develop a TWL. Definitions for the major topographic and structural features along the north and south site specific transects were identified from the elevations described in Section 3.2. Five separate simulations were performed with WHAFIS.

The FEMA flood zone results from CHAMP for each transect were plotted and interpolated to create potential flood zones for the proposed site elevations with the intact and failed bulkhead conditions, for present day 1% annual chance water levels. The resulting flood zones are shown in Figure 13. The panel on the left shows the FEMA effective zones under current conditions. This shows most of the site in an AE 13 zone with the coastline in a VE 15 zone.

The middle panel shows the flood zones for the proposed site conditions and the intact bulkhead. This shows a small AE 13 zone at the south end of the site near slip 2 where the bulkhead and surrounding ground elevations are lower. The higher bulkhead at elevation 9.0 ft NAVD88 along most of the site creates a VE/AE zone break at the crest of the bulkhead. An AE 12 zone is located landward of the bulkhead and at the northern portion of the site near the intersection with Luscombe Ave. The rest of the site, including the area of the proposed ferry terminal building, is located in an AE 11 zone.

The right panel of Figure 13 shows the proposed site conditions with the bulkhead failed. Under this scenario the seaward VE 15 zone moves inland of the bulkhead by approximately 50 feet. A small AE 12 zone is located at the southwest corner of the site and the remainder of the property is in an AE 11 zone. With the proposed site conditions and the ferry terminal design, the building is located in an AE zone and the first floor elevation at 13 ft NAVD88 is above the projected FEMA BFE of 11 ft NAVD88.

Figure 14 shows potential changes to the FEMA flood zones given the proposed site conditions and increased sea levels in 2070. The projected FEMA mapping for future conditions shows VE 20 and VE 17 zones along the seaward edge of the property, with AE 16 and AE 15 zones across the remainder of the site. The ferry terminal building would be located in an AE 16 zone, while the equipment shed would be in an AE 15 zone. Both of these AE zones would be considered Coastal AE zones (i.e., seaward of the LiMWA, or Limit of Moderate Wave Action), indicating that waves between 1.5 and 3.0 ft would occur during a 1% annual chance event. While the first-floor elevation of the ferry terminal building at 13 ft NAVD88 would be 3 ft below the BFE, with adequate wave protection and floodproofing design/deployment for the additional 4 ft of protection, the terminal building should be resilient to this future storm and sea level condition.

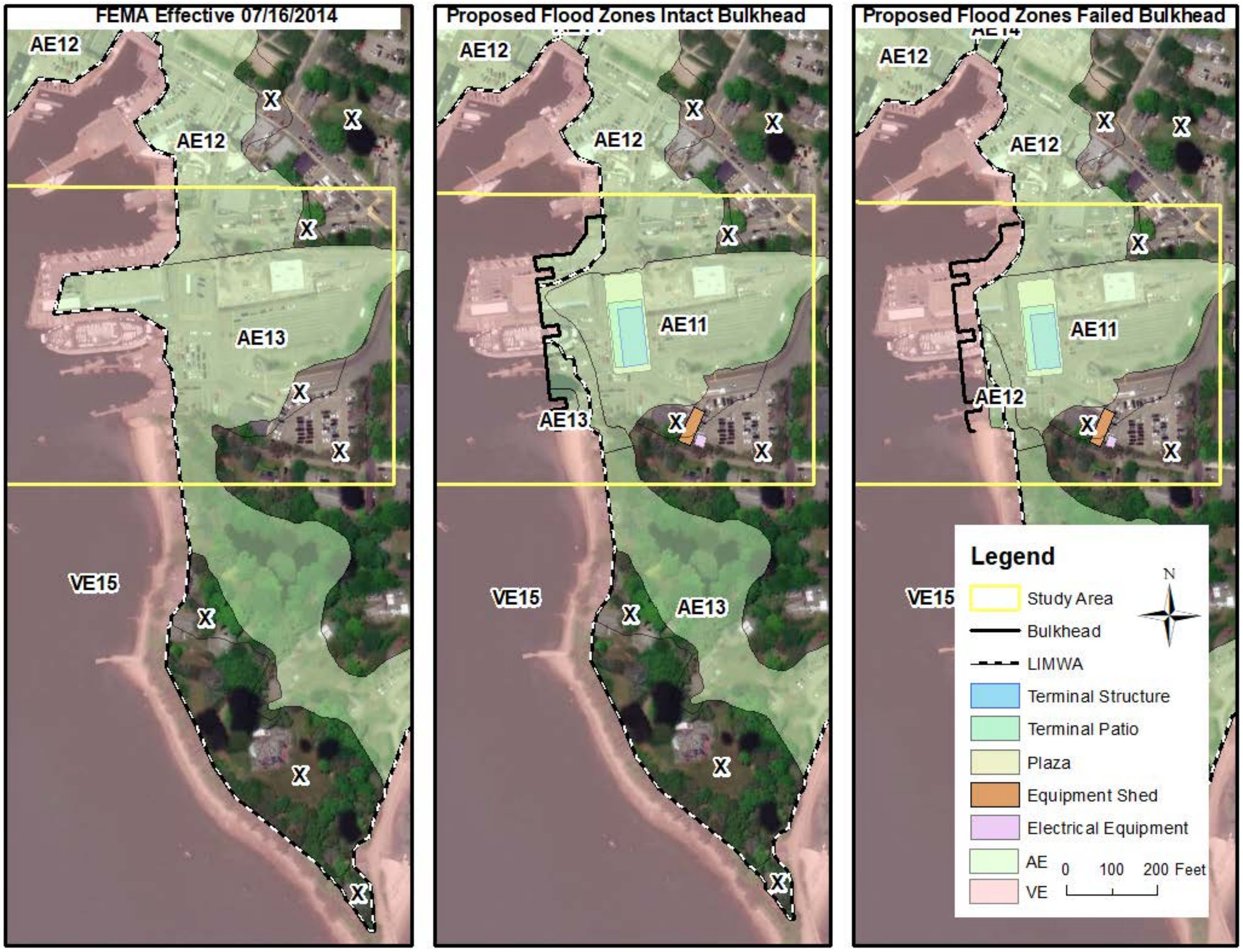

Figure 13: Present day flood zones created from the CHAMP modeling. Left panel shows the effective FEMA maps, the middle panel shows the flood zones with an intact bulkhead, and the right panel shows the flood zones with a failed bulkhead.

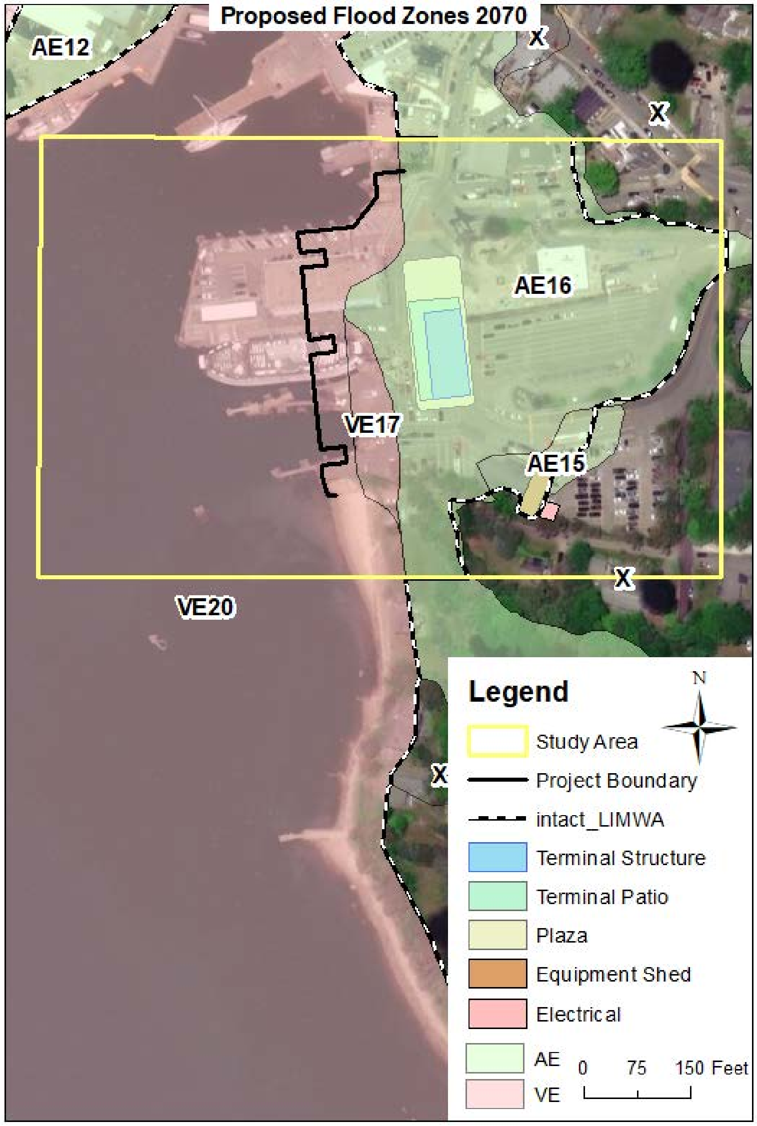

Figure 14: Flood zones created from the CHAMP modeling for the Ferry Terminal assuming increased sea levels in 2070.

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