ARCADIS Design & Consultancy for natural and built assets

COASTAL HYDRAULICS REPORT

FINAL DESIGN

October 2019

EAST SIDE COASTAL RESILIENCY

Coastal Hydraulics Report

Final Design

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ACRONYMS AND ABBREVIATIONS

BFE	Base Flood Elevation
CEM	Coastal Engineering Manual
CFR	Code of Federal Regulations
CFS/FT	cubic feet per second per foot
DTL	Mean Diurnal Tide
ESCR	East Side Coastal Resiliency
FDR	Franklin Delano Roosevelt
FEMA	Federal Emergency Management Agency
FT	Feet
HUD	Housing and Urban Development
MTL	Mean Tide Level
MSL	Mean Sea Level
MHW	Mean High Water
MHHW	Mean Higher-High Water
MLW	Mean Low Water
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
MTL	Mean Low Tide
Lidar	Light detection and ranging
NAVD88	North American Vertical Datum of 1988
NYC	New York City
OT	Overtopping
PFIRM	Preliminary Flood Insurance Rate Maps
RBD	Rebuild by Design
SLR	Sea level rise
SWEL	Still water elevation
USACE	U.S. Army Corps of Engineers
WHAFIS	Wave Height Analysis for Flood Insurance Studies
VAMC	Veterans Administration Medical Center

EXECUTIVE SUMMARY

As part of the Rebuild-by-Design HUD grant award requirements, the ESCR flood protection system must mitigate the risk associated with the Federal Emergency Management Agency (FEMA) Preliminary Flood Insurance Rate Map (PFIRM) 100-year storm event and address potential impacts of climate change over the design life of the project and beyond. The project design includes measures to address the potential effects of future sea level rise based on values established by the New York City Panel on Climate Change (NPCC). During the evaluation of potential sea level rise (SLR) over time, the 2050s 90th percentile SLR projection was selected as most appropriate for this project. This case also falls within the mid-range projection for the 50th percentile scenario in the 2100s. In addition to SLR and the minimum mitigation requirements of the HUD grant, the City required the design team to include an adaptability and resiliency evaluation to help inform the selection of the system's minimum design elevation.

Updated alignment and project features during the progression from conceptual to final design necessitated the re-evaluation of the coastal hydraulic model. This updated hydraulic model also provides necessary wave loads for the design, as well as updated predicted system overtopping rates.

The following is a high-level summary of the storm mitigation requirements and associated resiliency evaluation of the current design and alignment, which includes the elevation of East River Park and the extension of the flood protection system to the Veterans Administration Medical Center (VAMC) hospital floodwall along East 25th Street. Model results were evaluated to identify any potential flood threat increase of the current project on adjacent areas. Results were also used to update predicted overtopping rates and confirm the future adaptability of the flood protection features. The following is a summary of the minimum requirements to satisfy:

1. Initial FEMA Accreditation Required by the HUD Grant:

Mitigate the risk associated with a 100-year storm event the at the end of construction per FEMA guidelines (Code of Federal Regulations (CFR) Title 44 §65.10 (b) (iii-iv)) and including requirements for assessments of wave runup and freeboard.

2. Minimum Design Elevation for the Project's Future Design Case:

Mitigate the risk associated with a 100-year storm event with the 2050s 90th percentile SLR projection of 30 inches resulting in a still water elevation of +13.5 ft NAVD88). Note that this elevation does not include wave considerations or freeboard. Elevation requirements based on this criterion varied between +15.5 ft NAVD88 and +16.5 ft NAVD88.

3. Resiliency Assessment

As part of the City's commitment to providing a resilient design, the report assesses performance of the current design elevation under a 500-year storm event with the 2050s 50th and 90th percentile SLR projections. Design elevations between +15.5 ft NAVD88, +16.0 ft NAVD88 and +16.5 ft NAVD 88 were evaluated to assess performance for these scenarios with the result being that +16.5 ft NAVD88 was selected to prevent free flow of surge over walls. For this case, significant wave overtopping volumes could occur, but protection against catastrophic failure of the wall system has been designed for by setting the elevation at the projected 500-Year still water level.

Based on analysis of the design condition wave requirements as well as resiliency considerations, the current minimum flood protection system design height has been established at +16.5 ft NAVD88. This elevation satisfies the design criteria and provides additional resiliency when subjected to surge events higher than the design condition.

The following is a summary of additional considerations related to the design criteria:

1. Future Adaptability Requirement

As part of the future adaptability evaluation, the City team direction was to mitigate the risk associated with a 100-year storm event with the 2120s 50th percentile SLR projection. Foundations for floodwalls have been designed to allow for an additional minimum 2 feet of wall height (18.5 ft NAVD88) to be incorporated into the system as sea level rise progresses and is monitored over the next 100 years. For Areas within East River Park, the buried floodwall top of wall is set at +16.5 ft NAVD88 and ground elevations vary between +18.0 to +25.0 ft NAVD88. Future adaptability in the park can be achieved by a combination of the initial overbuild of +18.0 ft NAVD88 (with materials above the buried floodwall verified to be impervious in nature), additional elevation added within the park or park areas, elevation of the esplanade structure, addition of knee walls, addition of seat walls or other features which raise the overall grade. The current design has been analyzed for the 2120s condition and waves are shown to be limited by the park grades (+18.0 to +25 ft NAVD88) as well as the geometry of the esplanade deck and mass of the park.

2. Impact to Adjacent Areas

The updated hydraulic modeling evaluated the new alignment and East River Park elevation’s impact on surrounding areas flooding potential during storm events. The model results are the same as the 2015 model in that there is no measurable change in storm surge heights in the adjacent areas based on construction of the project.

3. Sea Level Rise for Future Accreditation Periods

Based on the assumption that the system is operated and maintained in accordance with the design and maintenance plans and there are no changes to the FEMA base flood elevations as shown in the FEMA PFIRMS, the current design elevation will accommodate 30 inches of sea level rise and still have the ability to function as an accredited system. This extends the system’s future accreditation potential, at a minimum, into the 2050s and beyond.

4. Overtopping Rates for Input into Interior Drainage Model

The elevated East River Park design and current alignment were modeled to determine the impact to the predicted overtopping rates. As expected, there is a significant reduction in the model overtopping rates for the design condition of the 100-Year surge event plus 30 inches of sea level rise as compared to the 2015 project alignment and analysis results. The final project design and alignment model predicts both lower rates for the area outside the elevated areas of East River Park and no overtopping in the elevated portions of East River Park, thereby reducing volume that will have to be managed by the interior drainage system.

Overtopping estimates at the initial accreditation period (assumed to be the year 2025) with a 100-year surge shows practically no overtopping volumes.

Summary

Based on results of the revised analysis, the design elevation of +16.5 ft NAVD 88 exceeds the requirements for FEMA accreditation for current day conditions. Additionally, the design elevation meets elevation requirements for future accreditation until 30 inches of sea level rise is reached and has an additional 24 inches of adaptability for extending the elevation to +18.5 ft NAVD 88 built into the design of the floodwalls. In the current design, park elevations in some cases exceed +18.5 ft NAVD88 and/or can be adapted.

While not required for initial FEMA accreditation, the condition of a resilient design was set forth by the City as part of the project design requirements to minimize the potential for catastrophic failure of the structures and uncontrolled flow over the walls associated higher surge events. This resiliency check resulted in a design elevation slightly higher (0.5 to 1.0 feet) than the 100-Year future condition 2050s 90th percentile sea level rise wall height requirements in some areas of the project. This increase for the line of protection to the minimum design elevation of 16.5 ft NAVD88 provides a significant reduction in estimated overtopping rates where wall design heights have been modified and provides added stability to the floodwalls. The increase also reduces the future overtopping potential to manageable levels through the design life of the project in 2120s for the 100-year design condition.

Based on results of modeling using 2-Dimensional wave data and established FEMA baseline still water elevations, no changes to the minimum design elevation are recommended. While the current design lowers the potential for wave overtopping to contribute to interior ponding, it is still possible in the event that a storm that exceeds either the flood protection design event or interior drainage design storm, flooding could occur.

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 design of the “Big U” flood protection strategy for two segments: from Montgomery Street north to East 14th Street (Reaches A-J) and from East 14th Street north to East 25th Street (Reaches K-Q), referred to as the East Side Coastal Resiliency project and as “Project Area 1” and “Project Area 2” respectively. In October 2015, an initial coastal hydraulic study was completed to help establish design elevations for the alternative's analysis. As the project has progressed through the final design phase; decisions and design solutions have occurred that dictated the need to update the coastal hydraulic models.

This report builds upon the findings of the initial coastal hydraulic analysis and summarizes updated predicted surge and wave heights from various storm and sea level rise scenarios throughout the design life of the project. In addition, the new hydrodynamic modeling results provide updated wave forces necessary to complete the final design of the project. The storm tide levels, New York City Panel on Climate Change (NPCC) sea level rise (SLR) projections (Horton et al. 2015), and wave conditions have been quantified for the wave overtopping analysis. Wave overtopping rates are presented to inform the minimum required crest elevations (top of wall or flood protection feature 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 30 inches of sea level rise, representing the 90th percentile SLR projection in the 2050s. Wave overtopping rates are also presented for the 500-year event in the 2050s and for SLR projections in the 2120s to discuss resiliency and adaptability of the system in the future using system elevation, armoring or other resiliency improvements.

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).

Finally, the 500-year 2050s 90th percentile still water elevation is considered in order to evaluate resiliency of the floodwalls for an event exceeding the design case. This is equivalent to a 0.2% surge plus 30 inches of sea level rise. This condition limits the risk of a catastrophic failure from weir flow or full uninhibited flow over the walls. It is important to note that overtopping rates will exceed pavement damage thresholds and extensive damage to roads and other erosion may occur behind the walls as well as ponding of water from wave overtopping. This condition was selected by the design team as a reasonable case to analyze for resiliency. It exceeds both current day and future FEMA requirements and overtopping requirements for the 100-Year 2050s 90th percentile design storm and thus controls design for minimum system heights. There is an exception to this case for a small portion of the incorporated ConEdison floodwall, which exceeds current conditions in all cases, but is at a lower elevation than the project recommended future condition for 30 inches of sea level rise. This area will need to be monitored over time as sea level rise occurs to determine if retrofits are needed in the future as that system height is 1 foot lower than the adjacent walls at +15.5 NAVD88. Similarly, at the northern tie-in, the VAMC hospital wall is set 4 inches below the project design height of +16.5 NAVD88 at +16.2 NAVD88.

The report then concludes by presenting a no-impact analysis that evaluates effects to adjacent properties as a result of the flood protection system.

1.1 Background

As part of the initial conceptual design, a preliminary Coastal Hydraulics Report was completed in October 2015 which included a wave overtopping analysis based on a range of storm tide and wave conditions to quantify the wave overtopping rates for a baseline project configuration. This baseline project configuration consisted of a combination of floodwall and earthen features from Montgomery Street to East 25th Street. The overtopping rates were compared to tolerable rates in order to arrive at overtopping rates and wave loads based on preliminary design alignments and features as well as those features heights for system features such as elevated earthen sections and flood walls. 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.

Results of the initial 2015 model indicated that in some cases, the flood protection features needed to be raised from preliminary design elevations, which had been set as low as 15.5 ft NAVD88 and which ranged from 15.5 to 16.0 ft NAVD88. Overtopping volumes in some low-lying portions of the protected area allowed for moderate ponding in local roadways and a series of drainage mitigation features were researched including sub-surface storage, emergency pump stations and parallel conveyance improvements, which increased flows to the Manhattan Pump station during emergency events. Due to the financial and project budget implications as well as operation and maintenance cost of some of the preliminary design solutions, an elevation study was conducted by the team, where it was recommended that the minimum system height be raised to 16.5 ft NAVD88 to both allow for the previously mentioned resiliency benefits for higher than design storm tides, but also to reduce or eliminate the interior drainage ponding volumes which resulted from overtopping contributions.

To help frame the benefit of raising the system to the 16.5 ft NAVD88 elevation, Arcadis evaluated several factors including wall stability and potential surge and wave overtopping. Table 1 -1 provides a summary of an example of the resiliency assessment at E16th Street. Additionally, Table 1-1 characterizes the potential impacts to the flood protection system, as well as inundation behind the line of protection in the event of a 500-year storm event.

Table 1-1 Example Resiliency Assessment, East 16th St

Design Elevation	500-year Resiliency Assessment 2050s, 50th Percentile SLR			500-year Resiliency Assessment 2050s, 90th Percentile SLR		
NAVD88	Freeboard above Storm Tide + SLR (Ft)	Wall Stability OT Rates vs Damage Threshold	OT influence on potential Interior Ponding	Freeboard above Storm Tide + SLR (Feet)	Wall Stability OT Rates vs Damage Threshold	OT influence on Potential Interior Ponding
0.0		2.5x Greater	Extreme	-1.0	5x Greater	Extreme
16.0	0.5	Equal to or below	High	-0.5	3.5x Greater	Extreme
16.5	1.0	Below	High	0.0	2.5x Greater	Extreme

Red Numbers indicates Storm Tide Free Flow over wall.

1.2 Tide Range

The tide range in Table 1-2 has been adopted for the project design.

Table 1-2 Tide Ranges from Station: 8518750, The Battery, NY

Datum	Description	NAVD88 (feet)
MHHW	Mean Higher-High Water	2.28
MHW	Mean High Water	1.96
MTL	Mean Tide Level	-0.3
MSL	Mean Sea Level	-0.2
DTL	Mean Diurnal Tide Level	-0.24
MLW	Mean Low Water	-2.57
MLLW	Mean Lower-Low Water	-2.77

2 FLOOD PROTECTION ALIGNMENT

During the conceptual design phase, the baseline alternative alignment was evaluated as part of the initial coastal hydraulic modeling effort. This alignment was originally designed to follow the eastern edge of Franklin Delano Roosevelt (FDR) Drive for the portion of the project in most of East River Park. However, in 2018, this East River Park flood protection strategy was modified by the City, resulting in raising the elevation of the park starting just north of the Amphitheatre to the ConEdison Generating Facility at 15th Street (Reaches C through L). The ground elevation along the modified alignment will be raised and a cut-off wall buried below the surface of this park segment will now be the line of protection or “flood wall”. Furthermore, this buried flood wall will be located behind a water side bulkhead wall and esplanade structure that will form the east limit of the raised park. The esplanade structure and associated bulkhead wall will serve to dissipate wave energy and impede seepage during coastal storm events. The alignment south of the East River Park and north of the Con Edison Generating facility remains close to how it was originally planned during the concept design phase with some variations at the VA Medical Center and the crossing of Asser Levy Park. The previous alignment joined the VA Medical Center floodwall at 23rd Street, but now crosses the park at a mid-park location and the VA Medical Center floodwall at 25th Street is the project terminus.

The final design alignment is shown on Figure 2-1. The flood protection system has been updated to consist of several segments of above ground floodwalls, gates and buried sheet pile I-wall in the elevated portions of East River Park, or in the case of areas outside the park and/or adjacent to local roadways, reinforced concrete and pile founded I-walls or L-walls. The northern and southern ends of the alignment extend inland to higher elevations and “tie-back” the project to high ground on both ends. Closure structures are included at roadways and other pedestrian pathways. Sewer interceptors will be fitted with closure gates and sewer outfalls will continue to function with tide gates in order to isolate the protected area from both storm surge and sewer inflows from tidal surge. Sections 3 and 4 will describe the design water level conditions for both present day and with future SLR projections.

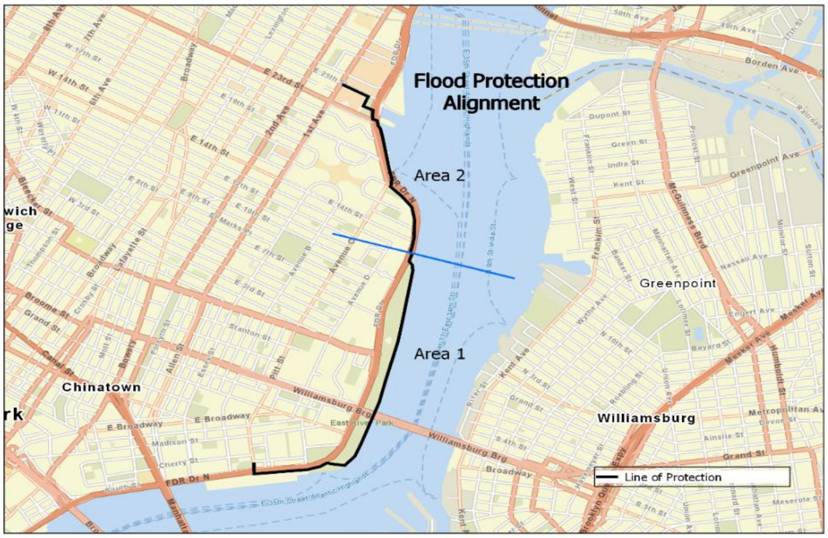

Figure 2-1 Final Design Flood protection alignment from Montgomery Street in the south to East 25th Street in the north.

The alignment shown in Figure 2-1 has been divided into geographic reaches, as shown in Figure 2-2 below. Each reach is approximately 900 feet in length. Several reaches have similar flood protection measures and are represented by the following typical sections. The primary flood protection measure implemented in Reaches A, B, portions of C in Project Area 1 and Reaches K, L, and M in Project Area 2 is an I-Wall. North of the Amphitheater in Reach C, and all of Reaches D, E, F, G, H, I and J are the areas of East River Park that will be raised and flood protection is provided by a buried sheet pile cutoff wall within the park and supplemented by additional structures at the waterfront. The northern Reaches N, O, and Q utilize an L-Wall design to provide the primary flood protection in these areas.

To facilitate the inclusion of the FEMA data, transect numbers generated in that study have been overlaid on the project reaches. Figure 2-2 provides a graphic depiction of the project reaches and the FEMA transects.

Figure 2-2 FEMA Transects along the project alignment, and project reaches.

Table 2-1 has been prepared to further assist in the cross comparison of the FEMA data to the physical location to project features.

Table 2-1 FEMA Transect Numbers, Approximate Location and Primary Flood Protection Measure.

FEMA PFIRM Transect #	Reach(es)	Approximate Location	Primary Flood Protection Measure
23	Q	Asser Levy/VAC	L-Wall
24	O-Q	East 23rd St/East River	L-Wall
25	O	East 22nd St/East River	L-Wall
26	N-O	East 20th St/East River	L-Wall
27	N-M	East 19th St/East River	L-Wall
28	M	East 18th St/East River	L-Wall/I-Wall
29	L-M	East 17th St/East River	I-Wall
30	K	East 14th St/East River/ConEdison	I-Wall
31-38	J through D	East 12th St/East River to Grand St/East River	Elevated Park with Buried Floodwall
40	B	Gouverneur - Jackson St/East River/Pier 42	I-Wall
41	A	Montgomery St	I-Wall

Typical sections have been generated to graphically depict the flood protection measure and physical features with a reach. Figure 2-3 represents a portion of the project that utilizes an I-Wall section for flood protection. Reaches that use I-Walls as the primary flood protection feature include Reaches A, B, C, I, J, K, L and M.

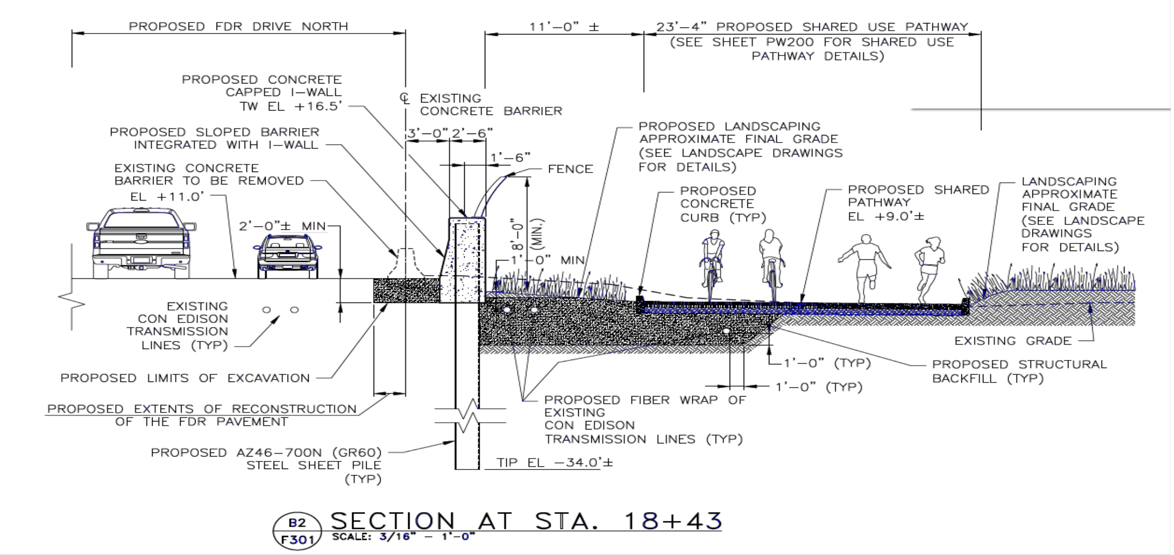

Figure 2-3 **Proposed cross-section at station 18+43 featuring an I-wall as flood protection measure.**

Reaches that are associated with the elevation of East River Park are Reaches D, E, F, G, H and I. Figure 2-4 is a representation of the flood protection features in these reaches.

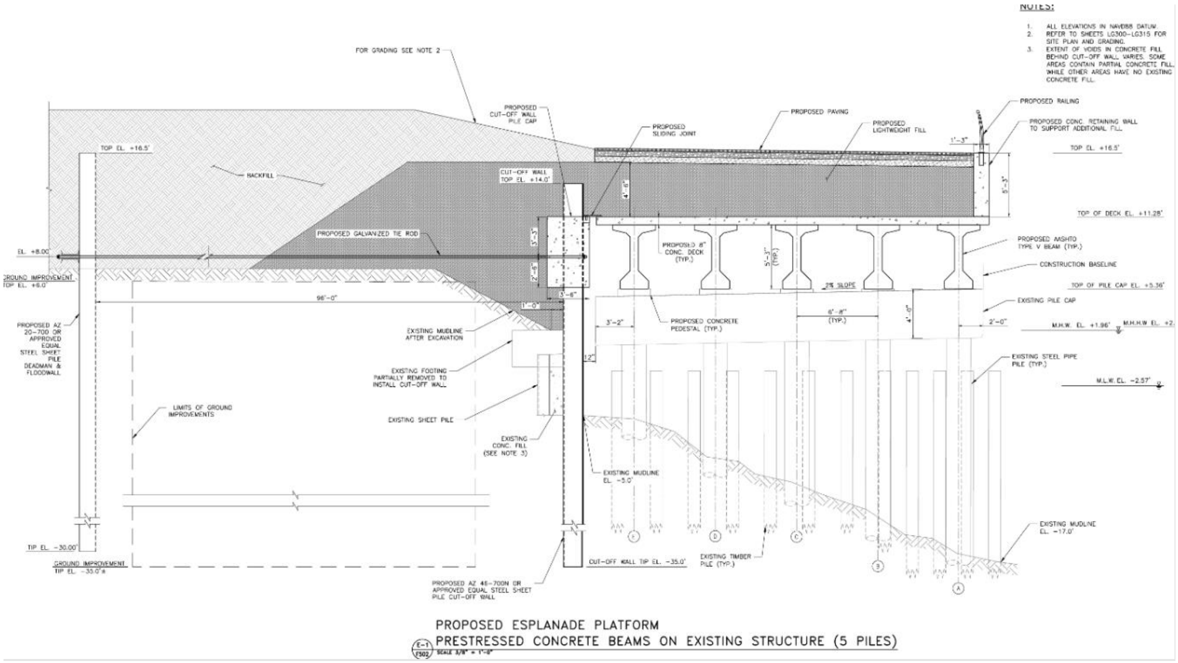

Figure 2-4 **Proposed cross-section at elevated park waterfront (buried floodwall not shown)**

The third primary flood protection measure is found in Reaches N, O and Q and is an L-Wall. Except for the foundation, the L-Wall is similar to an I-Wall. Figure 2.5 provides a graphical depiction of the L-Wall Section in Reach O.

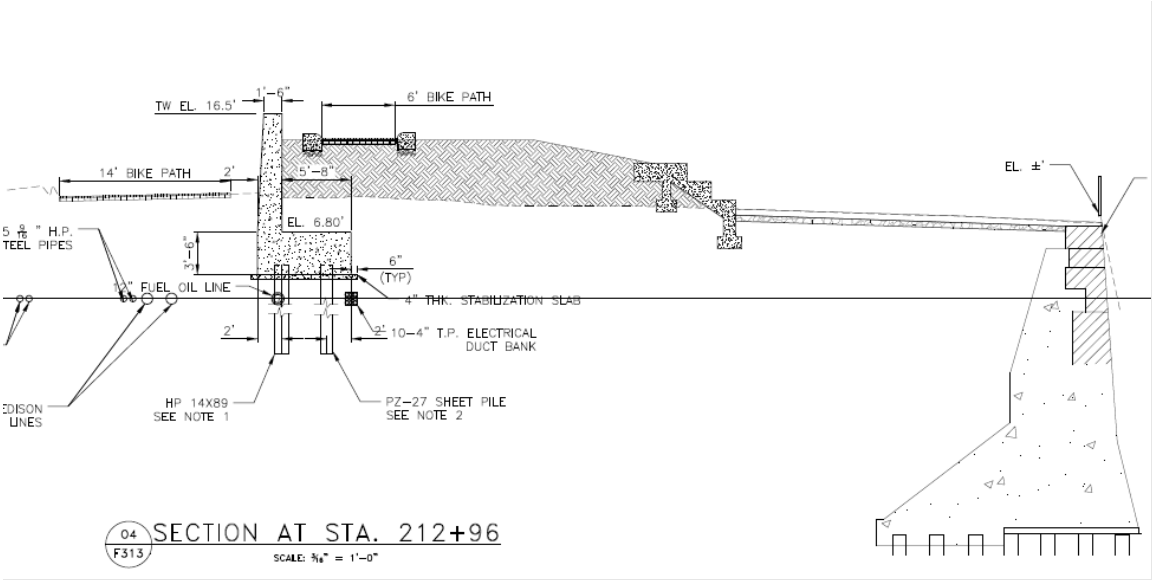

Figure 2-5 **Proposed cross-section at station 212+96 featuring a L-wall as flood protection measure.**

3 STORM TIDE CONDITIONS

3.1 100-Year Coastal Surge Elevation (Design Case)

The design coastal storm surge water elevation for this conceptual analysis is the FEMA 1-percent-annual–chance still water elevation (100-year storm tide) determined from the Preliminary Flood Insurance Rate Maps (PFIRMs) for NYC, released January 30, 2015. Although the PFIRMs are still preliminary and undergoing an update, the PFIRM still water elevations are higher (more conservative) than the those associated with FEMA's 2007 Effective FIRMs. NYC Local Law 96 currently requires the use of the higher of the two still water elevations (City of New York Law Department 2013) in the design of coastal protection features.

Still water elevations do 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 still water elevations along the flood protection alignment. As noted, the still water elevations do not match the BFEs shown on the PFIRM maps, as the BFEs include the effects of waves. The 100-year still water levels vary approximately 0.1 ft along the alignment, with higher elevations north of East 19th Street. It should also be noted that the still water elevations presented on the FEMA PFIRMs are referenced to NAVD88 vertical datum and do not include any sea level rise considerations.

Table 3-1 FEMA PFIRM 100-year and 500-year Still Water Elevations

FEMA PFIRM Transect #	100-Year Storm Tide (ft NAVD88)	500-Year Storm Tide (ft NAVD88	Reach	Approximate Location
23	11.0	14.0	Q	Asser Levy/VA Medical Center
24	11.0	14.0	O - Q	East 23rd St/East River
25	11.0	14.0	O	East 22nd St/East River
26	11.0	14.0	N - O	East 21st St/East River
27	11.0	14.0	N - M	East 19th St/East River
28	10.9	13.9	M	East 18th St/East River
29	10.9	13.9	L-M	East 17th St/East River
30	10.9	13.9	K	East 14th St/East River/ConEdison
31	10.9	13.9	J	East 12 th St /East River
32	10.9	13.9	I	East 10 th St /East River
33	10.9	13.9	H-I	East 8 th St /East River
34	10.9	13.9	H	East 6th St /East River
35	10.9	13.9	G	East 2nd St /East River

FEMA PFIRM Transect #	100-Year Storm Tide (ft NAVD88)	500-Year Storm Tide (ft NAVD88	Reach	Approximate Location
36	10.9	13.9	F	Rivington St/East River
37	10.9	13.9	H	Delancey St/East River
38	10.9	13.9	D	Grand St/East River
39	10.9	13.9	C	Jackson - Cherry St/East River
40	10.9	13.9	B	Gouverneur - Jackson St/East River/Pier 42

3.2 500-Year Storm Tide (Resiliency Case)

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 current day 500-year storm tide elevations range from +13.9 ft NAVD88 to +14.0 ft NAVD88 along the flood protection alignment. 500-Year storm tide elevations in future design conditions with 30 inches of sea level rise are set at +16.5 ft NAVD88 and control the minimum future design height for the proposed project flood protection features (with the exception of incorporated ConEdison and VA Medical Center features, which may have to be slightly adapted as future storm tide conditions develop to match the 30 inches of future adaptation).

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 and seepage 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.

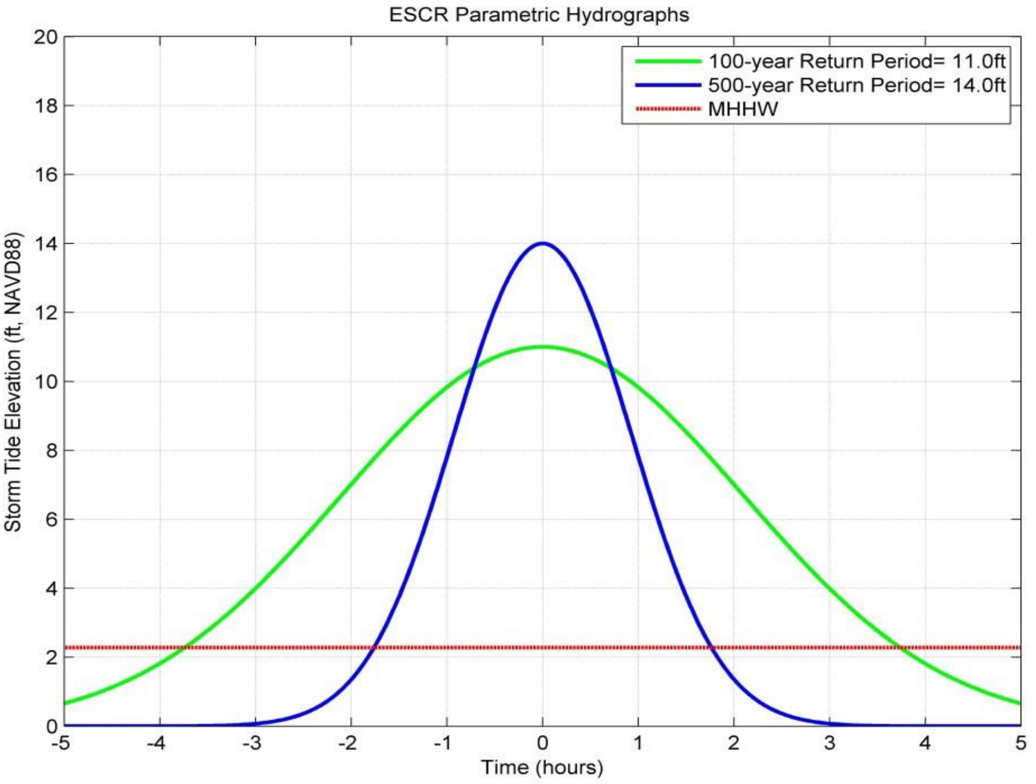

Figure 3-1 **Parametric storm tide time series for the 100-year and 500-year events.**

4 SEA LEVEL RISE CONDITIONS

The NYC Panel on Climate Change (NPCC) 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 (NPCC 2013). These and other components attributing to SLR in NYC are projected independently to inform a total SLR (Horton et al. 2015).

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 with lower probability of not being exceeded, the 50th percentile is a middle range estimate and high probability of being met or a mean value, and the 90th percentile is a high estimate with a low probability of occurring. 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. An additional row shows an extrapolated value for the 2120s, which was used in modeling the 50th percentile SLR scenario for the adaptability condition.

It should be noted that the NPCC periodically reviews and updates SLR projections. The latest update (March, 2019) noted that the 2015 NPCC projections are reaffirmed as the projections of record for New York City.

Table 4-1 SLR Projections in the 2050s/2100s/2120s for NYC for the 10th/50th/90th Percentile

Year	10th Percentile	50th Percentile	90th Percentile
2050s	8 in	16 in	**30 in**
2100s	15 in	36 in	75 in
2120s	-	43 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).

In consultation with the design team and NYC, 30 inches of SLR (2050s 90th percentile) was selected as the design SLR scenario.

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 25th Street, as shown on Figure 2-2. 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[1], vegetation, and building parameters. Transects 23 and 24 also intersect 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 except for the exclusion of overtopping volumes in those areas as appropriate.

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.

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. 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. Project variations in the alignment along the East River Park did not affect the wave information that needs to be used as input for both the wave load calculations and the overtopping calculations in the raised park areas where the landform is to be raised.

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 L-wall), 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.

The maximum wave runup associated with the 1-percent-annual-chance (100-year) still water elevation (storm tide) was calculated using either the Shore Protection Manual (FEMA 2011) or the Goda (2010) formula at vertical walls.

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[1] Fetch is the distance of open water over which wind-generated waves can develop. Larger fetch typically correlates with larger wave heights for a given wind speed and duration.

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 deep water wavelength of the shoreline, and the Shore Protection Manual estimates were used when the vertical wall was offset inland.

Table 5-1 100-year Wave Height and Wave Period.

FEMA PFIRM Transect #	Reach	Approximate Location	100-Year Wave Height (ft)	100-Year Wave Period (seconds)
23	Q	Asser Levy/VA Medical Center	Limited	Wave dissipation from existing Bridge Abutment and inland location.
24	Q	East 23rd St/East River	Limited	Wave dissipation from existing Parking Garage and Structures
25	O (O6)	East 22nd St/East River	3.2	3.2
26	N-O (N8-N11)	East 21st St/East River	3.2	3.3
27	N-M (N1-N5)	East 19th St /East River	3.2	3.2
28	M (N5-N7)	East 18th St /East River	3.2	3.3
29	L-M	East 17th St East River	3.1	3.2
30	K	East 14th St/East River/ConEdison	3.3	3.5
31	J	East 12th St /East River	3.3	3.5
32	I	East 10th St /East River	3.3	3.5
33	H-I	East 8th St/East River	3.3	3.5
34	H	East 6th St/East River	3.2	3.5
35	G	East 2nd St/East River	3.2	3.4
36	F	Rivington St/East River	3.2	3.4
37	H	Delancey St/East River	3.1	3.3
38	D	Grand St/East River	3.1	3.3
39	C	Jackson - Cherry St/East River	2.7	2.8
40	B	Gouverneur - Jackson St/ East River	2.6	2.7

5.3 100-Year Waves at Levee/Wall

For portions 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 levee/wall. Transformed wave conditions were extracted roughly one deep water wavelength 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.

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 levee/wall.

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.

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,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 heights averaged in the range of approximately a 10% percent increase in wave height at the shoreline relative to the 100-year wave.

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 LOADS

Wave loads have been determined for both the flood protection features in Reaches A-C and K-Q as well as to inform marine structure designs for the waterfront esplanade and bulkheads in reaches C-J in East River Park. The wave loads that have been calculated are:

- **Horizontal loads**, applied on vertical surfaces such as the vertical wall.
- **Uplifting loads**, applied on horizontal overhanging elements for the waterfront esplanade structure, which is not a flood protection feature. Loads calculated to inform the esplanade design.

6.1 Horizontal Wave Loads

Horizontal wave loads have been determined following Goda's method (Goda, 2010) to determine wave pressure under wave crests (see Figure 6-1).

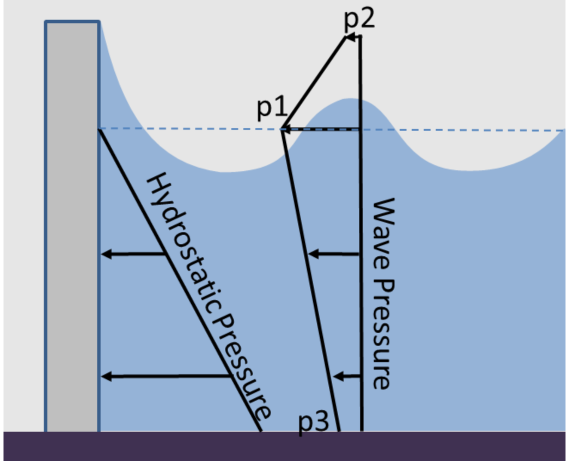

Figure 6-1 Schematic of horizontal pressure distributions on a vertical wall.

The Goda Method formulas used to calculate the wave pressures shown on Figure 6-1 on the front of a vertical wall are:

$$p_1 = 12\ 1 + cos\beta\ \alpha1\lambda1 + \alpha2\lambda2cos\beta2\rho gHmax$$

$$p_2 = \frac{p_1}{\cosh\left(\frac{2\pi h}{L}\right)}$$

$$p_3 = \alpha_3 p_1$$

With:

$$\alpha_1 = 0.6 + \frac{1}{2}\left[\frac{\frac{4\pi h}{L}}{\sinh\left(\frac{4\pi h}{L}\right)}\right]^2$$

$$\alpha_2 = min\left\{\frac{h_b - d}{3h_b}\left(\frac{H_{max}}{d}\right)^2, \frac{2d}{H_{max}}\right\}$$

$$\alpha_3 = 1 - \frac{h'}{h}\left[1 - \frac{1}{\cosh\left(\frac{2\pi h}{L}\right)}\right]$$

Where:

H_{max}: The highest wave in the design sea state

d: water depth above the foundation

h_b: water depth at a distance of $5H_s$ from the vertical wall

h’: distance from the design water level to the bottom of the upright section

β: Angle between the direction of wave approach and a line normal to the breakwater

L: wavelength

6.2 Vertical Wave Loads

Uplifting (vertical upwards) loads on overhanging structures can be calculated based on equations adapted from (McConnell, 2004). These equations were derived from the analysis of two-dimensional (2D) physical model tests and are intended to present easily applicable equations for quasi-static and impact wave forces on decks. These constitute a statistically equivalent load for a first estimation of the effect of these short-duration loads (see Figure 6-2).

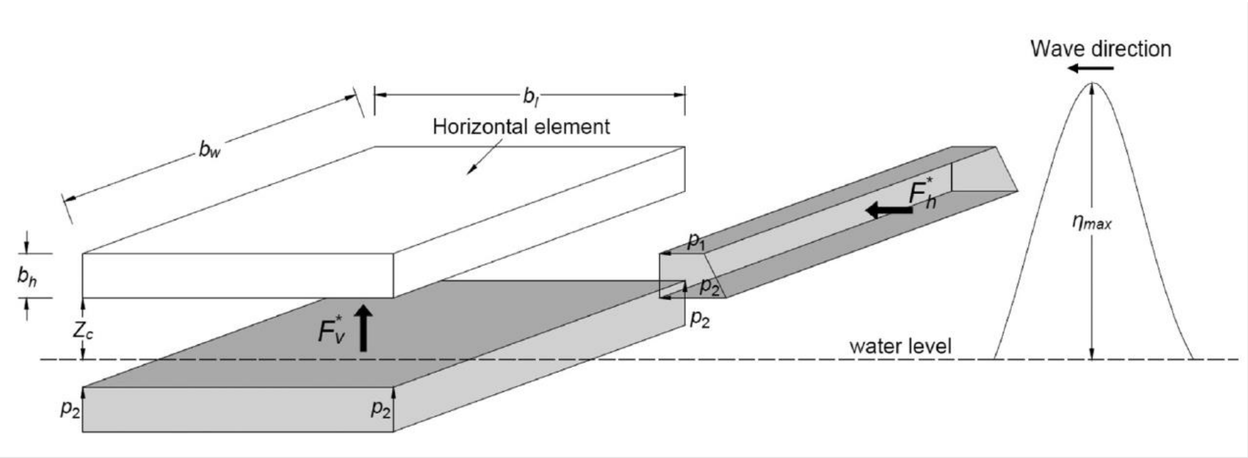

Figure 6-2 Basic wave loads on a horizontal element.

The **vertical hydrostatic pressure applied at the bottom of the horizontal element** (which in turn corresponds to the horizontal hydrostatic pressure applied at the bottom of the vertical face of the horizontal element (see Table 6-2) can be calculated as:

$$p_2 = [\eta_{max} - Z_c] \times \rho_{sw} \times g$$

6.3 Wave Load Calculations for Features Not Related to Flood Protection.

Horizontal wave loads have been calculated following the methods described in Sections 6.1 and 6.1, for reaches C through I which run along the East River park Figure 6-3.

Figure 6-3 Reaches along the East River Park.

These wave loads were calculated to inform the design of waterfront structures and are not related to flood protection features for the project. Results are summarized in Table 6-1.

Table 6-1 Horizontal Wave Loads Results - Flood Protection and Non-Flood Protection Structures - 100-year 90th percentile SWL scenario

Transect ID	Structure	SWL Scenario	SLR	Pressure [psf]		
				p1	p2	p3
C-1	Bulkhead/Esplanade	100 year	2050s 90th	177.7	113.7	13.1
D-1	Bulkhead/Esplanade	100 year	2050s 90th	183.3	221.7	11.7
D-2	Bulkhead/Esplanade	100 year	2050s 90th	188.9	278.5	18.4
E-1	Bulkhead/Esplanade	100 year	2050s 90th	186.7	122.7	13.5
E-2	Bulkhead/Esplanade	100 year	2050s 90th	186.1	122.1	18.8
F-1	Bulkhead/Esplanade	100 year	2050s 90th	186.5	226.4	12.7

Transect ID	Structure	SWL Scenario	SLR	Pressure [psf]		
				p1	**p2**	**p3**
F-2	Bulkhead/Esplanade	100 year	2050s 90th	185.6	108.8	16.7
G-1	Bulkhead/Esplanade	100 year	2050s 90th	190.4	126.4	15.6
G-2	Bulkhead/Esplanade	100 year	2050s 90th	192.1	332.8	11.7
H-1	Bulkhead/Esplanade	100 year	2050s 90th	193.0	116.2	9.6
I-1	Bulkhead/Esplanade	100 year	2050s 90th	195.8	119.1	12.8
I-2	Bulkhead/Esplanade	100 year	2050s 90th	197.5	120.7	18.0

Table 6-2 Vertical Wave Load - Waterfront Structures - 100-year 90th percentile SWL

Transect ID	Structure	SWEL	Vertical Effective Force
		[ft NAVD88]	[lb/linear ft]
C-1	Bulkhead/Esplanade	13.50	6,991
D-1	Bulkhead/Esplanade	13.50	0.0
D-2	Bulkhead/Esplanade	13.50	7,506
E-1	Bulkhead/Esplanade	13.50	11,060
E-2	Bulkhead/Esplanade	13.50	11,058
F-1	Bulkhead/Esplanade	13.50	N/A
F-2	Bulkhead/Esplanade	13.50	N/A
G-1	Bulkhead/Esplanade	13.50	7,320
G-2	Bulkhead/Esplanade	13.50	N/A
H-1	Bulkhead/Esplanade	13.50	10,875
I-1	Bulkhead/Esplanade	13.50	11,185
I-2	Bulkhead/Esplanade	13.50	11,389

7 WAVE OVERTOPPING ANALYSIS

EurOtop (Pullen et al. 2007) and USACE Coastal Engineering Manual (CEM) (USACE 2002) methodologies were used for the wave overtopping analysis along the flood protection alignment. Overtopping rates are used to inform the interior drainage inputs and to check if any additional scour protection should be anticipated. For vertical walls, CEM's Franco overtopping formula was used, which is the basis of the vertical wall formula in EurOtop. Figure 7-1 schematically shows the wave overtopping process and some of the parameters needed for estimating overtopping rates at a vertical wall.

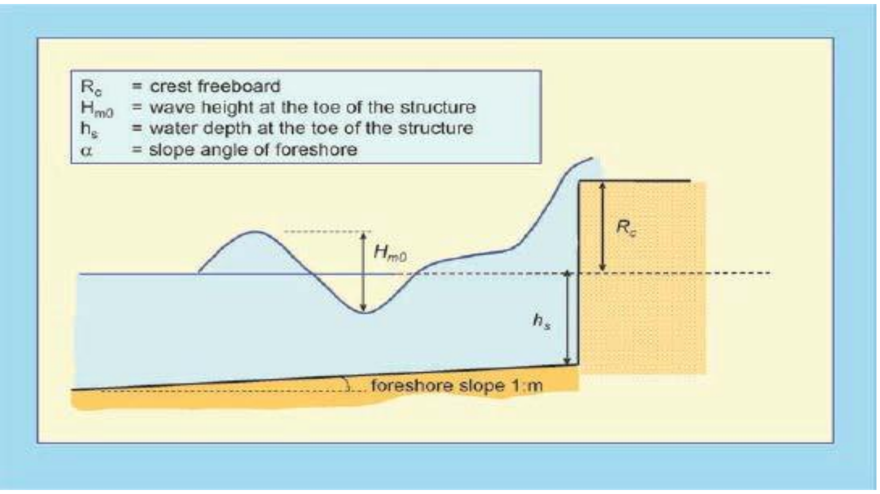

Figure 7-1 Schematic of Wave Overtopping at a Vertical Wall

Source: Pullen et al. 2007.

7.1 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 walls were discussed in Section 5.

Table 7-1 shows the various wave overtopping events and scenarios that were used in the development of project estimates. For each of the events and scenarios, the following conditions were analyzed:

- Crest elevations 16.5 ft minimum with earthworks and berms shoreward of the flood protection system and higher elevation land masses in the park for the 2050s condition.
- Crest elevations 18.5 ft minimum with earthworks and berms shoreward of the flood protection system and higher land masses in the park for the 2120s condition using the value listed in the table for the 2100 value of 36 inches of SLR and extrapolating to the 2120s value of 43 inches of SLR for the 100-Year surge condition.

- Vertical wall (I- or L- walls) geometry (see Section 2)

Table 7-1 Summary of Wave Overtopping Analysis SLR basis

	SLR Projections						
		2050s (Percentiles)			2100s/2120 (Percentiles)		
Timeframe	Current Day	10th	50th	90th	10th	50th	90th
SLR	0.0 in.	8 in.	16 in.	30 in.	15 in.	36 in./43 in. (2120)	6 ft-6 in.

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. Current-day sea levels are based on the middle year of the 1983-2001 National Tidal Datum Epoch.

7.2 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)**.
- **Wall Damage** – Damage to paved or armored section behind wall – **critical rate 2.1 cfs/ft**.

7.2.1 Minimum Required Crest Elevation for the 100-Year Event

7.2.1.1 90th Percentile SLR (Design Event)

Maximum overtopping rates along the flood protection alignment for the design event are shown in Table 7-2. 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.

Table 7-2 **Maximum Overtopping Rates - 100-year Event 2050s with the 90th percentile SLR.**

FEMA PFIRM Transect #	Reach	Approximate Location	Maximum Overtopping Rate for Design Condition of 90th (30 inches). Percentile SLR 2050s with 100 Year Surge [cfs/ft] 16.5 ft-NAVD88 Crest Elevation	Requirement Based on Overtopping Rate or Minimum Freeboard
23	Q	Asser Levy/VAMCr	Limited	15.5
24	Q	East 23rd St/East River	Limited	15.5
25	O-Q	Stuyvesant Cove Park/East River	0.06	15.5
26	N-O	Stuyvesant Cove Park/East River	0.07	16.0
27	N-M	Avenue C/East River	0.1	16.5
28	M	East 18th St/East River	0.09	16.5
29	L-M	East 17th St/East River	0.1	16.5
30	K	East 14th St/East River/ConEdison	0.1	16.5
31-38	J through D	East 12th St/East River to Grand St/East River	No Overtopping due to Elevated Land Mass/Buried Floodwall	15.5
39	C	Jackson - Cherry St/East River	0.01	16.5
40	B	Gouverneur - Jackson St/ East River/Pier 42	0.01	16.5

The design crest elevation chosen is 16.5 ft-NAVD88. This design crest elevation is based on the 500 Year resiliency for the 2050s 90th percentile condition. Requirements based on FEMA recognition of the flood protection system will be compared in Section 8.

7.2.1.2 Adaptations for the 2120s SLR (50th Percentile)

The adaptability of the flood protection system to the 2120s 50th percentile SLR projection of 43 inches for the 100-year event was also considered. The SLR values were derived for the 2120s by taking the 36 inches of rise at the year 2100 and extrapolating the linear trend line out an additional 20 years to provide an analysis at 43 inches of sea level rise. This was done using a linear extrapolation of the NPCC sea level rise data. Foundations are designed for the system to be raised by 2 feet to an elevation of +18.5 NAVD88. Maximum overtopping rates for the design crest elevation of 18.5 ft is shown in Table 7-3. Still water elevation in this condition (100-Year Surge) was modelled at +14.6 NAVD88. A resiliency check was also performed for the 500-Year surge at +17.6 NAVD88 for the 2100s condition.

For this future condition, where 43 inches of SLR is assumed, the vertical wall sections meet or exceed the design criteria with 1% waves plus freeboard resulting in requirements that range from +18.3 to +18.5 NAVD88. For the resiliency condition, the rates exceed the upper limit overtopping rate of 0.5 cfs/ft for transportation behind the wall, but do not exceed the upper limit overtopping rate of 2.1 cfs/ft for well-protected walls. It is anticipated that the areas immediately behind the walls, including local bike lanes, intersections and parks will be monitored and adapted as necessary over the next 80-100 years as SLR rates are monitored. For the elevated portions of East River Park, initial construction in most areas will have the landform set at +18.0 to +25.0 ft NAVD88, exceeding the adaptability scenario of +14.6 ft NAVDD88 SWL and the resiliency SWL check for +17.6 NAVD88. Materials in the upper soils above the buried flood wall will need to be monitored or analyzed to ensure that the materials adhere to requirements for stability and porosity in the future condition. Some areas may already be paved and or concrete and would satisfy this requirement. In areas where this solution does not apply, other features added such as independent low walls or augmented existing walls as well as possible soils-based solutions such as berms would need to be considered.

Table 7-3 Maximum Overtopping Rates 2120s 100-year event with the 50th percentile SLR and Increase Wall Height (+18.5 NAVD88)

FEMA PFIRM Transect #	Reach	Approximate Location	Maximum Overtopping Rate in 100-Year Sea Level Rise (43 inches) and 2 feet of additional wall height raise [cfs/ft] 18.5 ft-NAVD88 Crest Elevation
23	Q	Asser Levy/VAMC	Limited
24	Q	East 23rd St/East River	Limited
25	O-Q	Stuyvesant Cove Park/East River	0.3
26	N-O	Stuyvesant Cove Park/East River	0.3
27	N-M	Avenue C/East River	0.3
28	M	East 18th St/East River	0.02
29	L-M	East 17th St/East River	0.04
30	K	East 14th St/East River	0.04
31-38	J through D	East 12th St/East River to Grand St/East River	No Overtopping due to Elevated Land Mass/Buried Floodwall
39	C	Jackson - Cherry St/East River	0.01
40	B	Gouverneur - Jackson St/ East River/Pier 42	0.01

7.2.2 Minimum Required Crest Elevations for the 500-Year Event and No SLR.

As previously stated, if areas exposed to wave overtopping (directly behind wall foundations) are well protected by pavement or concrete, they can be exposed an overtopping rate up to 2.1 cfs/ft with minimal scour behind the wall, which will preserve stability of the floodwall. Additionally, the critical upper limit overtopping rates for vehicular transportation behind well-protected vertical walls is 0.5 cfs/ft in areas. All vertical wall sections designed to the minimum crest elevation of 16.5 ft NAVD88 have overtopping rates below 0.5 cfs/ft during a 500-year event with no SLR and therefore mitigate this risk in the limited project areas that have roadways adjacent to the walls (FDR on-ramp at Montgomery Street, FDR drive and portions of other intersections.

Table 7-4 Maximum Overtopping Rates Current Day 500-year Event with no SLR.

FEMA PFIRM Transect #	Reach	Approximate Location	Maximum Overtopping Rate for Current Day Sea Level and 500 Year Surge [cfs/ft] 16.5 ft-NAVD88 Crest Elevation
23	Q	Asser Levy/VAMC	0.0
24	Q	East 23rd St/East River	0.0
25	O	Stuyvesant Cove Park/East River	0.1
26	N-O	Stuyvesant Cove Park/East River	0.2
27	N-M	Avenue C/East River	0.3
28	M	East 18th St/East River	0.2
29	L-M	East 17th St/East River	0.2
30	K	East 14th St/East River	0.2
31-38	J through D	East 12th St/East River to Grand St/East River	No Overtopping. Water does not enter the local city side drainage system.
39	C	Jackson - Cherry St/East River	0.1
40	B	Gouverneur - Jackson St/ East River/Pier 42	0.1

7.2.2.1 500-Year Event and 50th Percentile SLR

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 in terms of limiting pavement or wall damage as shown in Table 7-5. In all cases, the project minimum of +16.5 exceeds requirements for this scenario.

Table 7-5 Minimum Required Crest Elevations 2050s- 500-year event with the 50th percentile SLR.

FEMA PFIRM Transect #	Reach	Approximate Location	500 Year 2050s 50th Percentile SLR Condition (16”) for Wall and Pavement Protection 2.1 cfs/ft
25	O	Stuyvesant Cove Park/East River	16.0 ft
26	N-O	Stuyvesant Cove Park/East River	16.0 ft
27	N-M	Avenue C/East River	16.0 ft
28	M	East 18th St/East River	16.0 ft
29	L-M	East 17th St/East River	16.0 ft
30	K	East 14th St/East River	16.0 ft
31-38	J through D	East 12th St/East River to Grand St/East River	Exceeds Requirements.
39	C	Jackson - Cherry St/East River	15.5 ft
40	B	Gouverneur - Jackson St/ East River/Pier 42	15.5 ft

7.3 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 wave overtopping volumes have been reduced to negligible amounts or eliminated for the initial accreditation and have been calculated at approximately 3 MG for the mean overtopping wave and at below 5 MG for the 68th percentile overtopping wave. The 2015 concept design yielded 19 MG for the 68th percentile wave. Note that the original configuration of the alignment in the 2015 study allowed for more overtopping due to the fact that wall heights were set lower than the current design minimums for portions of the alignment and the design also did not incorporate a raised park section.

7.4 Spatial Extent of Overtopped Discharge for Raised Landforms

To determine zones affected by direct wave overtopping hazard, the determination of the spatial distribution of overtopped discharge may be used. There are two main scenarios that may lead to the overtopped volumes to travel a certain distance inland:

- **Non-impulsive conditions** (greenwater): the distribution of the overtopped water will depend on the form of the area landward of the structures crest, and according to the EuroTop Manual, no generic guidance can be offered.

- **Impulsive conditions** (violent): laboratory tests have been used to identify an upper bound on the possible wind-driven spatial distribution of the fall back to ground footprint of these type of overtopped volumes. The conservative guidance indicates that:
  - 50% of the overtopped discharge will land within a distance of 0.06 x $L_{m-1,0}$[2]
  - 90% of the overtopped discharge will land within a distance of 0.20 x $L_{m-1,0}$
  - 95% of the overtopped discharge will land within a distance of 0.25 x $L_{m-1,0}$

The guidance above has been applied to determine the overland propagation extent of overtopped volumes for each of the alignments considered in this study. Since drainage collection in the park is designed to route water downstream of tide gates from the water's edge to about 80 to 100 feet inland, any volume in this area cannot be considered overtopping volume since the water never enters the City-side. Results are summarized in Table 7-6.

Table 7-6 Upper Boundary of Overtopped Water Volumes in Elevated Land Mass of East River Park.

Transect location	SWEL	Height of System at Edge of Esplanade/Waterfront	Distance of travel of overtopped wave	Overtopping Rate Entering City Side
Station	ft-NAVD88	ft-NAVD88	ft	CFS/LF
C-1	13.50	16.00	12.56	0.00
D-1	13.50	12.00	23.03	0.00
D-2	13.50	10.00	32.43	0.00
E-1	13.50	16.00	12.53	0.00
E-2	13.50	16.00	12.33	0.00
F-1	13.50	11.95	17.30	0.00
F-2	13.50	16.50	50.07	0.00
G-1	13.50	16.00	12.43	0.00
G-2	13.50	8.00	26.36	0.00
H-1	13.50	16.50	12.54	0.00
I-1	13.50	16.50	12.65	0.00
I-2	13.50	16.50	12.76	0.00

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[2] Deepwater wave length.

8 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 minimum freeboard requirements of levee systems are greater of values summarized below as taken from CFR Title 44 §65.10 (b) (iii-iv):

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

Exceptions to the minimum freeboard requirement may be approved for a lesser freeboard with engineering analysis to demonstrate:

- Analysis must evaluate the uncertainty in the estimated base flood loading conditions.
- Effects of wave attack and overtopping are considered in assessing stability of the floodwall/levee.

A minimum of 2 feet of freeboard is provided.

The elevation requirements based on overtopping rate for the design event are presented in Section 7.2.1 summarizes the minimum required crest elevations along the length of the flood protection system. 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 without use of the exception. The design elevation of +16.5 ft NAVD88 will satisfy the initial freeboard and the design condition requirements.

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

The system will likely meet the freeboard criteria during the initial certification period, but the exception category will be required for the design condition (100-year storm, 2050s 90th percentile sea level rise). The overtopping analysis and design of the flood wall confirms that the design would meet the requirements for the exception approval, if or when needed.

The system wide minimum has been set at +16.5 NAVD88 to assure that the flood protection system continues to be recognized by FEMA in the future. However, two incorporated flood protection systems at the ConEdison generating station (**+15.0 NAVD88**) and at the VA Medical Center (**+16.2 NAVD88**) will need to be monitored as sea level rise occurs and adjusted accordingly if necessary. The ConEdison area will require more scrutiny and monitoring over the next 50-100 years.

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 PFIRMs.

9 NO IMPACT ANALYSIS

An 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.

9.1 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 produced peak storm tide close to the 100- year storm tide were identified. Figure 9-1 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 9-1 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.

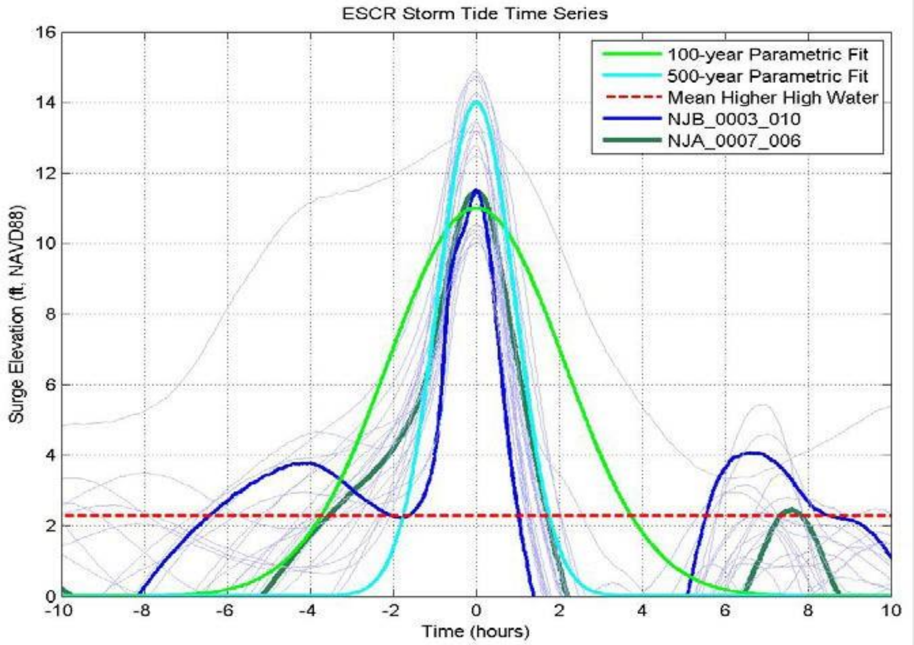


Figure 9-1 Storm Tide Time Series for all FEMA PFIRM Events, the Parametric Fit Time Series, and Two Potential 100-year Storm Tide Events.

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).

9.2 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 9-2 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).

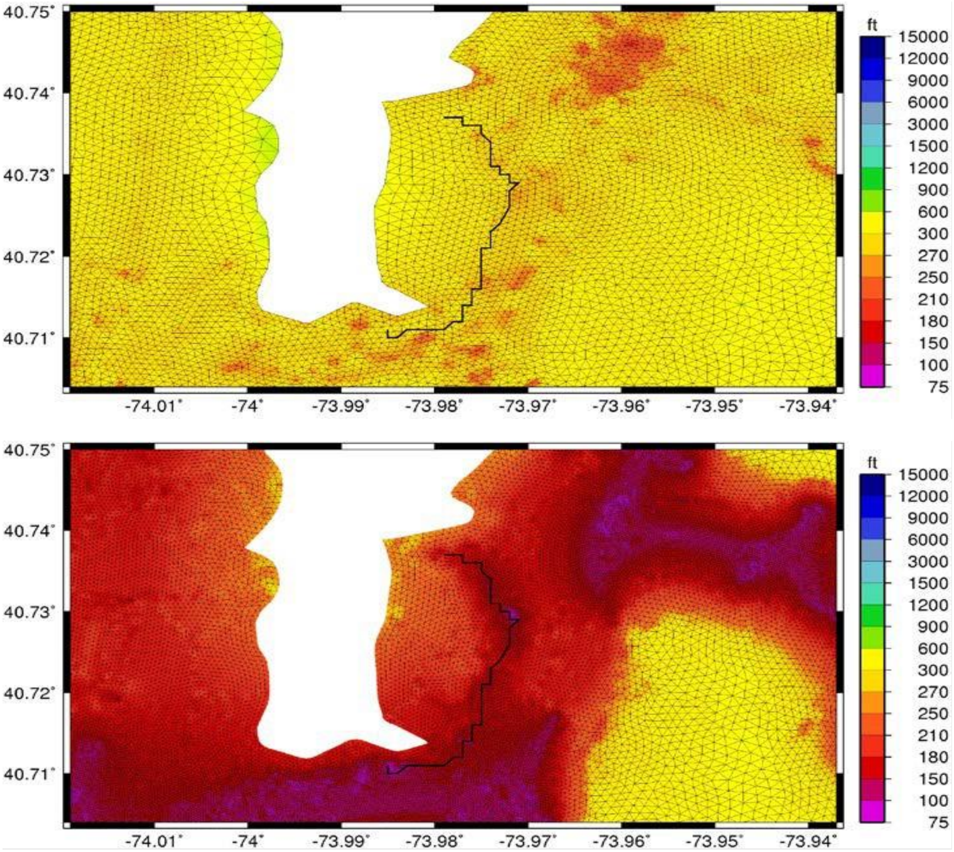


Figure 9-2 Raw comparison of FEMA PFIRM mesh (top) and the enhanced mesh (bottom) used in this analysis. Mesh size shown in ft. Alignment shown by solid black line.

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 7-2.

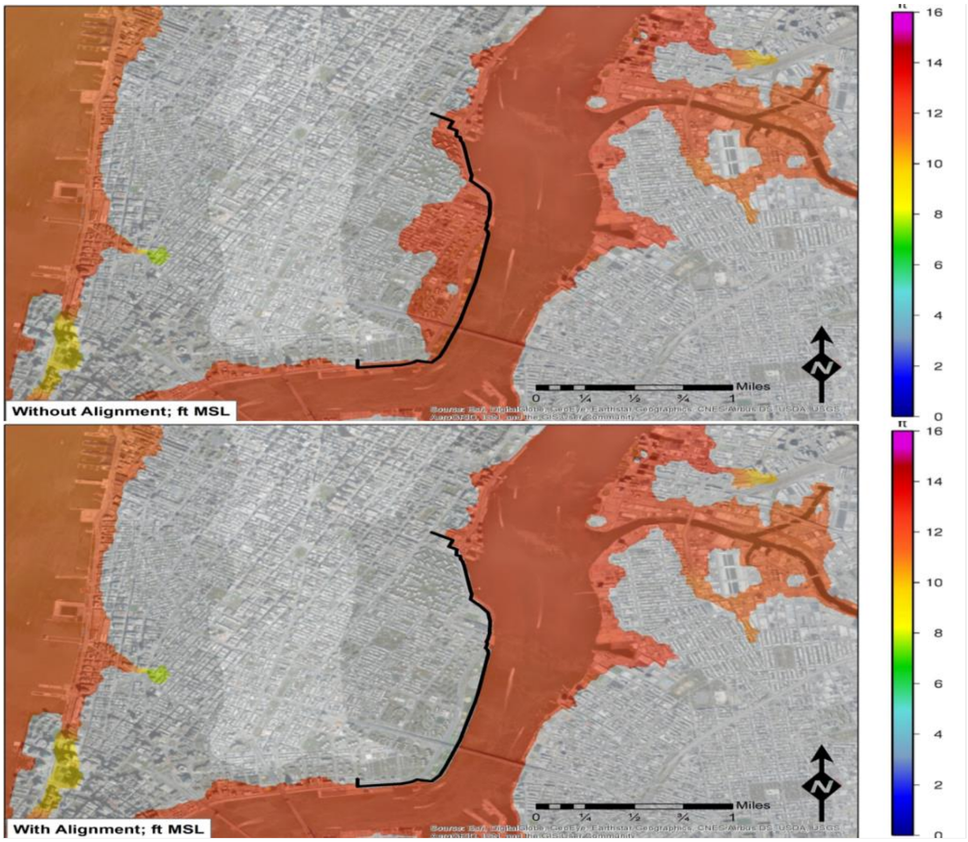
9.3 Water Level Comparisons

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 9-3 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 9-4 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.

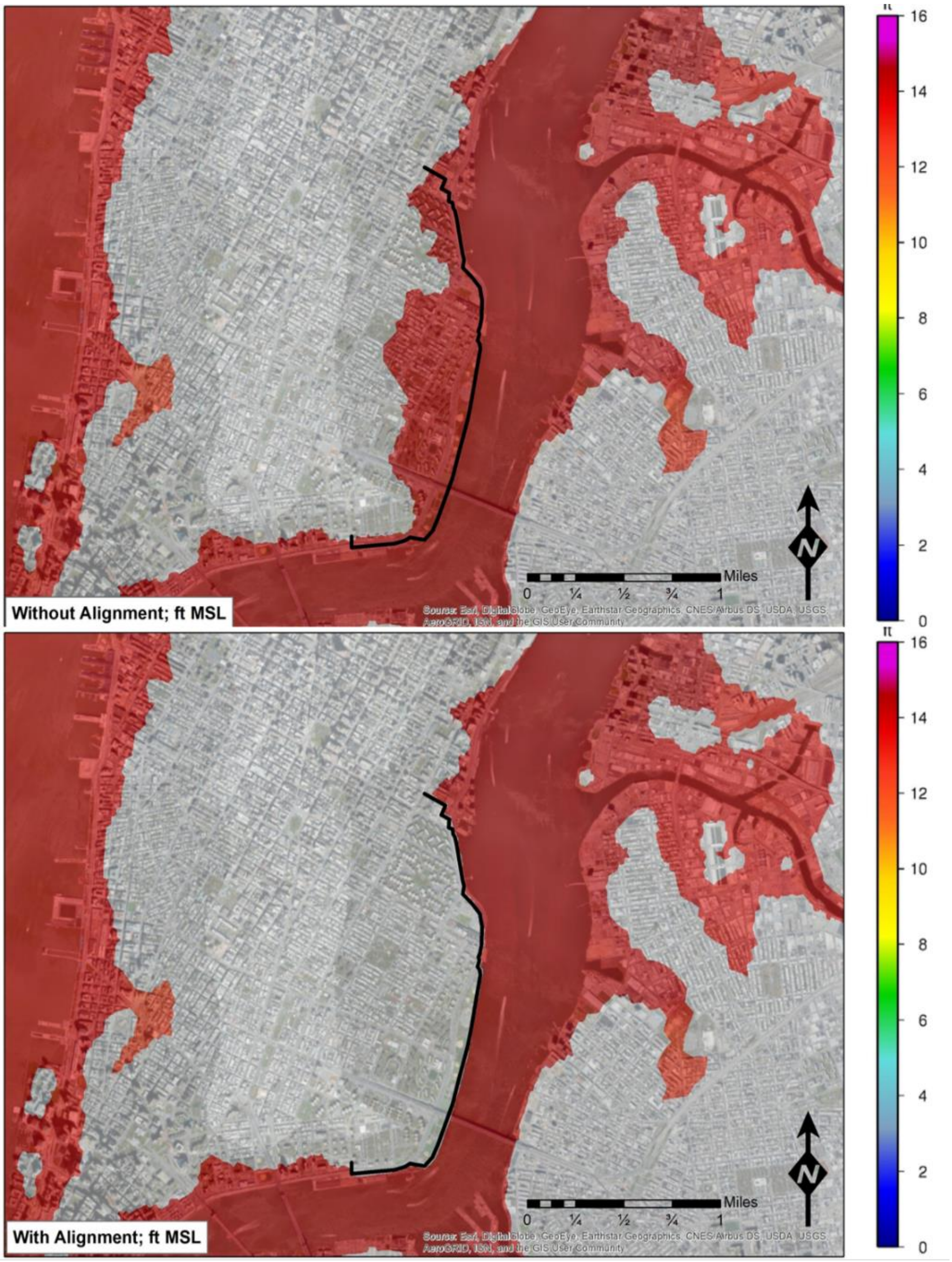
Comparisons of the peak storm tide with and without the flood protection alignment for current-day sea levels and 2050s SLR projections are shown on Figure 9-5. Outside the flood protection alignment, no increase or decrease of peak storm tide elevations are caused by the flood protection alignment, with or without SLR.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

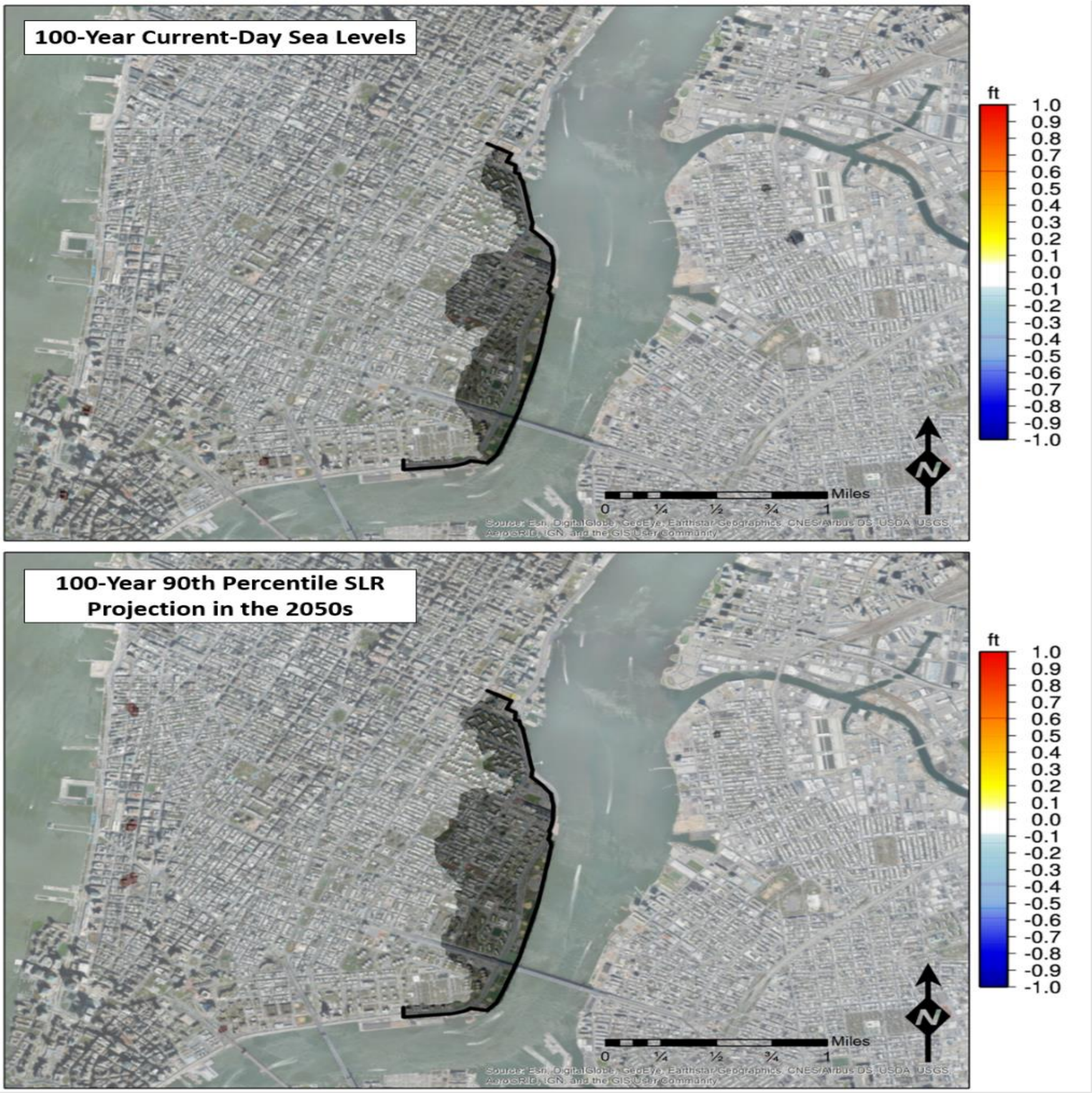
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 9-3 **100-year Peak Storm Tide Elevations With and Without the Flood Protection Alignment, Current-Day Sea Levels.**



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 9-4 100-year peak storm tide elevations With and Without the Flood Protection Alignment, 90th percentile SLR projection in the 2050s.



100-Year Current-Day Sea Levels

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

100-Year 90th Percentile SLR Projection in the 2050s

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 9-5 100-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 (protected floodplain in gray shadow)

Figure 9-6 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.

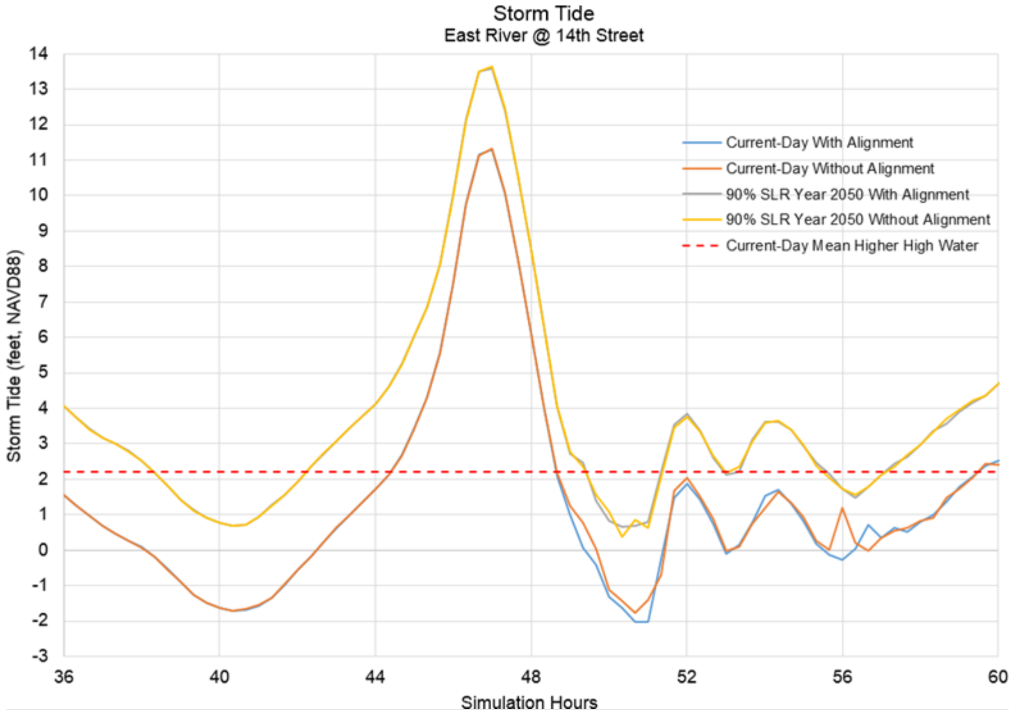


Figure 9-6 **Storm Tide Time Series Comparisons With and Without the Flood Protection Alignment for the 100-year event,Current-Day Sea Levels,90th percentile SLR projection in the 2050s.**

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.

10 SUMMARY OF FLOOD PROTECTION ELEVATION REQUIREMENTS

This report has presented storm tide and wave conditions for the proposed flood protection alignment from East 25th 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 vertical wall sections. A design overtopping rate of 0.1 cfs/ft to protect transportation and the flood protection alignment itself was then used to inform minimum flood protection system wall heights or crest elevations. However, the resiliency check for the 500-Year 2050s 90th percentile condition was the controlling factor in most cases for wall minimums, as summarized in Table 10-1.

Table 10-1 Summary of Minimum Required Crest Elevations for the Design Event (2050s 30 inches of SLR)

Below is a summary of minimum required crest elevations for the design event in the 2050s with 90th percentile sea level rise predictions (30 inches) based on an overtopping design rate of 0.1 cfs/ft for the alignment/geometry as well as minimums set by resiliency consideration for a 500 Year 2050s 90th percentile Sea Level Rise still water elevation is shown on Figure 2-1. Controlling elevations shown in bold.

FEMA PFIRM Transect #	Reach	Approximate Location	Geometry	Requirement Based on Overtopping Rate or Minimum Freeboard	Requirement Based on 500 Year 2050s 90th Percentile Still Water Level Resiliency Check
25	O	Stuyvesant Cove Park/East River	Vertical wall	15.5	**16.5**
26	N-O	Stuyvesant Cove Park/East River	Vertical wall	15.5	**16.5**
27	N-M	Avenue C/East River	Vertical wall	15.5	**16.5**
28	M	East 18th Street/East River	Vertical wall	**16.5**	**16.5**

FEMA PFIRM Transect #	Reach	Approximate Location	Geometry	Requirement Based on Overtopping Rate or Minimum Freeboard	Requirement Based on 500 Year 2050s 90th Percentile Still Water Level Resiliency Check
29	L-M	East 17th Street/East River	Vertical wall	**16.5**	**16.5**
30	K	East 14th Street/River/FDR Drive	Vertical wall	**16.5**	**16.5**
31-38	J through D	East 12th St/East River to Grand St/East River	Elevated Land Mass/Buried Floodwall	15.5	**16.5**
39	C	Jackson - Cherry Street/East River	Vertical wall	15.5	**16.5**
40	B	Gouverneur - Jackson Street/ East River/Pier 42	Vertical wall	15.5	**16.5**

Beyond the design event for 30 inches of SLR, adaptation requirements for the 100-year event with SLR projections in the 2120s were demonstrated, as summarized in Table 10-2. The adaptations that would be required in that scenario 100 years from construction, with 43 inches of SLR at vertical walls, 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 10-2. A 2 feet increase in system height is built into the design of the floodwalls to allow for a future adaptability-based increase in wall height, without impacts or required modifications to the foundations or significant alterations to the base of the structures, allowing for less challenging retrofits. For the ConEdison and VA Medical Center, adaptation may need to occur sooner.

Table 10-2 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 2120s.

Geometry	500-Year With 50th Percentile SLR Projection (16”) in the 2050s	100-Year With 50th Percentile SLR Projection (43”) in the 2120s
To Maintain Overtopping Rates Below 0.1 cfs/ft (Design Rate for Earthen Levees/Unarmored areas)		
Vertical Wall	Increase top of wall 0.5 ft to 1.0 ft	Increase top of wall 2 ft and provide additional scour protection where required
Elevated Park	No change Required	Analysis of Existing Elevations with Targeted improvements where required. Initial park elevations are set at +18.0 to +25.0
To Maintain Overtopping Rates Below 0.5 cfs/ft (*Levees Protected and Upper Limit for Transportation Safety*)		
Vertical Wall	No change	Increase top of wall 2 ft
Elevated Park	No change Required	Analysis of Existing Elevations with Targeted improvements where required. Initial park elevations are set at +18.0 to +25.0

Ranges in the crest elevation adaptations shown in Table 10-2 are the result of variation in wave climate along the flood protection system, with more exposed locations requiring the higher range of adaptation.

For the future condition 100-year event with the 50th percentile SLR projection of 43 inches in the 2120s, only minor or no changes based on the current design will be required if the planned 2 feet of wall height is added before those conditions are met in 100 years. For the 100-year event with the 90th percentile SLR projection in the 2120s, a major adaptation or total system re-design may be needed as over 6.5 feet of sea level rise would have occurred.

To assess if the proposed flood protection alignment would impact surge elevations at 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 9-5.

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