EAST SIDE COASTAL RESILIENCY

TASK 3 – COASTAL HYDRAULICS REPORT

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BOROUGH OF MANHATTAN, NEW YORK

Mayor's Office of Recovery and Resiliency

Department of Design and Construction

NYC Parks

Prepared for:

New York City Department of Design and Construction

In partnership with:

New York City Mayor's Office of Recovery and Resiliency
and
New York City Department of Parks and Recreation

Project ID: SANDRESM1
Contract No. HWDRCW02

Submitted by:

The AKRF-KSE JV

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Acronyms and Abbreviations

CEM	Coastal Engineering Manual
CFR	Code of Federal Regulations
HUD	Housing and Urban Development
FDR	Franklin Delano Roosevelt
FEMA	Federal Emergency Management Agency
lidar	Light detection and ranging
NAVD88	North American Vertical Datum of 1988
NYC	New York City
PFIRM	Preliminary Flood Insurance Rate Maps
RBD	Rebuild by Design
SLR	Sea level rise
USACE	U.S. Army Corps of Engineers
WHAFIS	Wave Height Analysis for Flood Insurance Studies

1. Introduction

Following the devastation of Hurricane Sandy, the Department of Housing and Urban Development (HUD) initiated the Rebuild by Design (RBD) competition to develop innovative and resilient coastal flooding solutions against future storms. The “Big U” RBD strategy for the Manhattan waterfront from East 42nd Street south to the Battery and then north to West 57th Street was selected as a winning concept. HUD ultimately provided funding to develop a 30% conceptual design of the “Big U” flood protection strategy for two segments: from Montgomery Street north to East 14th Street and from East 14th Street north to East 23rd Street, referred to as the East Side Coastal Resiliency project. This report presents the coastal hydraulic analysis performed to establish elevation requirements for both segments of the flood protection system.

Specifically, a wave overtopping analysis was conducted based on the storm tide and wave conditions to quantify the wave overtopping rates for a range of levee/wall crest elevations from Montgomery Street to East 23rd Street. The rates were compared to tolerable rates to inform the selection of minimum required crest elevations. Tolerable wave overtopping rates were based on criteria summarized in EurOtop (Pullen et al. 2007) to prevent impacts to critical transportation routes immediately behind the flood protection system and to prevent damage to the flood protection system itself.

This report first discusses the proposed alignment and geometry of the flood protection system. The storm tide levels, New York City (NYC) Panel on Climate Change sea level rise (SLR) projections (Horton et al. 2015), and wave conditions are then quantified for the wave overtopping analysis. Wave overtopping rates are then presented to inform the minimum required crest elevations along the full length of the flood protection system. The rates are first presented for the design event, predefined by the design team as the 100-year event with the 90th percentile SLR projection in the 2050s. Wave overtopping rates are then presented for the 500-year event and for SLR projections in the 2100s with an emphasis on additional elevation or armoring requirements to provide added resiliency for events exceeding design.

This evaluation then compares the wave overtopping-based crest elevation requirements to the crest elevations needed for Federal Emergency Management Agency (FEMA) recognition of the flood protection system based on criteria from federal regulations, Code of Federal Regulations (CFR) Title 44 §65.10 (b) (iii-iv). The report then concludes by presenting a no-impact analysis that evaluates effects to adjacent properties as a result of the flood protection system.

2. Flood Protection Alignment

To best manage the uses and needs associated with existing infrastructure, transportation, utilities, and parks, a flood protection alignment was selected to generally follow the eastern edge of Franklin Delano Roosevelt (FDR) Drive. The proposed alignment at the time of this analysis is as shown on Figure 2-1. Segments of the alignment are either levee or vertical wall. The northern and southern ends of the alignment extend inland to elevations that provide flood risk reduction for the 100-year event plus the 90th percentile SLR projection in the 2050s. Sections 3 and 4 will describe the storm tide and SLR projections associated with this event in more detail.

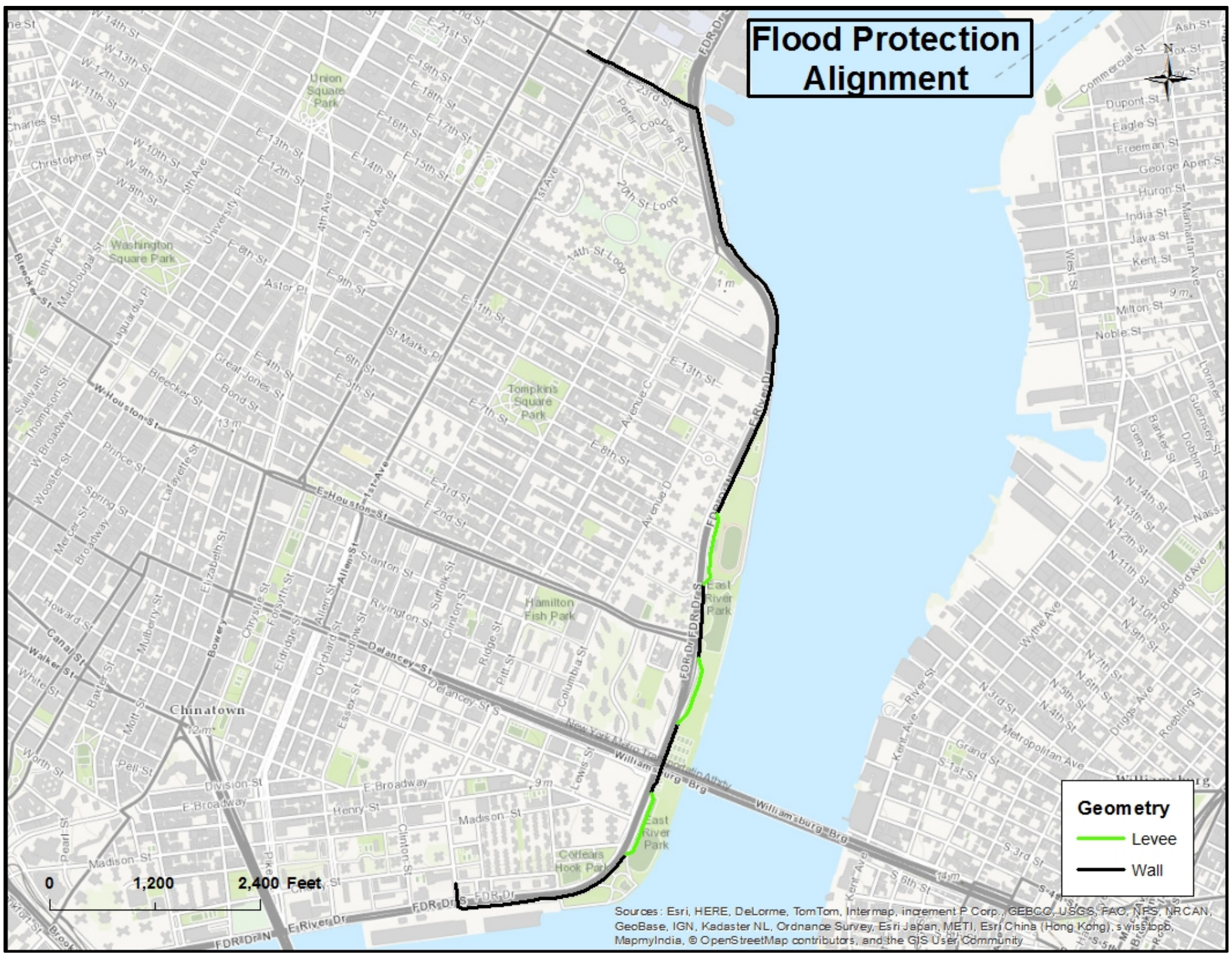

Figure 2-1 Flood protection alignment from Montgomery Street in the south to East 23rd Street in the north.

Figure 2-2 demonstrates a typical cross section for the levee sections of the flood protection system. The levee is grass-covered with a slope of 3:1 or 4:1. The back side toe transitions from grass to existing or proposed impervious surfaces. The allowable overtopping rates to ensure stability of the grass-covered levee are discussed in Section 6. The East River facing, or flood side, toe transitions to a proposed shared pathway at elevation 10 ft North American Vertical Datum of 1988 (NAVD88), as shown on Figure 2-2.

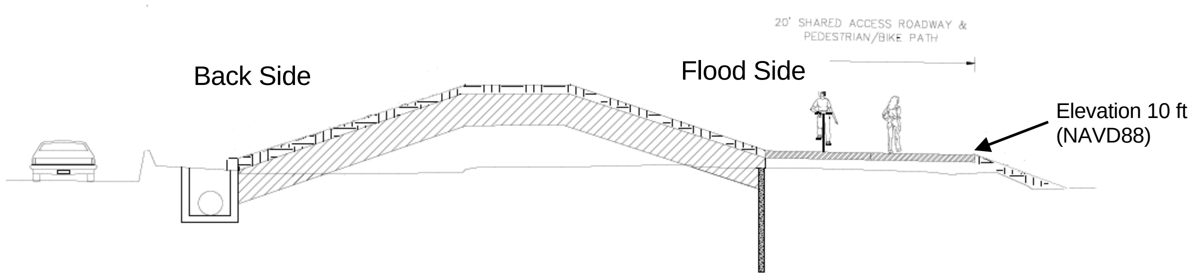

Figure 2-2 Typical cross section of the levee segments of the flood protection alignment.

The vertical wall portions of the alignment in general follow FDR Drive. In some areas, such as Cherry Street to East 12th Street, this places the vertical wall system roughly 300 ft inland from the East River shoreline, providing wave energy dissipation that reduces wave heights, before waves from the East River reach the flood protection alignment. In other areas, such as East 14th Street to East 18th Street, the vertical wall is aligned at the shoreline, providing the largest wave exposure. A typical vertical wall, T-wall, concept is shown on Figure 2-3. Portions of the alignment could contain I-wall or L-wall designs, but these details are not required for wave overtopping analysis of vertical walls. The back side toe of vertical walls will tie into asphalt or concrete, making the toes well protected from erosion and allowing for higher limits of wave overtopping, as will be discussed in Section 6.

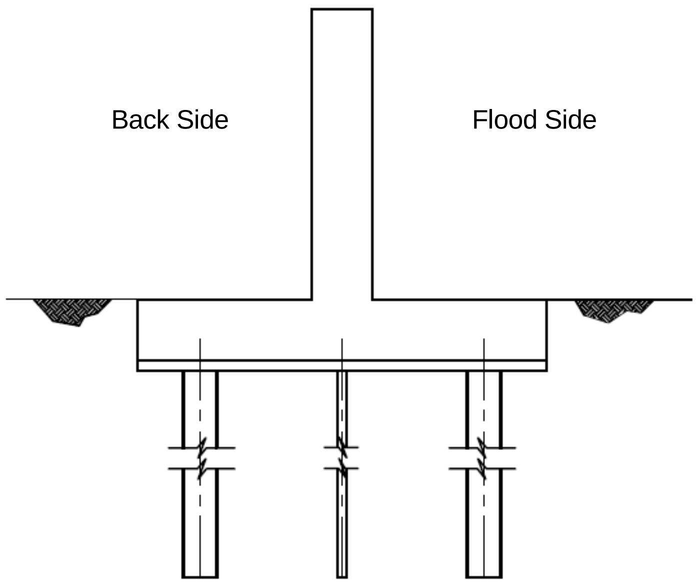

Figure 2-3 Typical T-wall cross section of the vertical wall segments of the flood protection alignment.

3. Storm Tide Conditions

3.1 100-Year Storm Tide

The design storm tide for this conceptual analysis is the FEMA 100-year storm tide[1], associated with the coastal analysis used to develop the Preliminary Flood Insurance Rate Maps (PFIRMs) for NYC, released January 30, 2015. Although the PFIRMs are still preliminary, the storm tide elevations are higher than the storm tides associated with FEMA's 2007 Effective FIRMs. NYC Local Law 96 currently requires the use of the higher of the two storm tides (City of New York Law Department 2013) in the design of coastal protection features.

Storm tide does not include the additional effects of waves or wave runup, which are included in the Base Flood Elevations (AE and VE zones), presented on the PFIRMs. Table 3-1 shows 100-year FEMA PFIRM storm tide elevations along the flood

[1]In FEMA terminology the storm tide is referred to as the stillwater elevation and the 100-year event is also referred to as the 1-percent-annual-chance event.

protection alignment. Direct comparison of these elevations with FEMA PFIRM AE or VE designations will result in different numbers because of the absence of waves. Storm tide levels vary 0.1 ft along the alignment, with higher storm tides north of East 19th Street. It should also be noted that the storm tide elevations presented on the FEMA PFIRMs are in current-day sea levels.

Table 3-1 FEMA PFIRM 100-year storm tide elevations along the flood protection alignment.

100-Year Storm Tide (ft, NAVD88)	Approximate Location
11.0	East 23rd Street/East River
11.0	East 22nd Street/East River
11.0	East 21st Street/East River
11.0	East 19th Street/East River
10.9	East 18th Street/East River
10.9	East 17th Street/East River
10.9	East 14th Street/East River
10.9	East 12th Street/East River
10.9	East 10th Street/East River
10.9	East 8th Street/East River
10.9	East 6th Street/East River
10.9	East 2nd Street/East River
10.9	Rivington Street/East River
10.9	Delancey Street/East River
10.9	Grand Street/East River
10.9	Jackson - Cherry Street/East River
10.9	Gouverneur - Jackson Street/East River

NAVD88 North American Vertical Datum of 1988

3.2 500-Year Storm Tide

In addition to the 100-year storm tide, the 500-year storm tide was analyzed to provide an understanding of the performance of the flood protection alignment and design elevations if exposed to a lower probability event. The 500-year storm tide elevations range from 13.9 ft NAVD88 to 14.1 ft NAVD88 along the flood protection alignment.

3.3 Storm Tide Time Series

FEMA does not provide a time series of storm tide elevations, only peak levels associated with the return period events. However, a time series associated with storm tide is important for determining:

- Wave overtopping volumes over the duration of a storm.
- Boundary conditions for interior drainage analysis.
- Gate and valve closure operations.
- Lead times for deployment of mechanically implemented flood protection features.

To generate a representative storm tide time series for wave overtopping analysis, the parametric method supported by the U.S. Army Corps of Engineers (USACE 2009) was used. The 189 historical extratropical (nor'easters) and synthetic tropical (hurricanes) storm time series used in the FEMA PFIRM analysis were used to determine the best fit shape of the storm tide time series. The parametric method assumes a Gaussian shape to the time series and fits a correlation between the 30 percent width and the peak storm tide for all 189 storms. Figure 3-1 shows the parametric storm surge time series for 100-year and 500-year storm tide events relative to mean higher high water.

Although the 500-year event generates larger peak storm tide elevations than the 100-year event, the duration in which water levels would be expected to be above mean higher high water, for example, are approximately double for the 100-year event when compared to the 500-year event. The reason for this is that nor'easters are longer-duration storms than hurricanes and contribute more heavily to the fit of the 100-year event than the 500-year event. The implementation of these storm tide time series for the estimation of time-integrated wave overtopping volumes is discussed further in Section 6.

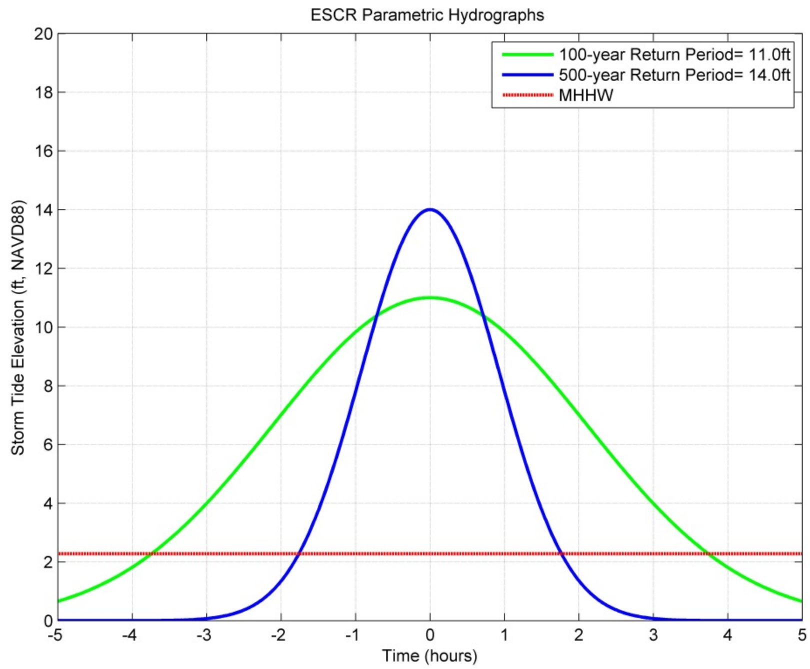

Figure 3-1 Parametric storm tide time series for the 100-year and 500-year events.

4. Sea Level Rise Conditions

The NYC Panel on Climate Change released updated climate projections specific to NYC in January 2015 (Horton et al. 2015). The SLR projections include the effects of multiple physical processes, primarily:

- Land subsidence
- Expansion of warming ocean waters
- Melting of global ice

Warming of oceans has been the leading cause of global SLR over the last century, with melting of global ice expected to be the leading cause in the next century. In NYC, land subsidence has accounted for 45 percent of historical SLR (NYC Panel on Climate Change 2013). These and other components attributing to SLR in NYC are projected independently to inform a total SLR (Horton et al. 2015 [Table 2.1]).

Uncertainties are inherent in the projection of each component of SLR; therefore, projections are listed using the distributions of outputs from numerous SLR model simulations, i.e., the 10th percentile is a low SLR estimate relative to other estimates, the 50th percentile is a middle range estimate, and the 90th percentile is a high estimate. In simple terms, the majority of the SLR model simulation outputs are associated with the 50th percentile, with fewer simulation outputs associated with the 10th and 90th percentiles. The range of SLR projections for the 2050s and the 2100s for NYC are shown in Table 4-1.

Table 4-1 SLR projections in the 2050s/2100s for NYC for the 10th/50th/90th percentile simulation outputs.

Year	10th Percentile	50th Percentile	90th Percentile
2050s	8 in.	16 in.	30 in.
2100s	15 in.	36 in.	75 in.

For the current analysis, SLR was linearly added to the storm tide conditions to inform the total water levels used in the wave conditions and wave overtopping analysis discussed in Sections 5 and 6. Orton et al. demonstrated that this linear superposition is an appropriate approximation for the majority of the NYC region, including the area adjacent to the flood protection alignment (2014).

5. Wave Conditions

5.1 Wave Transects

Wave conditions for the 100-year event were extracted from the FEMA PFIRM analysis, specifically from the Wave Height Analysis for Flood Insurance Studies (WHAFIS; FEMA 2008) wave transects at the East River shoreline from Montgomery Street to East 23rd Street, as shown on Figure 5-1. FEMA's WHAFIS transects contain the parameters associated with the variation of wave heights and periods as they move from the shoreline inland toward high ground. FEMA transect numbers 25 through 40 intersect the flood protection alignment and were reviewed for appropriate topographic, wind fetch[2], vegetation, and building parameters. Transects 23 and 24 also intersect

[2] Fetch is the distance of open water over which wind-generated waves can develop. Larger fetch correlates with larger wave heights.

the alignment, but large waterfront infrastructure on the flood side of the alignment provides shelter from wave exposure; therefore, the transects are not considered as part of this assessment.

Review of the WHAFIS parameters was completed using the NYC 2010 light detection and ranging (lidar) dataset (City of New York 2012), project-specific topographic surveys, on-site photographs, street view imagery, and aerial imagery. Any topographic discrepancies deemed of significance to the wave overtopping analysis were adjusted to the project specific topographic survey or the NYC 2010 lidar data.

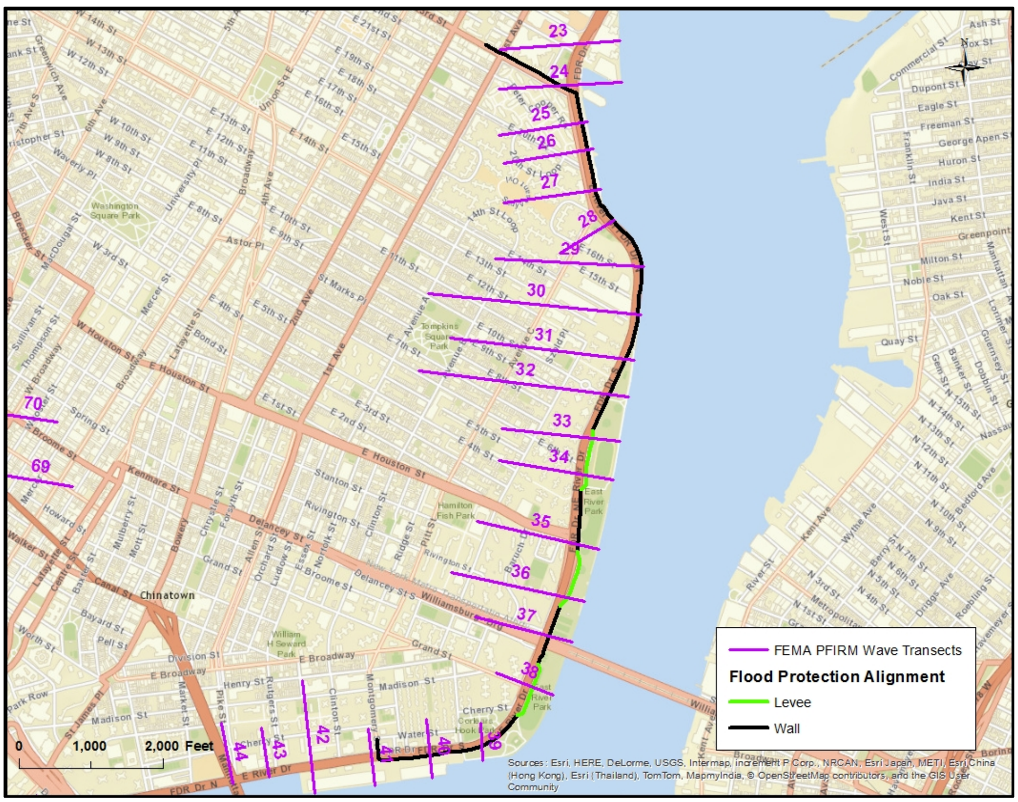

Figure 5-1 WHAFIS wave transects from the FEMA PFIRM analysis. Numbers 25 through 40 intersect the flood protection alignment.

5.2 100-Year Waves at Shoreline

The 100-year wave heights and wave periods reviewed and extracted from the FEMA WHAFIS transects at the East River shoreline are shown in Table 5-1. The terms "wave height" and "wave period" will be used throughout the document to refer to significant wave height and spectral peak wave period, respectively. It can be seen that the wave heights at the East River shoreline vary from 2.6 ft to 3.3 ft along the alignment, with the lower wave heights occurring along the shoreline between Gouverneur and Cherry Streets. Wave periods range from 2.7 to 3.5 seconds, which is a range expected for harbor waters during larger storm events.

Table 5-1 100-year wave height and wave period at the East River shoreline as reviewed and advanced from FEMA WHAFIS transects 25 to 40 along the flood protection alignment.

FEMA PFIRM Transect #	Approximate Location	100-Year Wave Height (ft)	100-Year Wave Period (seconds)
25	East 22nd Street/East River	3.2	3.2
26	East 21st Street/East River	3.2	3.3
27	East 19th Street/East River	3.2	3.2
28	East 18th Street/East River	3.2	3.3
29	East 17th Street/East River	3.1	3.2
30	East 14th Street/East River	3.3	3.5
31	East 12th Street/East River	3.3	3.5
32	East 10th Street/East River	3.3	3.5
33	East 8th Street/East River	3.3	3.5
34	East 6th Street/East River	3.2	3.5
35	East 2nd Street/East River	3.2	3.4
36	Rivington Street/East River	3.2	3.4
37	Delancey Street/East River	3.1	3.3
38	Grand Street/East River	3.1	3.3
39	Jackson - Cherry Street/East River	2.7	2.8
40	Gouverneur - Jackson Street/ East River	2.6	2.7

5.3 100-Year Waves at Levee/Wall

For the majority of the flood protection alignment, the levee/wall is offset inland from the East River shoreline as presented in Section 2. Wave overtopping analysis requires wave conditions at the toe of the levee/wall; therefore, the FEMA PFIRM wave transects were evaluated in WHAFIS to transform wave properties from the East River to the toe of the wall/levee. Transformed wave conditions were extracted roughly one deep water wave length flood side of the wall/levee.

The wave transformation is controlled by the depth of water, the inland topography, buildings and other infrastructure, and vegetation. Each of these parameters has the effect of dissipating wave energy. On the contrary, the local wind speed acts to increase wave heights as waves propagate inland. FEMA's recommended wind speed of 60 miles per hour for inland fetch areas was used for the 100-year wave transformation analysis (FEMA 2007). Increases in water depth, which reduce energy dissipation, were included due to the 500-year storm tide and the SLR projections presented in Section 4.

A sample wave profile demonstrating the inland propagation of waves and the associated wave heights is shown on Figure 5-2. The wave profile is along the East 2nd Street transect, which is a vertical wall section offset inland from the East River shoreline. The design event storm tide, storm tide plus waves, and the topography are shown on the profile. Note that the wave component shown on the wave profile is 0.7 times the controlling wave height and the controlling wave height is 1.6 times the significant wave height (FEMA 2007). The 0.7 factor accounts for the portion of the wave that is above the storm tide in shallow water wave conditions, and the controlling wave height represents 1 percent of the incoming waves.

It is clear that the shallowing of the water depth in the first 30 ft from the shoreline has the effect of decreasing wave heights. After this initial decrease in wave height close to the shoreline, water depths and wave heights remain roughly constant until reaching the vertical wall.

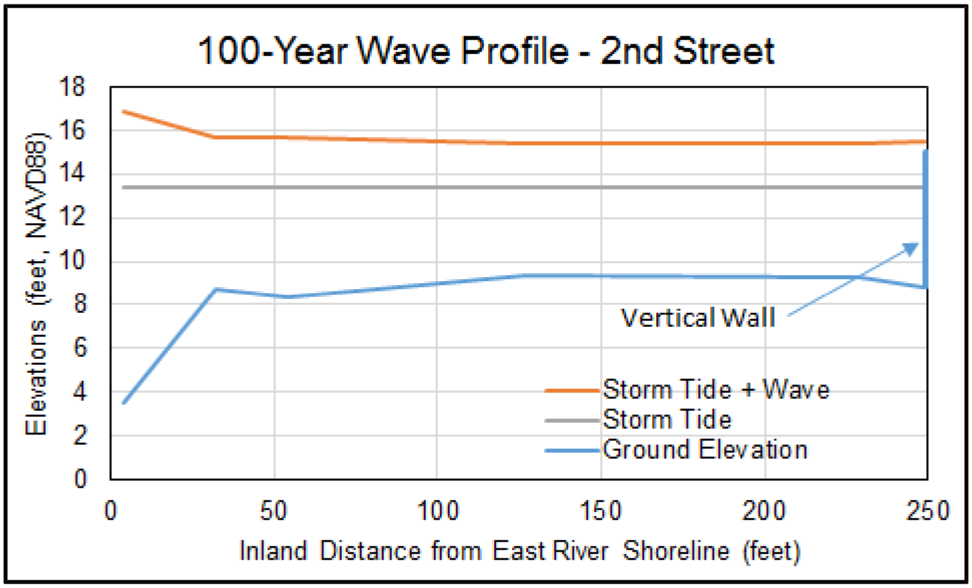

Figure 5-2 **Profile of ground elevations and design event waves and storm tide from the East River shoreline to an inland offset vertical wall at East 2nd Street.**

The resulting wave heights at the toe of the wall/levee are shown on Figure 5-3 for the 100-year event with no SLR, the design event, and the 500-year event with no SLR. Three locations are shown:

- East 22nd Street, where it is roughly 75 ft shoreline to toe
- East 8th Street, where it is roughly 350 ft shoreline to toe, with portions of vegetation
- Jackson Street, where it is roughly 320 ft shoreline to toe, and buildings are present

The effects of width from shoreline to toe, vegetation, and buildings at reducing wave energy can be inferred from Figure 5-3, but more importantly the effects of increasing water depth on inland wave transformation are demonstrated. SLR and larger storm tide events (e.g., the 500-year) allow larger wave heights to propagate to the toe of the flood protection system. Highlighting the East 8th Street wave transect, wave height reductions by inland transformation are 73 percent for the 100-year event with no SLR, but only 43 percent and 39 percent, respectively, for the design event and the 500-year event with no SLR. This demonstrates that increasing water levels allow more wave energy to reach the flood protection system.

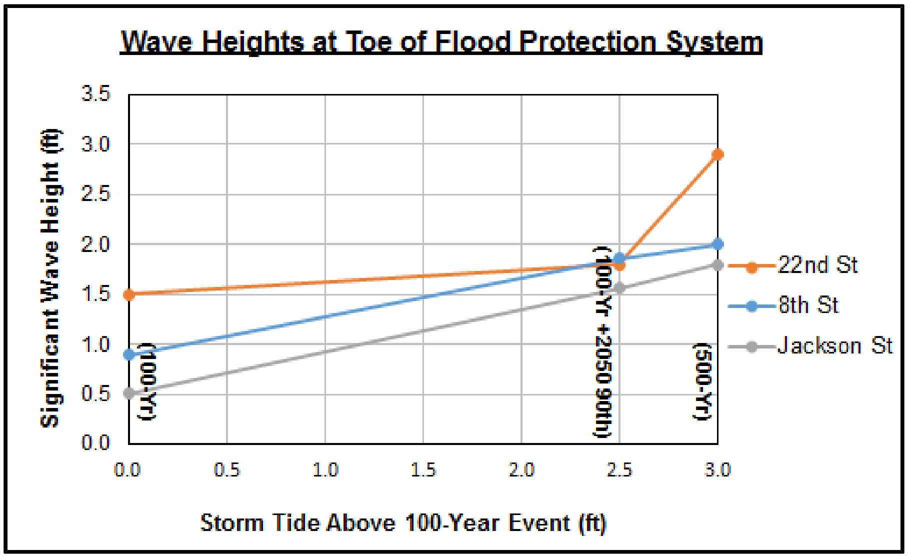

Figure 5-3 Wave heights at the toe of the flood protection system for increasing storm tides at East 22nd Street, East 8th Street, and Jackson Street. Storm tides shown for the design event and the 100-year/500-year events with no SLR.

5.4 Wave Time Series

The discussion so far has been about peak wave conditions at the toe of the levee/wall; however, during a storm, wave conditions will vary with changing water levels and wind forcing. Wave condition time series are not available from the FEMA PFIRM analysis; therefore, the variability of the wave conditions needed to be approximated. To approximate this variability, wave height and wave period time series were generated assuming the same variation from the peak as assumed for the storm tide time series presented in Section 3.

Figure 5-4 shows the wave height time series over the duration of the 100-year event at the toe of the levee/wall alignment at East 8th and East 19th Streets. The East 19th Street alignment is at the shoreline, explaining the larger magnitude of wave heights relative to the inland offset alignment at East 8th Street.

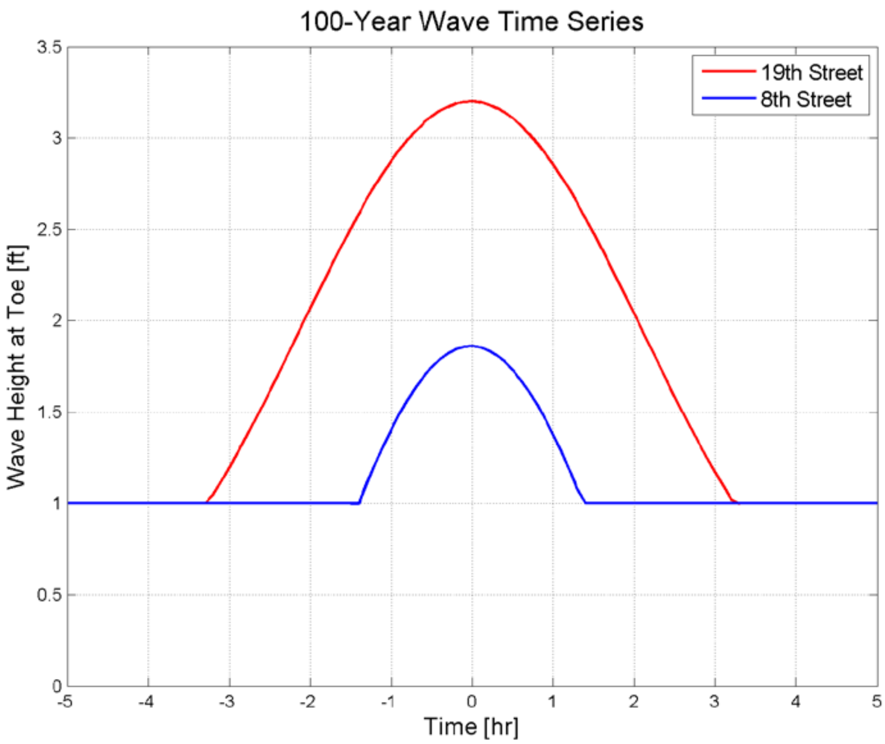

Figure 5-4 Wave height time series for the design event (100-year event with the 90th percentile SLR projection in the 2050s) at the flood protection alignment near East 8th and East 19th Streets.

Wave heights are set to a minimum of 1 ft as water depths become shallower, allowing the presence of locally generated wind waves associated with storm events to be replicated. The wave period was also varied over time in the same manner as the storm tide series, with the minimum value set at 1.56 seconds. This minimum wave period was calculated based on the minimum wave height using Goda's formula for wind generated waves (Goda 2010).

5.5 500-Year Waves

Even though the flood protection alignment is designed for the 100-year event, the 500-year event was analyzed as well to determine flood protection system response to a lower probability event. To determine the 500-year wave conditions, the 189 historical and synthetic storms simulated in the FEMA PFIRM coastal study were reviewed. Wave conditions from simulated storms with a peak storm tide in proximity to the 500-year FEMA storm tide were extracted for use in this analysis.

Shoreline values of the 500-year wave height were 3.9 ft with a wave period of 3.5 seconds. This is on average a 24 percent increase in wave height at the shoreline relative to the 100-year wave. When considering the effects of both increased wave height and increased water level associated with the 500-year event, increases in wave height reaching the toe of the levee/wall were 90 percent on average, ranging from 18 percent to 252 percent along the alignment.

The 500-year wave conditions were then used in all WHAFIS and wave overtopping analyses associated with the 500-year event. Time series for the 500-year wave height were generated in the same manner as the 100-year wave height and wave period time series.

6. Wave Overtopping Analysis

EurOtop (Pullen et al. 2007) and USACE Coastal Engineering Manual (CEM) (USACE 2002) methodologies were employed for the wave overtopping analysis along the flood protection alignment. For levees, the EurOtop implementation of van der Meer's overtopping method was used. For vertical walls, CEM's Franco overtopping formula was used, which is the basis of the vertical wall formula in EurOtop. Figures 6-1 and 6-2 schematically show the wave overtopping process and some of the parameters needed for estimating overtopping rates at a vertical wall and at a levee, respectively.

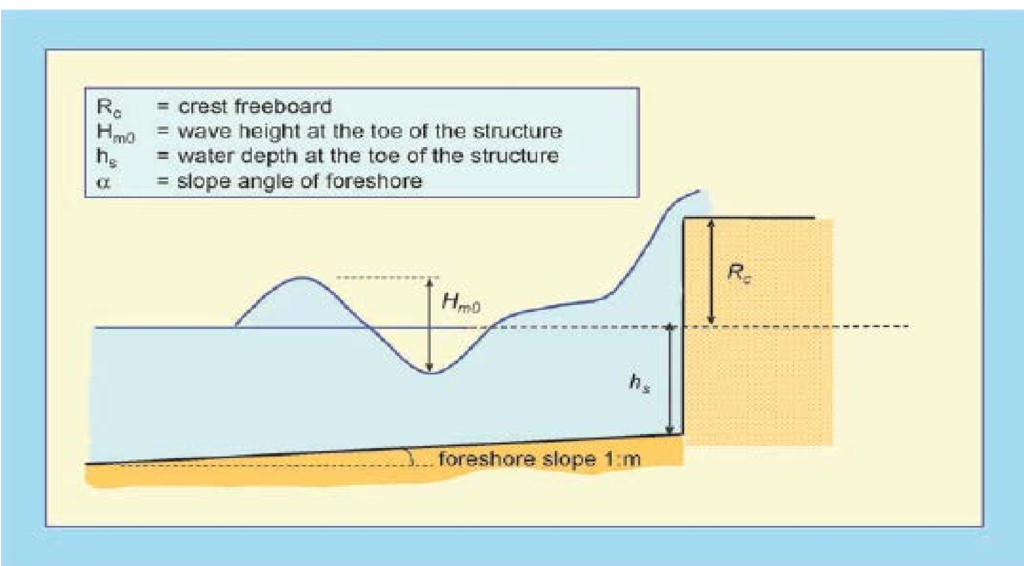

Figure 6-1 Schematic of wave overtopping at a vertical wall.

Source: Pullen et al. 2007.

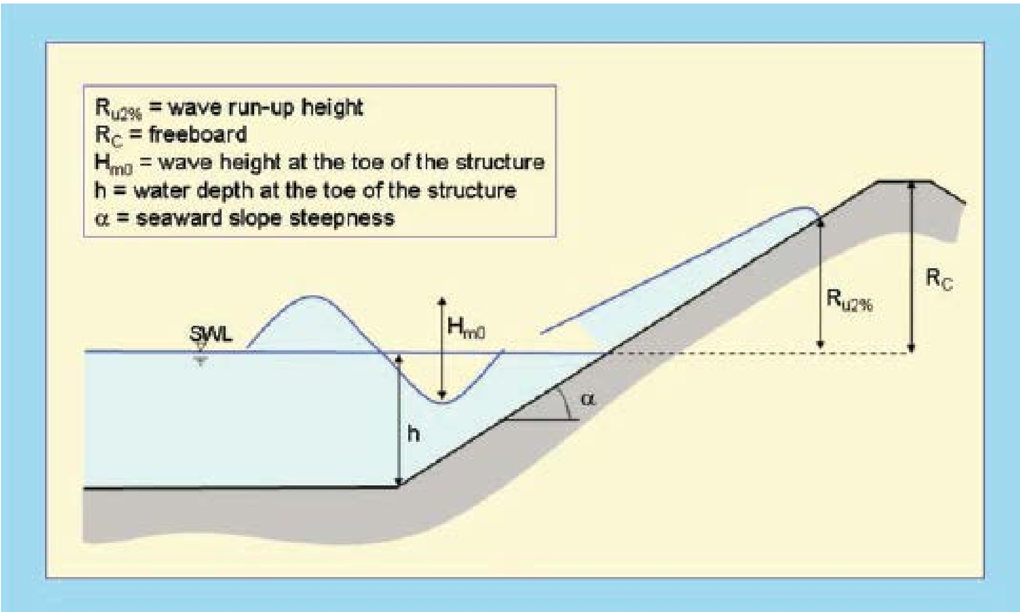

Figure 6-2 Schematic of wave overtopping at a levee.

Source: Pullen et al. 2007.

6.1 Wave Overtopping Scenarios

Freeboard and water depth parameters at the toe of the structure are related to the storm tide and associated SLR projection discussed in Sections 3 and 4. Methodologies to estimate wave height and wave period parameters at the toe of the levee/wall were discussed in Section 5.

Table 6-1 shows the various wave overtopping events and scenarios that were estimated. For each of the events and scenarios, the following conditions were analyzed:

- Crest elevations 15.0 ft to 16.5 ft in 0.5 ft increments
- Levee or vertical wall geometry (see Section 2)
- Levee slopes of 3:1 and 4:1

Table 6-1 Summary of wave overtopping analysis scenarios. Current-day sea levels are based on the middle year of the 1983-2001 National Tidal Datum Epoch.

Event	SLR Projections						
		2050s (Percentiles)			2100s (Percentiles)		
100-Year	Current Day	10th	50th	90th	10th	50th	90th
500-Year	Current Day	10th	50th	90th	10th	50th	90th

EurOtop's wave overtopping estimates are based on regression equations fit to an international database of experimentally observed and field-observed wave overtopping events. Deterministic and probabilistic estimates are available, with deterministic estimates including one standard deviation above the mean regression of the data. As a result, the deterministic estimate used in this analysis has the effect of including a factor of safety in design.

For the levee portions of the alignment, wave overtopping can be reduced based on the following factors, which were reviewed as potentially applicable to the current analysis:

- Wave approach angle
- Surface cover of the flood side slope
- Berms at the flood side toe

For this analysis, it was assumed that waves are perpendicular to the levee alignment; therefore, no reduction factor for wave angle was applied. The alignment of the levee portions of the flood protection system is generally aligned parallel to the shoreline.

Additionally, a surface roughness reduction factor was not applied, even though the levee is expected to be covered in grass. EurOtop presents two conflicting recommendations for grass cover reductions: one recommendation is to apply a reduction factor as a function of incoming wave height for waves less than 2.5 ft in height, yet another recommendation is to apply no reduction factor for grass cover. Because of uncertainties related to grass type and potential scale effects in the experimental data, the recommendation to apply no surface cover reduction for grass was chosen.

Berm reductions were also considered because of the proposed shared pathway at the flood side toe of the levee, as was shown on Figure 2-2. The elevation of the shared pathway is at 10 ft NAVD88, or 3.5 ft below the design event storm tide of 13.5 ft

NAVD88 (11 ft storm tide plus 2.5 ft associated with the 90th percentile SLR projection in the 2050s). Because the shared pathway is submerged by less than two times the incoming wave heights, which range from 1.8 ft to 2.2 ft, the shared pathway can act like a berm and reduce wave energy. Therefore, a berm reduction factor was applied and resulted in the reduction of maximum overtopping rates by 10 percent to 20 percent.

6.2 Critical Wave Overtopping Rates

The use of wave overtopping rates in the determination of minimum required crest elevations is based on the appropriate definition of the critical overtopping rate for the existing and proposed site conditions. The critical overtopping rates are based on EurOtop guidance, summarized here for conditions appropriate to the flood protection alignment (Pullen et al. 2007):

- **Vehicles** – Driving at low speeds and cars not immersed, overtopping at low, pulsating depths – **critical rate 0.1 to 0.5 cubic ft per second per ft (cfs/ft).**
- **Levee Damage** – No damage to crest and rear face of grass-covered levee on clay layer – **critical rate 0.01 to 0.1 cfs/ft;** no damage if crest and rear slope are well protected – **critical rate 0.5 to 2.1 cfs/ft**.
- **Wall Damage** – Damage to paved or armored section behind wall – **critical rate 2.1 cfs/ft**.

Although the range for levees is shown as 0.01 to 0.1 cfs/ft, review of recent literature on wave overtopping erosion experiments reveals that grass-covered levees on a clay layer exposed to overtopping rates of 0.1 cfs/ft for 6 hours show minor erosion of the grass from the clay layer. The erosion is more pronounced in weak spots, but the clay layer is not eroded and the root layer of the grass helps to further stabilize the clay layer (Steendam et al. 2012).

Weak spots in the grass layer are found near vehicle tire tracks, animal burrowing holes, bare spots in the grass cover, trees, and transitions from natural to manmade materials (i.e., grass to asphalt or concrete). The experiments reveal that minor damage will occur at weak spots, but that rates above 0.1 cfs/ft would be required to initiate substantial erosion damage at these weak spots (Steendam et al. 2012). Even with a robust levee maintenance plan or a design that minimizes to the extent possible any weak spots, the built levee will contain at least some weak spots. However, the recent experimental data reveal that only minor erosion will occur at these weak spots when exposed to 0.1 cfs/ft. Therefore, a rate of 0.1 cfs/ft is used as a design rate for this analysis because it provides protection to transportation and prevents damage to both levees and walls.

6.3 Minimum Required Crest Elevations for the Design Event

Maximum overtopping rates along the flood protection alignment for incremental crest elevations for the design event are shown in Table 6-2. Levee sections show rates for both 3:1 and 4:1 slopes. For each transect along the alignment, the rates at the minimum required crest elevation based on the design overtopping rate of 0.1 cfs/ft are highlighted in gray with bold text.

Table 6-2 Maximum overtopping rates along the flood protection alignment for the design event (100-year event with the 90th percentile SLR projection in the 2050s). Transects with levee geometry are for 3:1 and 4:1 slopes. Rates at minimum required crest elevations bold with gray highlight.

FEMA PFIRM Transect #	Approximate Location	Maximum Overtopping Rates (cfs/ft)			
		15.0 ft Crest	15.5 ft Crest	16.0 ft Crest	16.5 ft Crest
25	East 22nd Street/East River	**0.1**	0.02	0.01	0.002
26	East 21st Street/East River	**0.1**	0.02	0.01	0.002
27	East 19th Street/East River	0.5	0.3	0.2	**0.1**
28	East 18th Street/East River	0.5	0.3	0.2	**0.1**
29	East 17th Street/East River	0.5	0.3	0.2	**0.1**
30	East 14th Street/East River	0.6	0.3	0.2	**0.1**
31	East 12th Street/East River	**0.1**	0.03	0.01	0.01
32	East 10th Street/East River	0.1	**0.1**	0.02	0.01
33	East 8th Street/East River 3:1	0.3	0.2	**0.1**	0.03
	East 8th Street/East River 4:1	0.1	**0.1**	0.02	0.01
34	East 6th Street/East River 3:1	0.3	0.2	**0.1**	0.03
	East 6th Street/East River 4:1	0.1	**0.1**	0.02	0.01
35	East 2nd Street/East River	**0.1**	0.03	0.01	0.004
36	Rivington Street/East River 3:1	0.3	0.2	**0.1**	0.03
	Rivington Street/East River 4:1	0.1	**0.1**	0.02	0.01
37	Delancey Street/East River	**0.1**	0.03	0.01	0.01
38	Grand Street/East River 3:1	0.3	0.1	**0.1**	0.02

FEMA PFIRM Transect #	Approximate Location	Maximum Overtopping Rates (cfs/ft)			
		15.0 ft Crest	**15.5 ft Crest**	**16.0 ft Crest**	**16.5 ft Crest**
	Grand Street/East River 4:1	0.1	**0.03**	0.01	0.004
39	Jackson - Cherry Street/East River	**0.03**	0.01	0.003	0.001
40	Gouverneur - Jackson Street/ East River	**0.003**	0.0004	0.0001	0.00001

The minimum required crest elevations can be summarized as follows:

- **15.0 ft** at the inland offset vertical wall **between East 23rd and East 21st Streets**
- **16.5 ft** at the vertical wall at the shoreline **between East 19th and East 14th Streets**
- **15.0 ft** at the inland offset vertical walls **from East 12th Street to the south end of the alignment,** except at **East 10th Street**, where **15.5 ft** is required.
- Levee alignments at **16 ft for 3:1 slopes**, **15.5 ft for 4:1 slopes**.

These minimum required crest elevations are based on the design wave overtopping rate. Requirements based on FEMA recognition of the flood protection system will be compared in Section 7. Note that between East 19th and East 14th Streets, minimum required crest elevations are higher relative to other vertical wall segments because the alignment of the wall is directly at the shoreline, resulting in more direct wave exposure.

For the levee alignments, a 0.5 ft elevation reduction can be achieved by employing a 4:1 sloped levee instead of a 3:1 levee. However, in East River Park, space is at a premium and may limit the use of milder slopes in final levee designs.

Also, a 10 percent to 20 percent berm reduction factor was applied in the levee overtopping analysis due to the presence of the roadway berm at the flood side toe of the levee. If the conceptual design changes to a scenario where the berm cannot be included in the design or needs to be built to an elevation lower than 10 ft, the minimum required crest elevations at the 3:1 and 4:1 levees shown in Table 6-2 do not need to increase. This conclusion is based on additional wave overtopping simulations that compared minimum required crest elevations with and without the berm reduction factor.

6.4 500-Year Event Exposure

If the flood protection system is designed to the crest elevations specified in Table 6-2, the flood protection system could still be exposed to a lower probability event such as the 500-year event. Table 6-3 shows the maximum overtopping rates along the alignment during the 500-year event with no SLR. The minimum required crest elevations for the design event from Table 6-2 are highlighted in gray with bold number.

As previously stated, the wall sections of the alignment, if well protected, can be exposed up to 2.1 cfs/ft without damage. However, the critical upper limit overtopping rates for transportation behind well-protected vertical walls is 0.5 cfs/ft. Nearly all vertical wall sections designed to the design event crest elevation are still below 0.5 cfs/ft during a 500-year event with no SLR. The East 22nd and East 21st Street vertical wall segments, because they are closer to the shoreline than other locations, do exceed the 0.5 cfs/ft limit during the 500-year event. This exceeds the transportation overtopping rate criteria; therefore, vehicle access limitations in the East 22nd and East 21st Street locations would be required during a 500-year event with no SLR.

Table 6-3 Maximum overtopping rates along the flood protection alignment for the 500-year event with no SLR. Transects with levee geometry are for 3:1 and 4:1 slopes. Rates at minimum required crest elevations for the design event in bold with gray highlight.

FEMA PFIRM Transect #	Approximate Location	Maximum Overtopping Rates (cfs/ft)			
		15.0 ft Crest	15.5 ft Crest	16.0 ft Crest	16.5 ft Crest
25	East 22nd Street/East River	**0.7**	0.4	0.2	0.1
26	East 21st Street/East River	**0.7**	0.4	0.2	0.1
27	East 19th Street/East River	1.4	0.9	0.6	**0.4**
28	East 18th Street/East River	1.4	0.9	0.6	**0.4**
29	East 17th Street/East River	1.4	0.9	0.6	**0.4**
30	East 14th Street/East River	1.4	0.9	0.6	**0.4**
31	East 12th Street/East River	**0.3**	0.1	0.1	0.02
32	East 10th Street/East River	0.3	**0.2**	0.1	0.03
33	East 8th Street/East River 3:1	0.7	0.3	**0.2**	0.1
	East 8th Street/East River 4:1	0.4	**0.1**	0.04	0.02

FEMA PFIRM Transect #	Approximate Location	Maximum Overtopping Rates (cfs/ft)			
		15.0 ft Crest	15.5 ft Crest	16.0 ft Crest	16.5 ft Crest
34	East 6th Street/East River 3:1	0.8	0.4	**0.2**	0.1
	East 6th Street/East River 4:1	0.4	**0.2**	0.1	0.02
35	East 2nd Street/East River	**0.2**	0.1	0.04	0.02
36	Rivington Street/East River 3:1	0.9	0.5	**0.2**	0.1
	Rivington Street/East River 4:1	0.5	**0.2**	0.1	0.03
37	Delancey Street/East River	**0.3**	0.1	0.04	0.02
38	Grand Street/East River 3:1	0.7	0.3	**0.2**	0.1
	Grand Street/East River 4:1	0.4	**0.1**	0.05	0.02
39	Jackson - Cherry Street/East River	**0.2**	0.1	0.02	0.01
40	Gouverneur - Jackson Street/ East River	**0.1**	0.01	0.004	0.001

The upper limit for overtopping rate at unprotected grass-covered levees is 0.1 cfs/ft. As shown in Table 6-3, if the 3:1 slope levee segments at East 8th Street, East 6th Street, Rivington Street, and Grand Street are designed to a 16.0 ft crest elevation, upper limit overtopping rate of 0.1 cfs/ft would be exceeded during a 500-year event with no SLR. Similarly, if the 4:1 slope levee segments are designed to a 15.5 ft crest elevation, critical overtopping rates would be exceeded during a 500-year event. Two potential options are available to avoid levee damage during a 500-year event with no SLR:

- Design 3:1 levee sections to a 16.5 ft crest elevation and 4:1 levee sections to a 16.0 ft crest elevation to limit damage during a 500-year event and provide an additional factor of safety for the design event.

- Maintain 3:1 levee sections at a 16.0 ft crest elevation and 4:1 levee crest elevations at 15.5 ft, yet provide crest, back side slope, and toe armoring of the levee to withstand the 500-year event with no SLR and provide an additional factor of safety for the design event. This armoring method would actually allow the levee crest elevations to be reduced by 0.5 ft for the design event as well, considering that the low end of the critical overtopping rate increases to 0.5 cfs/ft.

The effects of SLR combining with a 500-year event were also considered. For the 500-year event with the 50th percentile SLR projection in the 2050s, maximum wave overtopping rates were compared with the range of allowable rates to determine minimum required crest elevations as shown in Table 6-4.

Table 6-4 Minimum required crest elevations along the flood protection alignment for the 500-year event with the 50th percentile SLR projection in the 2050s. Multiple maximum overtopping rates are compared to the design event elevations. Transects with levee geometry are for 3:1 and 4:1 slopes.

FEMA PFIRM Transect #	Approximate Location	Design Event	500-Year Event With 50th Percentile SLR Projection in the 2050s		
		0.1 cfs/ft	0.1 cfs/ft	0.5 cfs/ft	2.1 cfs/ft
25	East 22nd Street/East River	15.0 ft	18.5 ft	17.0 ft	16.0 ft
26	East 21st Street/East River	15.0 ft	18.5 ft	17.0 ft	16.0 ft
27	East 19th Street/East River	16.5 ft	19.5 ft	17.5 ft	16.0 ft
28	East 18th Street/East River	16.5 ft	19.5 ft	17.5 ft	16.0 ft
29	East 17th Street/East River	16.5 ft	19.5 ft	17.5 ft	16.0 ft
30	East 14th Street/East River	16.5 ft	19.5 ft	17.5 ft	16.0 ft
31	East 12th Street/East River	15.0 ft	18.0 ft	16.0 ft	15.0 ft
32	East 10th Street/East River	15.5 ft	18.0 ft	16.5 ft	15.0 ft
33	East 8th Street/East River 3:1	16.0 ft	18.5 ft	17.0 ft	NA
	East 8th Street/East River 4:1	15.5 ft	17.5 ft	16.5 ft	NA
34	East 6th Street/East River 3:1	16.0 ft	18.5 ft	17.0 ft	NA
	East 6th Street/East River 4:1	15.5 ft	17.5 ft	16.5 ft	NA
35	East 2nd Street/East River	15.0 ft	18.0 ft	16.0 ft	15.0 ft
36	Rivington Street/East River 3:1	16.0 ft	18.5 ft	17.5 ft	NA
	Rivington Street/East River 4:1	15.5 ft	18.0 ft	17.0 ft	NA
37	Delancey Street/East River	15.0 ft	18.0 ft	16.0 ft	15.0 ft
38	Grand Street/East River 3:1	16.0 ft	18.5 ft	17.0 ft	NA
	Grand Street/East River 4:1	15.5 ft	17.5 ft	16.5 ft	NA
39	Jackson - Cherry Street/East River	15.0 ft	17.5 ft	16.0 ft	15.0 ft
40	Gouverneur - Jackson Street/ East River	15.0 ft	16.5 ft	15.5 ft	15.0 ft

To maintain overtopping rates below the design rate of 0.1 cfs/ft at vertical wall locations, minimum required crest elevations increase by 1.5 ft to 3.5 ft relative to the design event, with the larger increases needed north of East 14th street where alignments are closer to the shoreline. If the upper limit overtopping rate for transportation behind the wall is used, i.e. 0.5 cfs/ft, vertical wall minimum required crest elevations increase by 0.5 ft to 2.0 ft relative to the design event.

If the upper limit overtopping rate for well protected vertical walls of 2.1 cfs/ft is used, minimum required crest elevations do not need to increase above the design event elevations, except at East 21st and East 22nd, where they would need to increase by 1.0 ft. This scenario would require that flood side and back side toes are well protected, walls are structurally designed to withstand the upper rates of wave overtopping, and that transportation access is restricted along the flood protection system during the peak of the storm event. Additionally, further evaluation would be required to assure that if any buildings behind the vertical wall are exposed to the overtopping rates, that they can withstand the exposure.

To maintain levee overtopping rates below the design rate of 0.1 cfs/ft, minimum required crest elevations increase by 2.0 ft to 2.5 ft relative to the design event. If the levees are well protected allowing them to be safely exposed to a rate of 0.5 cfs/ft, minimum required crest elevations only need to increase by 1.0 ft to 1.5 ft. Additional SLR conditions associated with the 500-year event will be discussed in Section 6.5.

6.5 Adaptations for the 2100s SLR

The adaptability of the flood protection system to the 2100s 50th percentile SLR projection for the 100-year event was also considered. Maximum overtopping rates for crest elevations ranging from 15.0 ft to 16.5 ft are shown in Table 6-5, with minimum required crest elevations for the design event from Table 6-2 shown in bold with gray highlight. At levee sections, the design rate of 0.1 cfs/ft is exceeded, but the upper limit critical overtopping rate of 0.5 cfs/ft is not. This indicates, as was shown for the 500-year event with no SLR, if the levee sections are well protected or if the design elevation is increased by 0.5 ft, design overtopping rates are not exceeded.

Similarly, the vertical wall sections do not exceed the upper limit overtopping rate of 0.5 cfs/ft for transportation behind the wall and do not exceed the upper limit overtopping rate of 2.1 cfs/ft for well-protected walls. In fact, for a majority of the locations, increasing the crest elevations by 0.5 ft maintains overtopping rates below the design rate of 0.1 cfs/ft.

Table 6-5 Maximum overtopping rates along the flood protection alignment for the 100-year event with the 50th percentile SLR projection in the 2100s. Transects with levee geometry are for 3:1 and 4:1 slopes. Rates at minimum required crest elevations for the design event in bold with gray highlight.

FEMA PFIRM Transect #	Approximate Location	Maximum Overtopping Rates (cfs/ft)			
		15.0 ft Crest	15.5 ft Crest	16.0 ft Crest	16.5 ft Crest
25	East 22nd Street/East River	**0.2**	0.1	0.03	0.01
26	East 21st Street/East River	**0.2**	0.1	0.03	0.01
27	East 19th Street/East River	0.9	0.5	0.3	**0.2**
28	East 18th Street/East River	0.9	0.5	0.3	**0.2**
29	East 17th Street/East River	0.8	0.4	0.2	**0.1**
30	East 14th Street/East River	0.9	0.5	0.3	**0.2**
31	East 12th Street/East River	**0.3**	0.1	0.05	0.02
32	East 10th Street/East River	0.3	**0.2**	0.1	0.03
33	East 8th Street/East River 3:1	0.7	0.3	**0.2**	0.1
	East 8th Street/East River 4:1	0.4	**0.1**	0.1	0.02
34	East 6th Street/East River 3:1	0.8	0.4	**0.2**	0.1
	East 6th Street/East River 4:1	0.4	**0.2**	0.1	0.02
35	East 2nd Street/East River	**0.2**	0.1	0.04	0.02
36	Rivington Street/East River 3:1	0.8	0.4	**0.2**	0.1
	Rivington Street/East River 4:1	0.4	**0.2**	0.1	0.02
37	Delancey Street/East River	**0.2**	0.1	0.04	0.02
38	Grand Street/East River 3:1	0.6	0.3	**0.1**	0.1
	Grand Street/East River 4:1	0.3	**0.1**	0.04	0.01
39	Jackson - Cherry Street/East River	**0.1**	0.04	0.02	0.01
40	Gouverneur - Jackson Street/ East River	**0.01**	0.002	0.0003	0.0001

The 90th percentile SLR projection in the 2100s was also analyzed and results showed that vertical wall minimum required crest elevations increase by 2.5 ft to 4.0 ft relative to the design event. For levees, minimum required crest elevations increase by 3.0 ft to 3.5 ft to maintain the maximum overtopping rate below 0.5 cfs/ft. These increases assume that levees and walls are well protected for critical rates up to 0.5 cfs/ft. To maintain maximum overtopping rates below the design rate of 0.1 cfs/ft, the required increases in crest elevation are 3.0 ft to 5.5 ft at vertical walls and 4.0 to 4.5 ft at levees.

On Figure 6-3, the effects of SLR and variability in the recurrence storm events on the maximum overtopping rate exposure are shown. At East 22nd Street, the rates are calculated for a vertical wall designed to the minimum required elevation of 15.0 ft. Similarly, East 8th Street rates are calculated for a 3:1 levee designed to the minimum required crest elevation of 16.0 ft.

As shown on Figure 6-3, for protected levee sections of the alignment, the minimum required crest elevations based on the design event are expected to provide protection for the 500-year event with no SLR. However, 500-year events with SLR or 100-year events with more than 50th percentile SLR projections in the 2100s result in critical overtopping rates exceeding the 0.5 cfs/ft upper limit for protected levees.

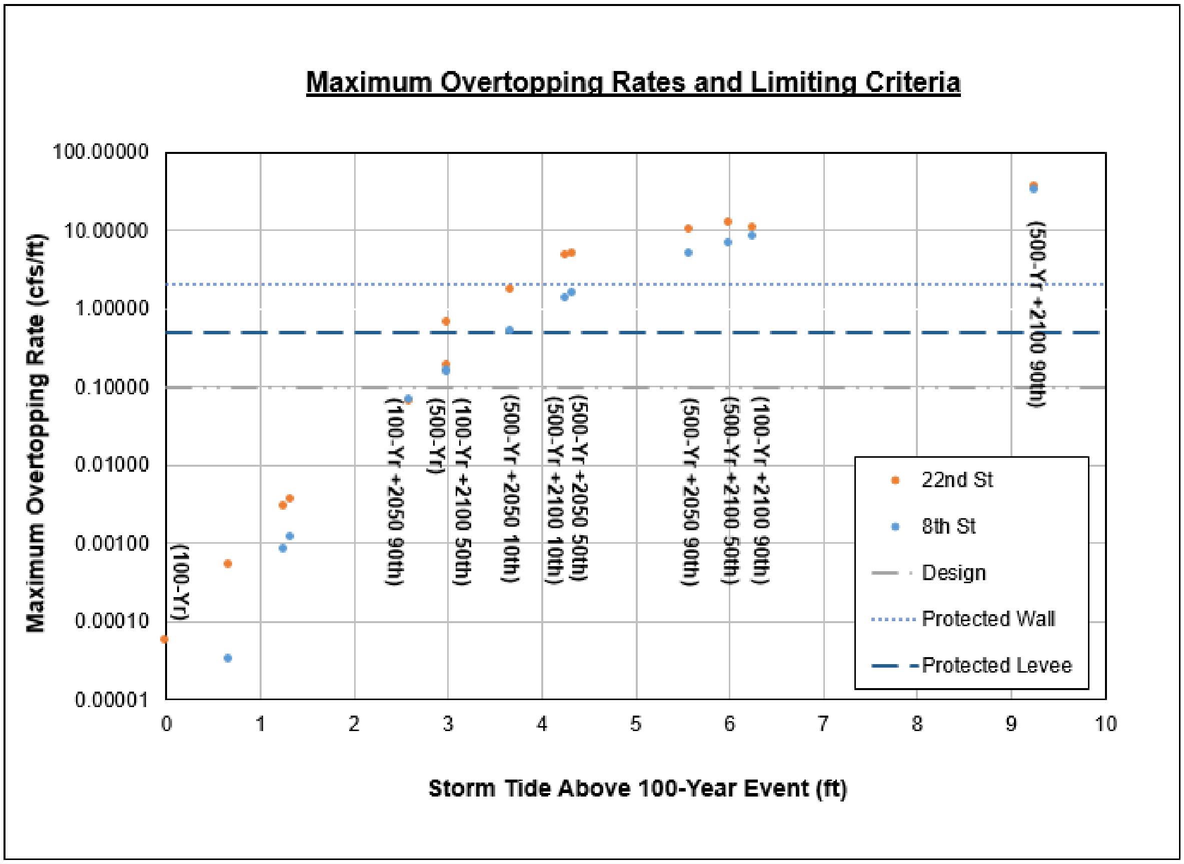

Figure 6-3 Maximum overtopping rates at East 22nd and East 8th Streets for all wave overtopping scenarios. Limiting criteria for design, walls, and levees are shown for comparison.

For the protected wall sections of the alignment, the minimum required elevations based on the design event are expected to provide protection even for the 500-year event with up to the 50th percentile SLR projection in the 2050s. However, 500-year events with SLR projections greater than the 90th percentile in the 2050s or 100-year events with SLR projections in the 2100s greater than the 50th percentile result in the exceedance of the upper limit critical overtopping rate of 2.1 cfs/ft.

6.6 Wave Overtopping Volumes

The maximum wave overtopping rates inform flood protection elevation requirements, while the total overtopping volume is used to inform the expected depth of flooding and interior drainage needs for flood mitigation on the back side of the flood protection system. The total overtopping volumes were integrated over the storm duration and over the full length of the flood protection alignment. The crest elevations for this analysis were the minimum required for the design event as shown in Table 6-2.

The wave overtopping volumes were estimated for the design event and compared with the 500-year event with no SLR and the 100-year event with the 50th percentile SLR projection in the 2100s. Table 6-6 summarizes the total wave overtopping volumes, 19 million gallons during the design event, increasing to 35 million gallons during the 500-year event with no SLR, and 44 million gallons for the 100-year event with the 50th percentile SLR projection in the 2100s.

Table 6-6 Total wave overtopping volumes along the full alignment for the design event (100-year event with the 90th percentile SLR projection in the 2050s) compared to the 500-year event with no SLR and the 100-year event with the 50th percentile SLR projection in the 2100s.

	100-Year 90th Percentile SLR Projection in the 2050s	500-Year No SLR	100-Year 50th Percentile SLR Projection in the 2100s
Total Wave Overtopping Volume (Million Gallons)	19	35	44

6.7 Potential Changes to Alignment or Alignment Geometry

The alignment and alignment geometry presented in Section 2 could change pending further coordination with project stakeholders beyond the timeline of this analysis. Two potential changes that have been identified and could be implemented in the final conceptual design are:

- Vertical wall sections may change to a levee design at East 22nd and East 21st Streets.
- Vertical walls may be shifted from the shoreline to the western edge of FDR Drive between East 19th and East 14th Streets.

The effects that these changes to the alignment or its geometry could have on the minimum required crest elevations were evaluated. Analysis included updated inland propagation of waves to alignments shifted farther inland and the recalculation of wave overtopping rates, including any geometry changes, for the design event. Tables 6-7 and 6-8 demonstrate required changes in crest elevations using the design overtopping rate criteria of 0.1 cfs/ft and analyzing a range of crest elevations from 15.0 ft to 16.5 ft in 0.5 ft increments.

Table 6-7 Minimum required crest elevations for the design event at East 22nd and East 21st Streets for multiple geometries. The geometry change is from a vertical wall to a levee (3:1 or 4:1).

FEMA PFIRM Transect #	Approximate Location	Vertical Wall	3:1 Levee	4:1 Levee
25	East 22nd Street/East River	15.0 ft	15.5 ft	15.0 ft
26	East 21st Street/East River	15.0 ft	15.5 ft	15.0 ft

Table 6-8 Minimum required crest elevations for the design event from East 19th Street to East 14th Street for multiple alignments. The alignment change is an inland shift of the vertical wall from the shoreline to the west edge of FDR Drive.

FEMA PFIRM Transect #	Approximate Location	Vertical Wall at Shoreline	Vertical Wall at West Edge of FDR
27	East 19th Street/East River	16.5 ft	15.0 ft
28	East 18th Street/East River	16.5 ft	15.0 ft
29	East 17th Street/East River	16.5 ft	15.0 ft
30	East 14th Street/East River	16.5 ft	15.0 ft

For the change of geometry from a vertical wall to a levee between East 22nd and East 21st Streets, the same minimum required crest elevation of 15.0 ft is needed if a 4:1 levee is employed. If the levee geometry is constrained to a slope of 3:1, the minimum required crest elevation increases to 15.5 ft.

Between East 19th and East 14th Streets, the effect of shifting the vertical wall inland from the shoreline to the west edge of FDR Drive results in a decrease of the required minimum crest elevation from 16.5 to 15.0 ft. This reduction is the result of the dissipation of wave energy due to the inland topography. This analysis shows that if significant alterations to the alignment of the flood protection system or its geometry are made, wave transformation and wave overtopping analyses must be updated accordingly.

7. FEMA Requirements for Flood Protection Systems

In order for FEMA to recognize a flood protection system and amend the FIRMs, the flood protection system must meet federal design requirements. FEMA regulations related to the design freeboard requirements of levee systems are summarized below as taken from CFR Title 44 §65.10 (b) (iii-iv):

For coastal levees, the freeboard must be established at 1 ft above the height of the 1-percent-annual-chance wave or the maximum wave runup (whichever is greater) associated with the 1-percent-annual-chance stillwater surge elevation at the site.

Exceptions to the minimum coastal freeboard requirements above may be approved if the following criteria are met:

- ***Appropriate engineering analyses demonstrating adequate protection with a lesser freeboard must be submitted.***
- ***The material presented must evaluate the uncertainty in the estimated base flood loading conditions. Particular emphasis must be placed on the effects of wave attack and overtopping on the stability of the levee.***

Under no circumstances will a freeboard of less than 2 ft above the 1-percent-annual-chance stillwater surge elevation be accepted.

To determine the FEMA elevation requirements along the length of the flood protection system, the requirements listed above were compared. The FEMA language above can be summarized into the following:

- 100-Year Storm Tide + 100-Year Wave Profile + 1 ft
  or
- 100-Year Storm Tide + Maximum Wave Runup + 1 ft

Because the wave height varies along the flood protection system and because the wave runup will vary depending upon the type of structure (vertical wall or levee), estimates of elevation requirements at each transect along the alignment were made.

The 1-percent-annual-chance (100-year) wave was calculated using significant wave heights at the toe of the flood protection alignment and converting them to FEMA's controlling wave height using the 1.6 and 0.7 multipliers discussed in Section 5 (FEMA 2007).

The maximum wave runup associated with the 1-percent-annual-chance (100-year) stillwater elevation (storm tide) was calculated using the EurOtop methodology at levees (Pullen et al. 2007) and either the Shore Protection Manual (FEMA 2011) or the Goda (2010) formula at vertical walls.

The Shore Protection Manual method was developed from data at vertical walls with toe slopes of 1:10 and 1:30, whereas the Goda method was developed from data of standing waves at a vertical wall. Therefore, the Goda estimates were used when the vertical wall was within one deepwater wave length of the shoreline, and the Shore Protection Manual estimates were used when the vertical wall was offset inland. The elevation requirements based on overtopping rate for the design event are presented in Section 6.

Table 7-1 summarizes the minimum required crest elevations along the length of the flood protection system. The wave overtopping-based elevations exceed the FEMA-based elevations for all locations with levees and for most vertical wall locations that are offset inland. However, for the vertical wall locations at or close to the water's edge, the FEMA maximum wave runup criteria is the control for elevation requirements.

At locations where the FEMA-based minimum required crest elevation exceeds the wave overtopping-based minimum required crest elevations (East 22nd Street to East 12th Street and Delancey Street), an exemption to FEMA requirements would need to be pursued as outlined in the regulatory language above. Armoring of the toe segments and design of the wall components to withstand the design wave overtopping rates and wave loads will be provided to justify the FEMA exemption for these portions of the flood protection alignment.

Table 7-1 Minimum required crest elevations along the flood protection alignment for the FEMA-based criteria compared to the wave overtopping-based criteria. Transects with levee geometries are shown for 3:1 and 4:1 slopes.

FEMA PFIRM Transect #	Approximate Location	Minimum Required Crest Elevation (ft)		
		FEMA 1%-Annual Chance Wave Criteria	FEMA Maximum Wave Runup Criteria (3:1/4:1 - Levee)	Wave Overtopping-Based Criteria
25	East 22nd Street/East River	13.6	16.2	15.0
26	East 21st Street/East River	13.1	16.2	15.0
27	East 19th Street/East River	15.5	16.9	16.5
28	East 18th Street/East River	15.5	17.0	16.5
29	East 17th Street/East River	15.4	17.2	16.5
30	East 14th Street/East River	15.6	17.0	16.5
31	East 12th Street/East River	12.9	16.2	15.0
32	East 10th Street/East River	13.1	14.8	15.5
33	East 8th Street/East River 3:1/4:1	12.9	14.0/13.6	16.0
34	East 6th Street/East River 3:1/4:1	13.0	14.0/13.6	16.0
35	East 2nd Street/East River	12.8	14.1	15.0
36	Rivington Street/East River 3:1/4:1	13.2	14.0/13.5	16.0
37	Delancey Street/East River	12.9	15.4	15.0
38	Grand Street/East River 3:1/4:1	12.8	13.9/13.5	16.0
39	Jackson - Cherry Street/East River	12.5	13.4	15.0
40	Gouverneur - Jackson Street/ East River	13.0	14.0	15.0

Obtaining FEMA recognition of the flood protection system will be based on current day SLR and FEMA FIRMs. However, considering the effects of SLR to understand adaptation requirements needed to obtain FEMA recognition in the future are important as well.

The minimum acceptability for FEMA recognition as highlighted in the regulatory language above is 2.0 ft above the 100-year storm tide, or 13.0 ft NAVD88 based on current-day sea levels and current FEMA PFIRM storm tide elevations. Assuming no change to the storm tide levels associated with future FIRMs and considering a

50th percentile SLR projection, the absolute minimum required crest elevation for FEMA recognition increases to 14.3 ft in the 2050s and 16 ft in the 2100s. For the design event, i.e., the 90th percentile SLR projection in the 2050s, the absolute minimum required crest elevation increases to 15.5 ft. These increases in absolute minimum elevation for FEMA recognition demonstrate the need to consider SLR adaptation strategies in the initial design to assure that the flood protection system continues to be recognized by FEMA in the future.

Again, this simple demonstration does not consider the impact of potential future storm events and how they could further increase the FEMA storm tide elevations on future FIRMs. Any storm tide increases would then need to be added to the SLR effects.

8. No-Impact Analysis

Analysis was performed to determine the effects of the flood protection alignment on 100-year storm tide elevations at properties adjacent to and outside of the flood protection alignment. A representative 100-year storm event was simulated using the ADCIRC+SWAN models with and without the flood protection alignment in place. An additional set of simulations were performed that considered the 100-year storm tide event with the 90th percentile SLR projection in the 2050s to determine any potential impacts in the future. The following section discusses the selection of the representative100-year storm event, the setup of the ADCIRC+SWAN simulations, and the demonstration of no-impact in the simulation results.

8.1 Selection of a Representative 100-Year Storm Tide Event

To determine a representative 100-year storm tide event, all of the tropical and extratropical storms used by FEMA to develop the 100-year storm tide shown on the PFIRMs were reviewed. Storm events that produce peak storm tide close to the 100-year storm tide were identified. Figure 8-1 shows all of the FEMA PFIRM storms, potential representative events, and the parametric fit hydrographs (previously shown on Figure 3-1).

It can be seen on Figure 8-1 that two tropical storm events, NJB_0003_010 and NJB_0007_006 result in peak storm tide slightly higher than the 100-year storm tide. Because the width of NJB_0007_006 matches the 100-year parametric fit hydrograph better than the NJB_0003_010 event, the NJB_0007_006 storm has been selected as a representative 100-year storm tide event.

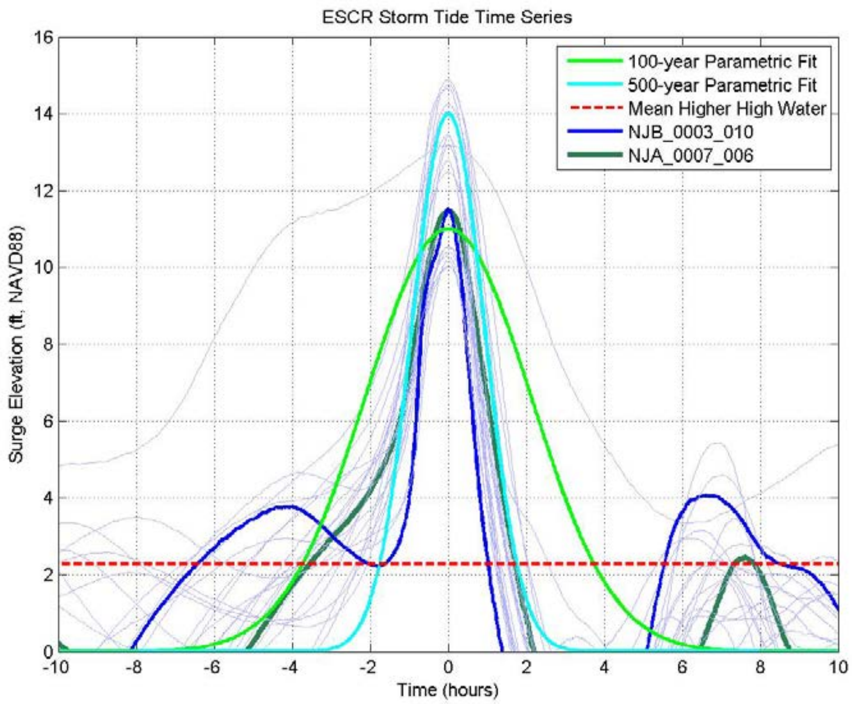

Figure 8-1 Storm tide time series for all FEMA PFIRM events, the parametric fit time series, and two potential representative 100-year storm tide events.

This event is a synthetic tropical storm, developed by FEMA, based on tropical storm parameters (storm track, storm size, storm speed, and atmospheric pressure distributions) that are statistically representative for the NYC region (FEMA, 2014a).

8.2 ADCIRC+SWAN Simulation Setup

The representative storm tide event was simulated using the same models used by FEMA during the analysis performed to generate the PFIRMs, i.e. coupled ADCIRC (Luettich et. al., 2004) and SWAN (SWAN, 2006). These models simulate hydrodynamics and waves respectively and are run in tandem so that hydrodynamic outputs can be used in calculating wave conditions and vice versa. The simulation of the representative 100-year storm tide event was performed using the model input files provided by FEMA, which are further described in the FEMA PFIRM documentation (FEMA, 2014b).

The bathymetric finite element grid, or mesh, used for the ADCIRC + SWAN simulations was based on the mesh used in the FEMA PFIRM study, but was enhanced with more resolution, especially in the areas adjacent to the flood protection alignment. Figure 8-2 shows raw images of the mesh, demonstrating that close to the flood protection alignment (shown by the solid black outline) the enhanced mesh size ranges from roughly 75 to 250 ft compared to roughly 200 to 600 ft in the FEMA PFIRM mesh. These same mesh enhancements were used in the simulations conducted for the NYC Mayor's Office following Hurricane Sandy (City of New York Mayor's Office, 2013).

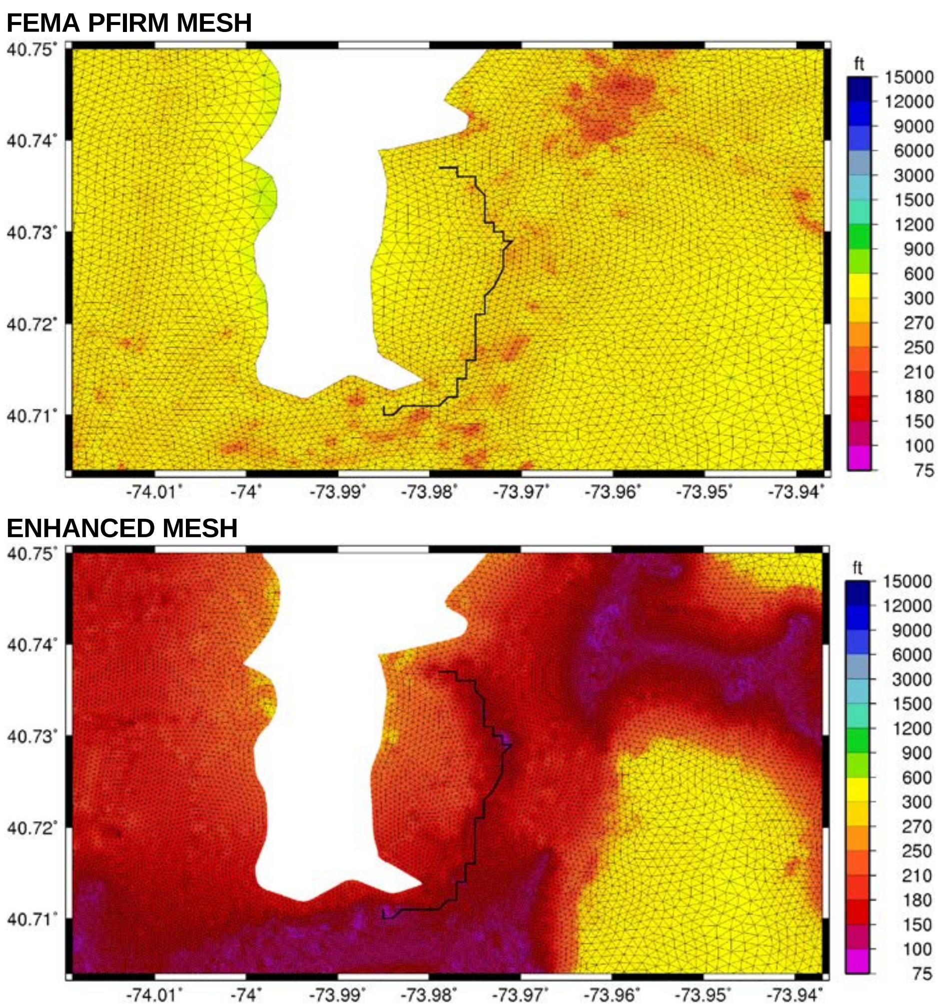

Figure 8-2 Raw comparison of FEMA PFIRM mesh and the enhanced mesh used in this analysis. Mesh size shown in ft. Alignment shown by solid black line.

The flood protection alignment, previously shown in Figure 2-1, was added to the enhanced mesh by raising the nodes in the model along the flood protection alignment to the elevation of the flood protection alignment. The alignment elevations were those developed for the design event as shown in Table 6.2. At levee sections of the alignment, the 3:1 slope elevations were used.

8.3 Water Level Comparisons

Simulations of the representative 100-year storm tide event were performed for the following four scenarios:

- With and Without the Flood Protection Alignment - Current-Day Sea Levels
- With and Without the Flood Protection Alignment - 90th Percentile SLR Projection in the 2050s

Figure 8-3 shows the peak storm tide elevations with and without the flood protection alignment for the current-day sea level. Comparison of the two simulations clearly shows that the flood protection alignment is providing the expected flood protection. Additionally, Figure 8-4 shows the peak storm tide elevations with and without the flood protection alignment for the scenario with the 90th percentile SLR projection in the 2050s. Again, the flood protection alignment clearly provides the expected flood protection.

Comparisons of the peak storm tide with and without the flood protection alignment for current-day sea levels and 2050s SLR projections are shown on Figure 8-5. Outside the flood protection alignment, no increase or decrease of peak storm tide elevations are caused by the flood protection alignment, with or without SLR.

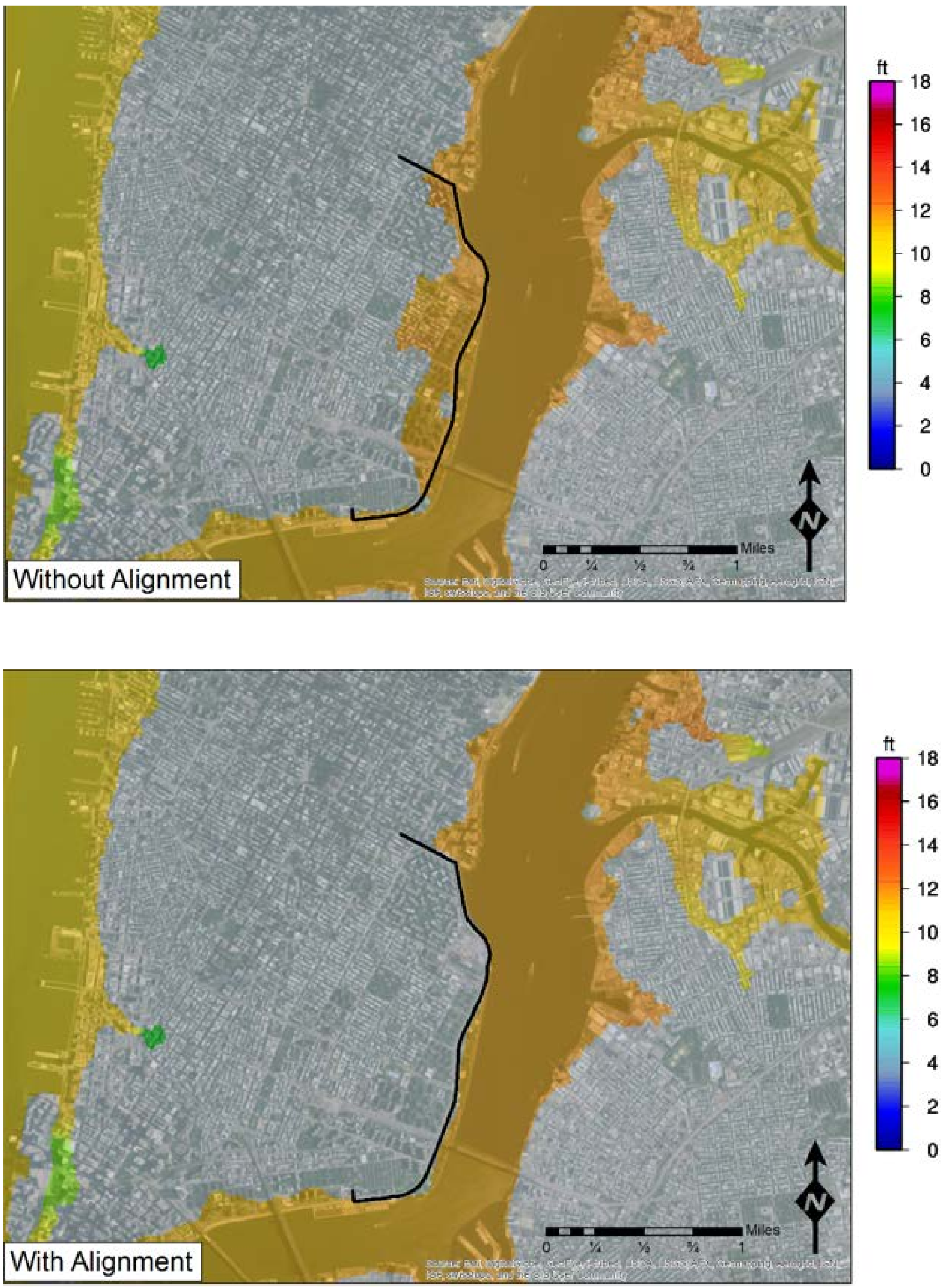

Figure 8-3 **100-year peak storm tide elevations with and without the flood protection alignment, current-day sea levels. Flood protection alignment in black outline.**

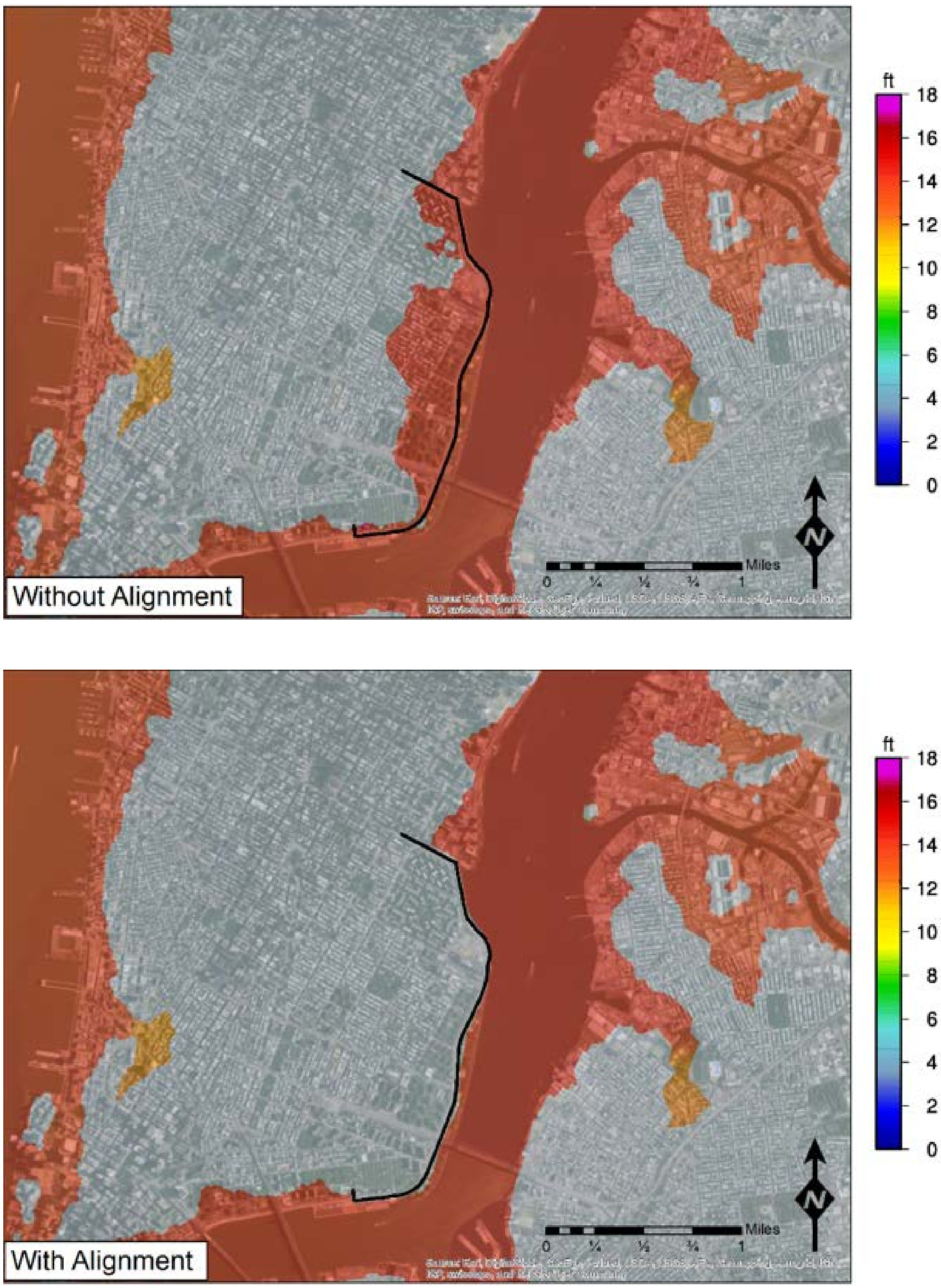

Figure 8-4 100-year peak storm tide elevations with and without the flood protection alignment, 90th percentile SLR projection in the 2050s. Flood protection alignment in black outline.

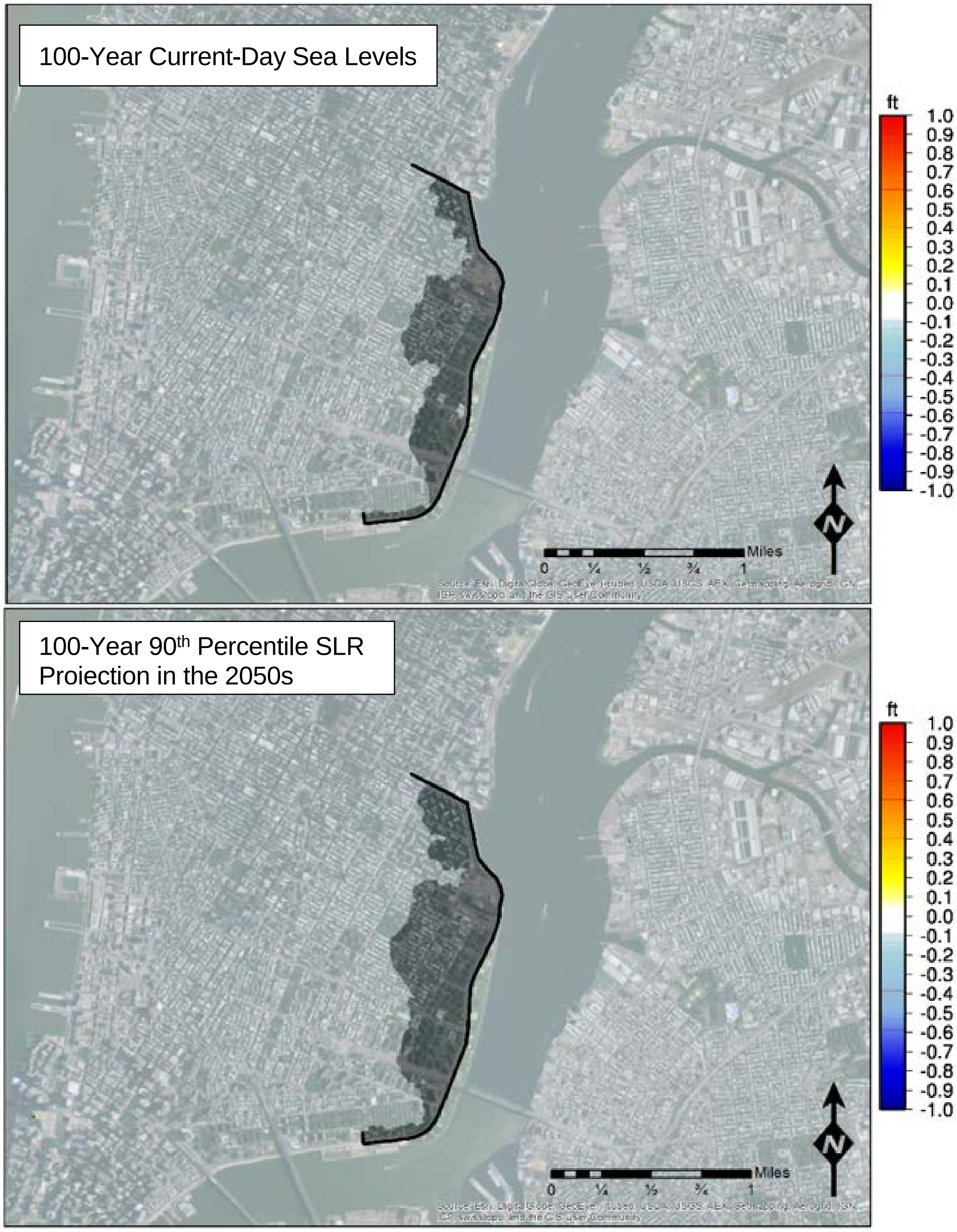

Figure 8-5 **100-year peak storm tide comparisons with and without the flood protection alignment for both current-day sea levels and the 90th percentile SLR projection in the 2050s. Flood protection alignment in black outline and protected floodplain in gray shadow.**

Figure 8-6 shows the storm tide comparisons over the event duration at the shoreline of the East River and East 14th Street. The time series shows no noticeable changes in storm tide by the flood protection alignment in current-day sea levels or the 90th percentile SLR projection in the 2050s. Note that some differences with and without alignment appear after the peak of the storm, but these differences occur below mean higher high water. The floodplain near the alignment begins to flood at roughly elevation 8 ft NAVD88, so is not flooded below mean higher high water. Therefore, the storm tide differences below mean higher high water cannot be attributed to the flood protection alignment.

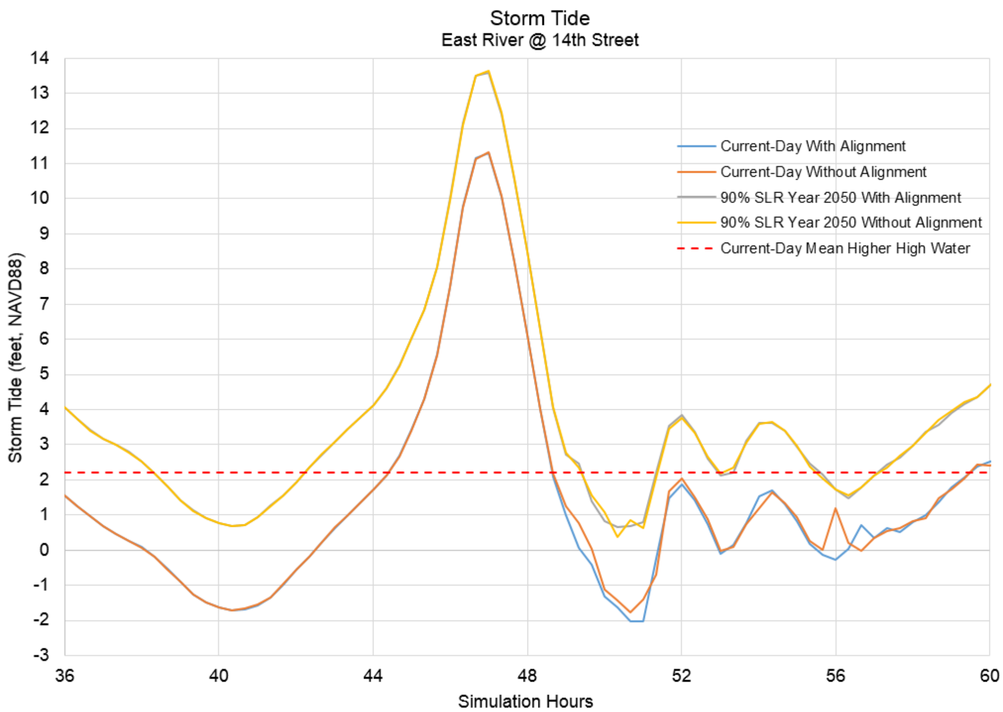

Figure 8-6 **Storm tide time series comparisons with and without the flood protection alignment for the 100-year event with current-day sea levels and the 90th percentile SLR projection in the 2050s.**

To verify the no-impact results associated with peak storm tides, the displaced floodplain volume for each scenario was calculated by multiplying the area of the protected floodplain by the average depth of water in the unprotected floodplain. The displaced floodplain volumes are then:

100-Year with Current-Day Sea Levels	500 acre-ft
100-Year with the 90th Percentile SLR Projection in the 2050s	1200 acre-ft

These displaced volumes are compared to the total volume conveyed through the East River by multiplying the surface area of the East River at mean sea level, 2,562 acres (Jay et.al. 1975) by a storm tide of 10 ft, for simplicity. The total storm tide volume conveyed through the East River is then 25,562 acre-ft. The volume displaced by the flood protection alignment is then roughly 2% and 5% of the total storm tide volume with and without SLR respectively. These small percentages demonstrate that the displaced volume is small compared to the total storm tide volume in the East River, confirming the simulation results.

9. Summary of Flood Protection Elevation Requirements

This report has presented storm tide and wave conditions for the proposed flood protection alignment from East 23rd Street to Montgomery Street along the East River. Storm tide levels, wave conditions, and SLR projections were quantified as inputs for wave overtopping analysis along the full alignment, considering both vertical wall and levee sections. A design overtopping rate of 0.1 cfs/ft to protect transportation and the flood protection alignment itself (walls and levees) was then used to inform minimum required crest elevations, as summarized in Table 9-1.

Table 9-1 Summary of minimum required crest elevations for the design event based on an overtopping design rate of 0.1 cfs/ft for the alignment/geometry shown on Figure 2-1.

FEMA PFIRM Transect #	Approximate Location	Geometry	Minimum Required Crest Elevation (ft)
25	East 22nd Street/East River	Vertical wall	15.0
26	East 21st Street/East River	Vertical wall	15.0
27	East 19th Street/East River	Vertical wall	16.5
28	East 18th Street/East River	Vertical wall	16.5
29	East 17th Street/East River	Vertical wall	16.5
30	East 14th Street/East River	Vertical wall	16.5
31	East 12th Street/East River	Vertical wall	15.0
32	East 10th Street/East River	Vertical wall	15.5

FEMA PFIRM Transect #	Approximate Location	Geometry	Minimum Required Crest Elevation (ft)
33	East 8th Street/East River	3:1 Levee	16.0
	East 8th Street/East River	4:1 Levee	15.5
34	East 6th Street/East River	3:1 Levee	16.0
	East 6th Street/East River	4:1 Levee	15.5
35	East 2nd Street/East River	Vertical wall	15.0
36	Rivington Street/East River	3:1 Levee	16.0
	Rivington Street/East River	4:1 Levee	15.5
37	Delancey Street/East River	Vertical wall	15.0
38	Grand Street/East River	3:1 Levee	16.0
	Grand Street/East River	4:1 Levee	15.5
39	Jackson - Cherry Street/East River	Vertical wall	15.0
40	Gouverneur - Jackson Street/ East River	Vertical wall	15.0

Recent experimental data on grass-covered levee erosion due to wave overtopping were discussed showing that weak spots in grass-covered levees are likely to result in minor erosion of the grass cover if exposed to the overtopping design rate of 0.1 cfs/ft. However, the erosion is not substantial enough to result in significant damage to the grass-covered levee, meeting the design and resiliency goals of the study.

Weak spots occur at bare spots in the grass, animal burrowing holes, vehicle tire tracks, trees, and transitions from grass to asphalt/concrete surfaces. To ensure optimal performance of the levee sections, the design team should make efforts to minimize weak spots as the conceptual and final designs progress. Also, a maintenance plan should be developed to prevent weak spots to the extent possible after construction, especially if a major storm event is forecasted. These measures will help reduce minor erosion that may occur during a design wave overtopping event and best prepare the grass-covered levee sections to handle wave overtopping.

Beyond the design event, adaptation requirements for the 500-year event (with no SLR and with the 50th percentile SLR projection in the 2050s) and the 100-year event with SLR projections in the 2100s were demonstrated, as summarized in Table 9-2.

The adaptations that are required at vertical walls and at levees to maintain maximum overtopping rates below 0.1 cfs/ft or 0.5 cfs/ft are shown. These adaptations are relative to the design event minimum required crest elevations shown in Table 9-1.

Table 9-2 Summary of adaptation requirements for the 500-year event (with no SLR and with the 50th percentile SLR projection in the 2050s) and for the 100-year event with SLR projections in the 2100s.

Geometry	500-Year With No SLR[1]	500-Year With 50th Percentile SLR Projection in the 2050s[2]	100-Year With 50th Percentile SLR Projection in the 2100s[3]	100-Year With 90th Percentile SLR Projection in the 2100s
To Maintain Overtopping Rates Below 0.1 cfs/ft (*Design Rate*)				
Vertical Wall	Increase Crest 0.5 ft to 1.5 ft	Increase Crest 1.5 ft to 3.5 ft	Increase Crest 0.5 ft	Increase Crest 3.0 ft to 5.5 ft
Levee	Increase Crest 0.5 ft	Increase Crest 2.0 ft to 2.5 ft	Increase Crest 0.5 ft	Increase Crest 4.0 ft to 4.5 ft
To Maintain Overtopping Rates Below 0.5 cfs/ft (*Levees Protected and Upper Limit For Transportation Safety*)				
Vertical Wall	Restrict Vehicle Access at East 21st/ East 22nd Streets	Increase Crest 0.5 ft to 2.0 ft	No Change	Increase Crest 2.5 ft to 4 ft
Levee	No Change	Increase Crest 1 ft to 1.5 ft	No Change	Increase Crest 3 ft to 3.5 ft

[1]See Table 6-3.
[2]See Table 6-4.
[3]See Table 6-5.

Ranges in the crest elevation adaptations shown in Table 9-2 are the result of variation in wave climate along the flood protection system, with more exposed locations requiring the higher range of adaptation.

It is clear that only minor adaptations are needed for the 500-year event with no SLR and the 100-year event with the 50th percentile SLR projection in the 2100s. However, more significant adaptations are required to maintain overtopping rates below these levels for the 500-year event with the 50th percentile SLR projection in the 2050s and the 100-year event with the 90th percentile SLR projection in the 2100s.

In addition to adaptations required for extreme SLR and low probability events, alignment and geometry changes were analyzed at locations that could change after the timeframe of this analysis. Results showed that if the vertical wall at the shoreline between East 19th and East 14th Streets is moved inland to the western edge of FDR Drive, minimum required crest elevations can be reduced from 16.5 ft to 15.0 ft.

Additionally, a change in geometry between East 22nd and East 21st Streets from a vertical wall to a levee was shown to require an increase in the minimum crest elevation from 15.0 ft to 15.5 ft for a 3:1 levee, but no change was required if a 4:1 levee can be implemented. These results clearly demonstrate that significant changes to alignment or alignment geometry require re-analysis of wave transformation and wave overtopping and that the minimum required crest elevations presented in this report are specific to the alignment and geometry shown on Figure 2-1.

To understand if the wave overtopping-based minimum required crest elevations also satisfy FEMA-based minimum required crest elevations, the federal regulations were reviewed CFR Title 44 §65.10 (b) (iii-iv). Comparisons were presented in Table 7-1 showing that the wave overtopping-based crest elevations exceeded FEMA-based crest elevations at all levee sections and at most vertical wall sections. The vertical wall segments from East 22nd Street to East 12th Street and at Delancey Street resulted in FEMA-based crest elevations being higher than the wave overtopping-based crest elevations.

The locations where FEMA-based crest elevations exceed wave overtopping-based crest elevations are where vertical walls are close to the shoreline. At these locations, future efforts will need to request an exemption from FEMA to allow crest elevations to be designed below the FEMA-based crest elevations.

The lower, wave overtopping-based, crest elevations pursued in the exemption allow for a cost savings and can help reduce impacts to the neighborhood site lines of the waterfront. Because these lower elevations are supported by a site-specific engineering analysis, the performance of the flood protection system at reducing the communities' flood risk has not been sacrificed. In fact, the site-specific engineering analysis provides a more detailed knowledge of the flood protection system and its expected performance when compared to the general FEMA-based crest elevations, which are not based on a detailed investigation of the site.

The absolute minimum elevation at which FEMA will recognize a flood protection system was presented at 13.0 ft, based on CFR Title 44 §65.10 (b) (iii-iv). A simple future projection of this elevation based on 50th percentile SLR projections showed that this minimum elevation increases to 14.3 ft in the 2050s and 16 ft in the 2100s. For the design event, with the 90th percentile SLR projection in the 2050s, this minimum elevation increases to 15.5 ft. At a minimum, adaptation strategies need to be developed to ensure that FEMA will continue to recognize the flood protection system in the future.

To verify that the proposed flood protection alignment does not impact the properties adjacent to and outside the flood protection alignment, a representative 100-year event was simulated using ADCIRC + SWAN with and without the flood protection alignment. For the 100-year event with no SLR and with the 90th percentile SLR projection in the 2050s, no increase (or decrease) of peak storm tide elevations were observed adjacent to and outside the flood protection alignment as was shown on Figure 8-5.

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