US Army Corps
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New York District

Storm Surge Barriers Sub-Appendix

Annex B – Storm Surge Barrier Crest Elevations

DRAFT

New York – New Jersey Harbor and Tributaries Coastal Storm Risk Management Feasibility Study

Annex B2.B

September 2022

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1 STORM SURGE BARRIER CREST ELEVATIONS

1.1 Approach for Determination of Storm Surge Barrier Crest Elevation

This section introduces a "step-wise" approach to establish the crest elevation of the storm surge barriers under the HAT Study. The approach is similar to the New Orleans "Step Wise" procedure as referenced in Appendix D of EC 1110-2-6067 and forms the basis of the evaluation methodology. The procedure allows for a probability and uncertainty-based approach for characterizing the flood hazard, associated with storm surge, wave characteristics and overtopping of coastal structures. As such this methodology is a risk-based approach that fits the risk framework approach as required by ER 1105-2-101.

The methodology is narratively explained using the example of a vertical wall, for other coastal structures the methodology may be the same, but the threshold criteria may be different. The overarching rationale is as follows. First the hydraulic parameters and characteristics in vicinity of the storm surge barriers (water levels and waves) for the AEPs of interest are determined. Then, overtopping is probabilistically assessed and evaluated with a Monte Carlo simulation for the 1% AEP conditions, (i.e. the 100-year return period) at the 90% Confidence Limit (CL) and a check is completed to see whether the overtopping rate is less than the specified 200 l/s/m criterion[1]. If the criterion is met, then no changes to the structure's geometry are warranted and the established elevation is sufficient from a coastal risk assessment point of view.

1.1.1 Step wise approach

Each step of the step wise approach to determine the crest elevation of the HAT Study Storm surge barriers is further detailed below:

Step 1: Still Water Elevation

1.1 Examine the AEP still water elevations (1% AEP) from the Still Water Level (SWL) frequency plots at the output points along the storm surge barrier under consideration. The North Atlantic Coast Comprehensive Study (NACCS) probabilistic water levels will be used for this Project (USACE ERDC, 2015).

1.2 Determine the AEP surge elevation (1% AEP) for the storm surge barrier, as well as mean value and standard deviation of the value.

Step 2: Wave Characteristics

2.1 Examine the AEP significant wave height and AEP peak period (1% AEP) from the frequency plots at output points along the reach. The AEP wave heights and peak periods are based on the model results of NACCS (USACE ERDC, 2015).

[1] During the Feasibility Phase of the study an overtopping threshold of 200 l/s/m was selected by USACE NAN based on internal coordination and consistency with other planning studies throughout the north east region. As such, these overtopping thresholds are adopted in Step 3 and Step 4 of the stepwise approach.

2.2 Determine the significant wave height and wave peak period (1% AEP) for the structure, as well as mean values and standard deviations of those values.

Step 3: Overtopping Rate - Dealing with Uncertainties

3.1 Assume a design crest elevation in increments of 1ft for the storm surge barrier.

3.2 Apply a Monte Carlo simulation to compute the chance of exceedance of the overtopping rate given the design elevation from Step 3.1. This method takes into account the uncertainties in the 1% AEP water elevation, the 1% AEP wave height and the 1% AEP peak wave period.

Wave overtopping rates are calculated based on the most recent version of the EurOtop Manual (Van der Meer, et al., 2018). For all storm surge barriers the mean value approach formulation will be applied[2].

3.3 Check if the wave overtopping is less than the adopted threshold rate as specified. If the criterion is exceeded it is recommended that the structure's geometry (i.e. height) should be adjusted such that this criterion is met by repeating Step 3.2.

The threshold for the mean overtopping rate is set at 2.15 cfs/ft (200 l/s/m) for the 90% Confidence Limit (CL) for the 1.0% AEP conditions.

3.4 Document the 50% and 90% CL mean overtopping rate for the 1% AEP event once the overtopping criterion is met.

1.1.2 Implementation of the Step Wise Approach to establish SSB Elevation

In order to implement the above approach for the HAT Study first the relevant hydrodynamic parameters and storm surge barrier characteristics had to be identified. Second, the methodology was implemented as an algorithm in MATLAB. Automation of the procedure allows for an efficient way of completing Monte Carlo simulations where many input variables and variations to these input variables need to be considered. Additional details on the input parameters, such as water levels and waves as well as structure geometry are provided in the next section.

1.2 Water Levels and Waves

1.2.1 NACCS Data set

The North Atlantic Coast Comprehensive Study (NACCS) datasets for water levels and waves are used for the HAT Study (USACE ERDC, 2015). As part of the NACCS, estimates of nearshore winds, waves, and water-levels, as well as the associated marginal and joint probabilities were evaluated. Statistics of water-levels at various recurrence intervals are available as part of this

[2] The uncertainty in the overtopping formula coefficients per the EurOtop guidance are not included to minimize the number of variables at the feasibility study level and to minimize the total number of Monte Carlo simulations that would need to be run.

study and are based on the ADCIRC modeling component of NACCS. The still water elevations from the modeling include the effects of astronomical tide, storm surge, and wave setup and are obtained from the dataset labeled "base + 96 tides". This dataset was developed by adding 96 randomly selected tide phases to to the still water level results from each storm of the simulation set.

As part of the NACCS modeling effort, the STWAVE model for nearshore waves allowed for simulation of local wind-generated waves, and was paired with the hydrodynamic circulation model ADCIRC to allow for dynamic interaction between surge and waves. Statistics for the significant wave height are also available and are obtained from the dataset labeled "base + 1 tide", where each storm was modeled with a unique randomly selected tide phase.

Statistics for the water level and significant wave height as model output parameters include the expected value, and the 84%, 90%, 95% and 98% Confidence Limit (CL) values. If a parameter is normally distributed, the 84% CL is one standard deviation removed from the mean. As such, the standard deviation is assumed to be equal to the difference between the 84% CL values and the expected value (the mean).

Similar statistics are not available for the peak wave period. An estimate of the peak period was derived based an analysis of additional available model output data in the vicinity of each storm surge barrier and the observed distribution of wave steepness for the area of interest. Details on this analysis and the determination of mean values and standard deviations for the peak wave period are explained in the following section.

1.2.2 Wave Heights and Periods

In order to obtain an estimate of the wave periods associated with the AEP wave heights as well as standard deviations of wave periods a subset of NACCS model results was analyzed. The subset of model results included all maximum significant wave heights and maximum peak wave periods for all simulated storm events for STWAVE output points in the coastal waters in the vicinity of the Verrazano Narrows barrier.

The 1% AEP wave heights for the area of interest are, for this example, at 5.9 ft. The steepness is a function of Hs/T_p^2 (Hs in meters). Figure 1-1 shows the distribution of steepness for this data set with a high density around values of approximately 0.05. E.g. for a wave height of 7ft (2.13 m) a steepness value of 0.05 would result in a Peak period of approximately 6.5 seconds. This distribution was subsequently used to simulate a distribution of peak wave periods for any given significant wave height. Per input wave height the simulation included 20,000 random draws from the distribution below to calculate a wave period. Subsequently the mean and standard deviation of those 20,000 simulated peak wave periods could be calculated. The end result is a mean value and standard deviation for the peak wave period corresponding to every wave height. Figure 1-2 shows the mean values and standard deviations for still water level level, sign. wave height and peak wave period (one standard deviation up and down indicated by the grey bands) for the

ADCIRC stations used for this example analysis for the Verrazano Narrows barrier. Similarly, the peak wave period and standard deviation were established for all other storm surge barriers.

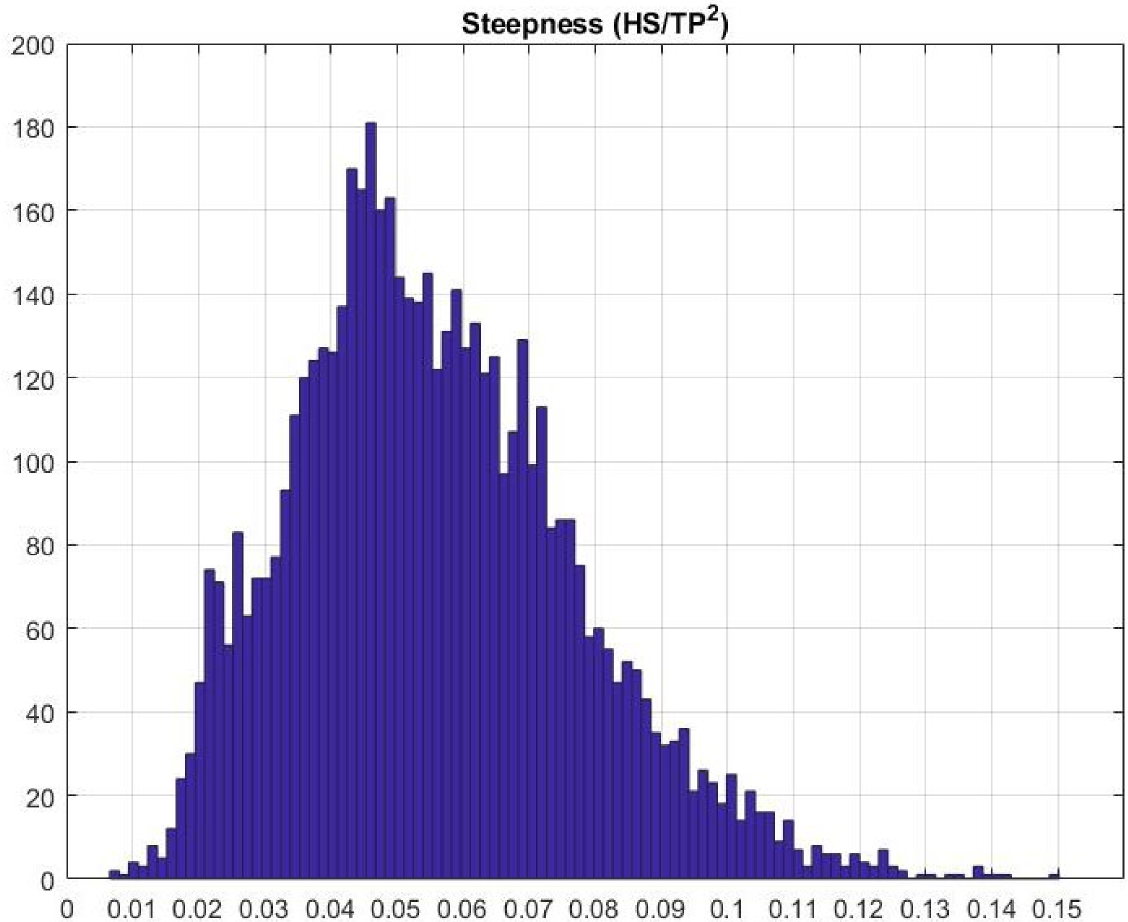

Figure 1-1: Histogram of Steepness measured as (Hs/Tp2 with Hs in meters)

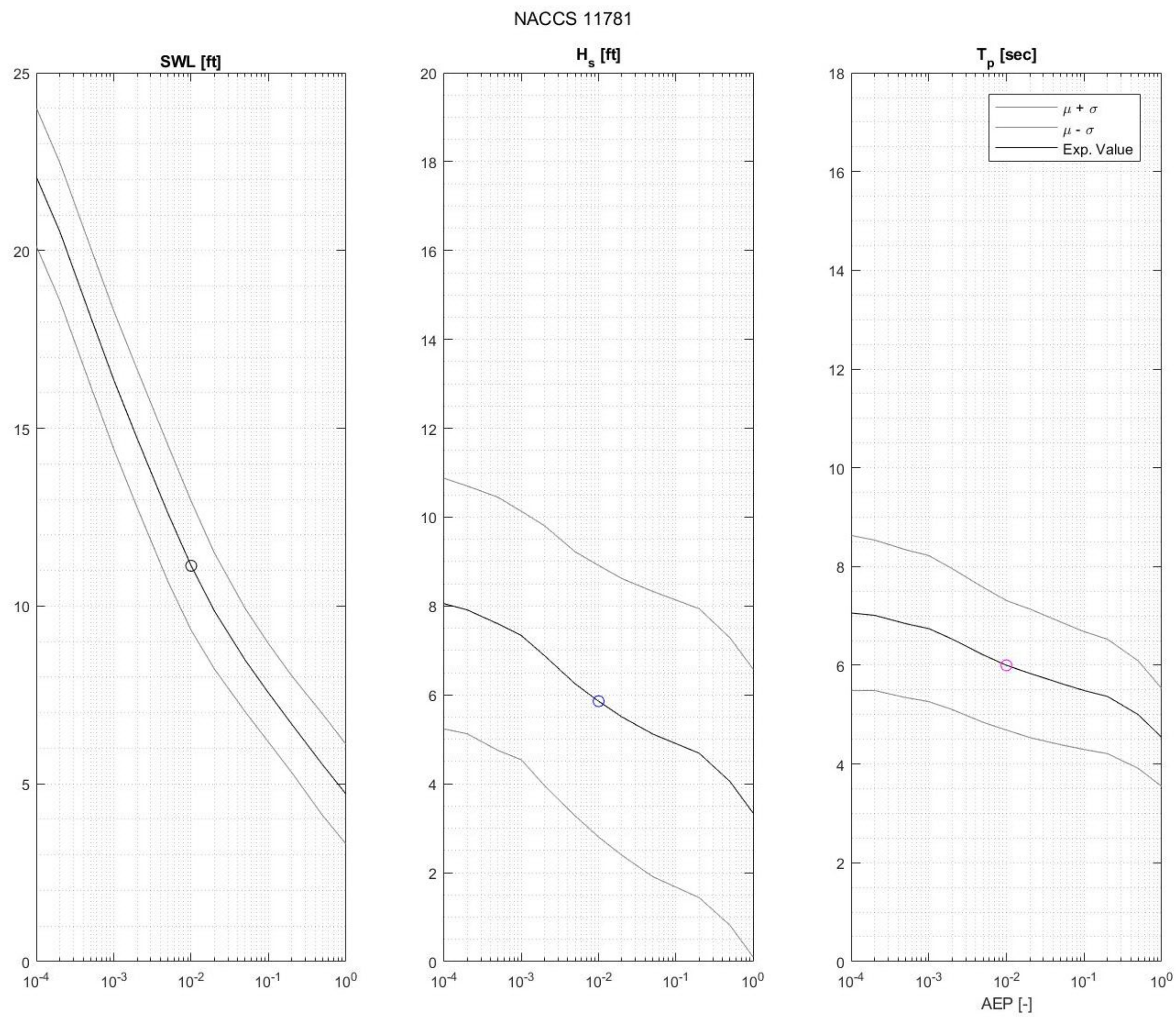

Figure 1-2: Mean values and standard deviations for still water level level, sign. wave height and peak wave period (one standard deviation up and down indicated by the grey bands).

1.2.3 Water Levels and Wave Characteristics for each Storm Surge Barrier

For each storm surge barrier, a NACCS save point in close vicinity to the storm surge barriers was selected. The selection of save points for the SSBs is listed in Table 1-1. The water levels vs return period and the wave-height and peak wave period vs return period statistics, both mean (μ) and the standard deviation (σ) at these locations from the data set as described in 1.2.1 are tabulated in Table 1-2. The tabulated water levels do not include sea level change (SLC). Sea level change is discussed separately in the following section.

Table 1-1: Storm Surge Barriers and Selected NACCS Output Stations for Water Levels and Waves

Storm Surge Barrier	HAT Study Alternative	NACCS output station	Bathymetric Elevation in front of Structure [ft NAVD88]	NOAA SLC Gauge
Verrazano Narrows	3A	11781	-50	Battery
Throgs Neck	2 and 3A	4347	-40	Kings Point
Arthur Kill	3A and 3B	11650	-40	Sandy Hook
Outer Harbor	2	3900	-25	Sandy Hook
Kill van Kull	3B	11766	-55	Battery
Jamaica Bay	3A, 3B and 4	3592	-25	Sandy Hook
Hackensack River	4	11816	-23	Battery
Flushing Creek	4	13059	-21	Kings Point
Newtown Creek	4	13898	-20	Battery
Gowanus Canal	4	11862	-22	Battery
Sheepshead Bay	3A, 3B and 4	11967	-20	Sandy Hook
Gerritsen Creek	3A, 3B and 4	14085	-19	Sandy Hook

Table 1-2: Water Levels (without SLC) and Waves for NACCS Output Points of Interest

Return Period	Still Water Level μ [ft NAVD88]	Still Water Level σ [ft]	Significant Wave Height μ [ft]	Significant Wave Height σ [ft]	Peak Wave Period μ [sec]	Peak Wave Period σ [sec]
NACCS output point 11781						
100	11.1	1.8	5.9	3.1	6.0	2.0
500	14.7	1.9	6.9	2.9	6.5	2.2
1000	16.4	1.9	7.3	2.8	6.8	2.3
NACCS output point 4347						
100	13.0	1.8	4.3	3.2	5.6	1.4
500	16.6	2.0	4.5	3.1	5.8	1.4
1000	18.3	2.0	4.6	3.1	5.9	1.5
NACCS output point 11650						
100	12.7	1.8	3.8	3.2	5.4	1.2
500	16.7	2.0	4.4	3.2	5.8	1.3
1000	18.4	2.0	4.6	3.2	5.9	1.3
NACCS output point 3900						
100	10.4	1.8	16.1	3.2	14.1	4.5
500	13.9	1.9	16.8	3.1	14.5	4.6
1000	15.5	1.9	17.1	3.1	14.6	4.6

Return Period	Still Water Level μ [ft NAVD88]	Still Water Level σ [ft]	Significant Wave Height μ [ft]	Significant Wave Height σ [ft]	Peak Wave Period μ [sec]	Peak Wave Period σ [sec]
NACCS output point 11766						
100	11.4	1.8	6.0	3.2	6.2	1.2
500	15.0	1.9	6.2	3.2	6.3	1.2
1000	16.7	1.9	6.3	3.2	6.3	1.2
NACCS output point 3592						
100	9.8	1.8	4.8	3.2	5.7	1.1
500	12.6	1.9	5.1	3.2	5.8	1.1
1000	13.9	1.9	5.2	3.2	5.9	1.1
NACCS output point 11816						
100	10.7	2.0	3.2	3.3	5.3	1.0
500	13.1	2.0	3.6	3.2	5.6	1.1
1000	14.1	2.0	3.7	3.2	5.7	1.1
NACCS output point 13059						
100	13.2	1.9	3.3	3.2	5.9	1.3
500	16.8	2.0	3.5	3.3	6.1	1.4
1000	18.6	2.0	3.5	3.2	6.1	1.4
NACCS output point 13898						
100	11.0	1.8	3.7	3.2	5.4	1.2
500	14.6	1.9	4.1	3.2	5.7	1.3
1000	16.2	1.9	4.3	3.2	5.8	1.3
NACCS output point 11862						
100	11.3	1.9	3.7	3.2	5.3	1.1
500	15.0	2.0	4.0	3.2	5.5	1.1
1000	16.7	2.0	4.1	3.2	5.6	1.2
NACCS output point 11967						
100	9.9	1.8	5.2	3.2	5.9	1.1
500	13.1	1.9	5.6	3.2	6.2	1.2
1000	14.6	1.9	5.8	3.2	6.2	1.2
NACCS output point 14085						
100	9.9	1.8	4.0	3.2	5.2	1.0
500	13.1	1.9	4.6	3.1	5.6	1.1
1000	14.6	1.9	4.9	3.1	5.7	1.1

1.2.4 Increase in SWL due to FWP Conditions

The Storm Surge Barrier has the function to impede storm surge and reduce the risk of flooding for the area behind it. In the scenario without the storm surge barriers, storm surge water levels have an unconstrained floodplain to flood. With a storm surge barrier in place, the existing floodplain is altered, causing more constraint and, in some instances, an increase in storm surge elevations on the flood side of the SSB. i.e. storm surge propagation will be different in the Future With Project (FWP) Condition than in the Future Without Project (FWOP) Condition as a result of the physical presence of the storm surge barrier. ERDC analyzed these conditions through additional ADCIRC simulations that included the FWP conditions for the HAT Study Alternatives (McAlpin, 2018). Based on these simulations additional water level hazard results were provided. NYNJ-HAT's water level hazards results included stage frequency curves for FWOP, Alt2, Alt3a, Alt3b and Alt4. Based on this data set the increase in SWL as a result of the project (also referred to as induced flooding) can be estimated for the 1% AEP SWL conditions. This increase was established as the maximum difference for the 1% AEP condition between the FWOP and the relevant FWP alternatives for each storm surge barrier. For each SSB an output point in close vicinity to the barrier was selected to establish this value and was subsequently included within the MC Simulations. This increase is assumed to be a linear addition to the 1% AEP SWL.

Table 1-3: Increase in 1% AEP SWL for FWP Conditions based on data from ERDC (October 2019)

Storm Surge Barrier	Increase in 1% AEP SWL for FWP conditions (compared to FWOP condition) [ft]
Verrazano Narrows	1.28
Throgs Neck	0.36
Arthur Kill	1.11
Outer Harbor	1.00
Kill van Kull	0.54
Jamaica Bay	2.13
Hackensack River	3.63
Flushing Creek	0.04
Newtown Creek	0.81
Gowanus Canal	0.17
Sheepshead Bay	1.18
Gerritsen Creek	1.35

1.2.5 Sea Level Change

Sea Level Change (SLC) is included in the Monte Carlo Simulations by increasing water levels as tabulated in Table 1-7. This value accounts for the change in Mean Sea Level (MSL) at a NOAA gauge between the middle of the current tidal epoch and the year 2105 using USACE's intermediate scenario. SLC is accounted for by selecting the NOAA gauge that is in close proximity of the SSB as tabulated in Table 1-1. The year 2105 is used as the end of the 50-year planning horizon for all storm surge barriers under the HAT Study. For completeness and comparison SLC values for USACE's high scenario, New York State's high projection and other years of interest are also presented, e.g. year 2055 indicates assumed year for construction completion. A graphical depiction of projections at the Battery is provided in Figure 1-3. SLC is assumed to be a linear addition to the AEP water levels [demonstrated in the NACCS report (USACE ERDC, 2015)] and uncertainty in SLC is not accounted for within the Monte Carlo Simulation.

Table 1-4: Sea Level Change per USACE's Intermediate and High scenarios for primary gauges within HAT Study region as well as New York State High Sea Level Rise Scenario for years of interest

Gauge Location (SLC in feet)	Gauge ID	1992	2030	2055	2105	2155
USACE's Intermediate Scenario[1]						
Sandy Hook	8561680	0.00	0.62	1.17	2.61	4.49
The Battery	8518750	0.00	0.49	0.96	2.22	3.92
Kings Point	8516945	0.00	0.42	0.84	2.01	3.63
USACE's High Scenario[1]						
Sandy Hook	8561680	0.00	1.03	2.29	6.21	11.97
The Battery	8518750	0.00	0.90	2.08	5.82	11.41
Kings Point	8516945	0.00	0.83	1.96	5.61	11.12
NY State High Projection[2,3]						
The Battery	8518750	0	1.16	2.60	6.86	N/A

Notes:

1. *Sea Level Change Projections using NOAA's regional rates. USACE's projections beyond the year 2100 are calculated using the equations from ER 1100-2-8162.*
2. *The base line year for NY State projections is 2002. Values are adjusted for X inches of SLR between the year 1992 and 2002 to provide values comparable with USACE's scenarios.*
3. *The values for year 2105 and 2155 are extrapolated using an exponential fit to the data.*

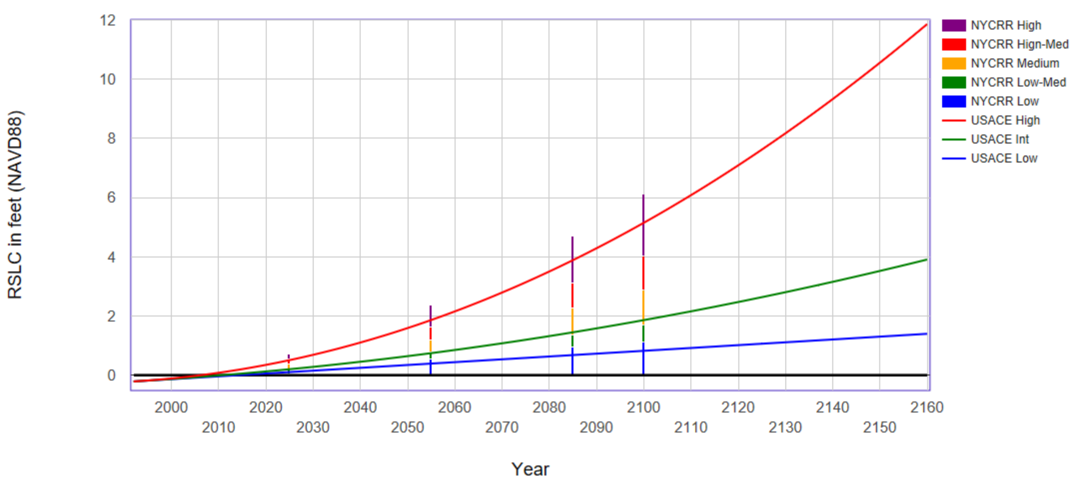

Figure 1-3: Estimated Relative Sea Level Change Projections – Gauge: 8518750, The Battery, NY

1.2.6 Summary: Water Levels and Waves

Water levels and wave parameters are summarized in Table 1-5. This summary presents base still water level levels for the 1%, 0.2% and 0.1% (100-Year, 500-Year and 1000-Year return period) AEP storm events acquired from the NACCS output points at vicinity of the storm surge barriers for the year 1992 (no sea level change). It also presents the adjusted still water level levels using the USACE intermediate sea level change curve, significant wave heights from the NACCS and the calculated associated wave peak periods Tp.

Table 1-5: Still water level Levels and Wave Characteristics for the selected NACCS Output Points near the Storm Surge Barriers

SSB	NACCS ID	RP	SWL 1992 (ft NAVD88)	SWL 2055 (ft NAVD88)	SWL 2105 (ft NAVD88)	SWL 2155 (ft NAVD88)	Hs [ft]	Tp [sec]
Verrazano Narrows	11781	100	12.4	13.4	14.6	16.3	5.9	6.0
		500	16.5	17.5	18.8	20.5	6.9	6.5
		1000	18.4	19.3	20.6	22.3	7.3	6.8
Throgs Neck	4347	100	13.4	14.2	15.4	17.0	4.3	5.6
		500	16.9	17.7	18.9	20.5	4.5	5.8
		1000	18.6	19.5	20.6	22.2	4.6	5.9
Arthur Kill	11650	100	13.9	15.0	16.5	18.3	3.8	5.4
		500	18.2	19.3	20.8	22.7	4.4	5.8
		1000	20.1	21.3	22.7	24.6	4.6	5.9
Outer Harbor	3900	100	11.4	12.6	14.0	15.9	16.1	14.1
		500	15.1	16.2	17.7	19.6	16.8	14.5
		1000	16.7	17.9	19.3	21.2	17.1	14.6
Kill van Kull	11766	100	11.9	12.9	14.2	15.9	6.0	6.2
		500	15.8	16.7	18.0	19.7	6.2	6.3
		1000	17.5	18.5	19.8	21.5	6.3	6.3
Jamaica Bay	3592	100	11.9	13.1	14.5	16.4	4.8	5.7
		500	15.4	16.5	18.0	19.8	5.1	5.8
		1000	16.9	18.0	19.5	21.4	5.2	5.9
Hackensack River	11816	100	14.4	15.3	16.6	18.3	3.2	5.3
		500	17.5	18.4	19.7	21.4	3.6	5.6
		1000	18.7	19.7	20.9	22.6	3.7	5.7
Flushing Creek	13059	100	13.3	14.1	15.3	16.9	3.3	5.9
		500	16.9	17.7	18.9	20.5	3.5	6.1
		1000	18.6	19.4	20.6	22.2	3.5	6.1

SSB	NACCS ID	RP	SWL 1992 (ft NAVD88)	SWL 2055 (ft NAVD88)	SWL 2105 (ft NAVD88)	SWL 2155 (ft NAVD88)	Hs [ft]	Tp [sec]
Newtown Creek	13898	100	11.8	12.7	14.0	15.7	3.7	5.4
		500	15.6	16.5	17.8	19.5	4.1	5.7
		1000	17.3	18.3	19.5	21.2	4.3	5.8
Gowanus Canal	11862	100	11.4	12.4	13.7	15.4	3.7	5.3
		500	15.2	16.2	17.4	19.1	4.0	5.5
		1000	16.9	17.9	19.2	20.9	4.1	5.6
Sheepshead Bay	11967	100	11.1	12.3	13.7	15.6	5.2	5.9
		500	14.9	16.1	17.6	19.4	5.6	6.2
		1000	16.7	17.8	19.3	21.2	5.8	6.2
Gerritsen Creek	14085	100	11.3	12.4	13.9	15.8	4.0	5.2
		500	15.2	16.4	17.8	19.7	4.6	5.6
		1000	16.9	18.1	19.5	21.4	4.9	5.7

1.3 Storm Surge Barrier Characteristics

For all overtopping discharge equations, structure characteristics are part of the input variables. Number and type of key structure characteristics depend on the type of structure and equation used, but typically include; the relative freeboard (the difference between the crest of the structure and the still water level), the slope of the structure and the ground elevation in front of the structure[3]. Storm surge barrier characteristics are shown in Table 1-6.

Table 1-6: Storm Surge Barrier Characteristics for Overtopping Calculations.

Storm Surge Barrier	Crest Elevation Range [ft NAVD88]	Bathymetric Elevation in front of Structure[1] [ft NAVD88]
Verrazano Narrows	To be determined, assumed to be between +18 and +22	-50
Throgs Neck	TBD, between +17 and +20	-40
Arthur Kill	TBD, between +17 and +20	-40
Outer Harbor	TBD, between +27 and +46	-25
Kill van Kull	TBD, between +18 and +22	-55
Jamaica Bay	TBD, between +16 and +19	-25
Hackensack River	TBD, between +17 and +20	-23

[3] In addition, when applicable, coefficients can be used to characterize the roughness of the structural elements placed on the structure slope, the presence of a berm or break in the slope, the influence of oblique wave attack and/or the presence of parapet walls or recurved walls.

Storm Surge Barrier	Crest Elevation Range [ft NAVD88]	Bathymetric Elevation in front of Structure[1] [ft NAVD88]
Flushing Creek	TBD, between +17 and +20	-21
Newtown Creek	TBD, between +18 and +22	-20
Gowanus Canal	TBD, between +15 and +18	-22
Sheepshead Bay	TBD, between +16 and +21	-20
Gerritsen Creek	TBD, between +16 and +19	-19

Notes:

1. *For the barriers in relative deep water the overtopping discharge rate is assumed not to be influenced by the foreshore.*
2. *All Storm Surge Barriers are assumed to be vertical coastal structures*

1.4 Overtopping Formulations

The means and standard deviations of the wave overtopping rates are calculated based on the most recent version of the EurOtop II Manual (Van der Meer, et al., 2018). The storm surge barrier structures are preliminarily schematized as vertical in-water walls and are within the following principal classification of structure type per EurOtop, 2018 manual: “Vertical and Steep Walls”. As such, the structures are relatively straightforward and structure slopes or roughness coefficients can be omitted. Details on the overall structure characteristics are provided in Table 1-6. Refer to the main body of the Engineering Appendix for additional detail and sections for the structures presented herein. Details on the specific overtopping discharge equation coefficients per EurOtop II are provided in Table 1-7.

A freeboard criterion as described in EurOtop, 2018, section 5.3.4 was incorporated to account for still water level level above the structure crest. If the still water level level is below or at the structure crest (freeboard ≤ 0ft), the wave overtopping equations are used. If the still water elevation is above the structure crest elevation, and the difference is small relative to the wave height ((SWL – Crest)/Hs < 0.3), wave overtopping equations with an assumed freeboard of 0ft are used and weir flow is added. If the still water elevation is above the structure crest elevation, and the difference is large relative to the wave height ((SWL – Crest)/Hs > 0.3), weir flow equations are used (weir flow is dominant physical process).

Table 1-7: Overtopping Discharge Equation Coefficients

Section	Relevant EurOtop II Manual Equation[1]	Equation Coefficient	Coefficient (mean)	Coefficient (std)
Vertical and Steep Walls	Equation 7.2	Coefficient a	0.047	0.007
		Coefficient b	2.35	0.23
	Equation 7.5	Coefficient a	0.05	0.012
		Coefficient b	2.78	0.17
	Equation 7.7	Coefficient a	0.011	0.0045
	Equation 7.8	Coefficient a	0.0014	0.0006

Notes:

1. *Equations numbers refer to the overtopping discharge equations in EurOtop Manual II (Van der Meer, et al., 2018).*

1.5 Overtopping Monte Carlo Simulation Algorithm

1.5.1 A Monte Carlo simulation algorithm was used to estimate wave overtopping rates at the 90% Confidence Limit. General Process of Algorithm

The project reaches, SSB characteristics and hydrodynamic input parameters described in the preceding sections were tabulated and formatted such that they could be read in by a MATLAB routine. An algorithm was coded in MATLAB to complete the Monte Carlo Simulation for each SSB such that it was able to compute the probability distribution function (and the confidence limits of exceedance) of the overtopping rate. The Monte Carlo Analysis algorithm covered the following steps:

1. Read input file for reach and structure characteristics (structure elevation, ground elevation, slope, assigned NACCS output point, etc.).
2. Compute the 1% AEP water level using a normal distribution with the mean and standard deviation as provided for the specific NACCS point. A random number between 0 and 1 is drawn to randomly select a water level from the defined normal distribution.
3. Compute a 1% AEP wave height and peak period using a normal distribution with the mean and standard deviation as provided for the specific NACCS point. A random number between 0 and 1 is drawn to randomly select the wave characteristics from the defined normal distributions.
4. Compute the overtopping rate with the input from the preceding steps.
5. Repeat Steps 2, 3 and 4 a large number of times (N times).
6. Sort all results and compute the probability density function and cumulative probability density function. Compute the 50% CL and the 90% CL for the overtopping rate[4] for the specific reach and structure.
7. Provide graphic results of the simulations and tabulate run results.

Test runs were completed that show that the number of simulations should be approximately 40,000 to reach a result that bring the estimate for the 90% CL overtopping rate within 1 l/s/m from the statistically stationary result.

1.6 Storm Surge Barrier Crest Elevations

1.6.1 Screening Cases

The various permutations of project SSBs and potential crest elevations were tabulated and converted into a matrix with run cases. A run case represents input settings for which a total of

[4] Analysis conducted herein is based on the 90% CL. 50% CL was not used in this analysis but was documented for thoroughness.

100,000 Monte Carlo simulations are completed. For each run case the 90% CL overtopping rate is compared to the threshold criteria and a positive finding is reported if the 90% CL is below the threshold criterion. All waves are assumed to be perpendicular to the coastal structure and, therefore, the wave obliqueness factor is conservatively set at 1.0 (γ_β).

1.6.2 Screening Results for the 1% AEP conditions

The Monte Carlo simulations and additional postprocessing resulted in the probability density function and cumulative probability density function for the overtopping discharge rate for each run case. An example of the graphical output is provided in Figure 1-4. The figure shows that, for this particular case, the 90% CL overtopping discharge rate is less than the threshold criterion (the red vertical line) and that the criterion is met. Furthermore, Figure 1-4 illustrates that the uncertainty in overtopping for the SSB as a result of the input variables is reflected in the "stretched-out" S-shape of the cumulative distribution function. The 90% CL value is an order of magnitude larger than the 50% CL value for the 1% AEP event and are 147 l/s/m and 45 l/s/m respectively. 50% CL and 90% CL for the overtopping are highlighted with the blue markers in the figure below.

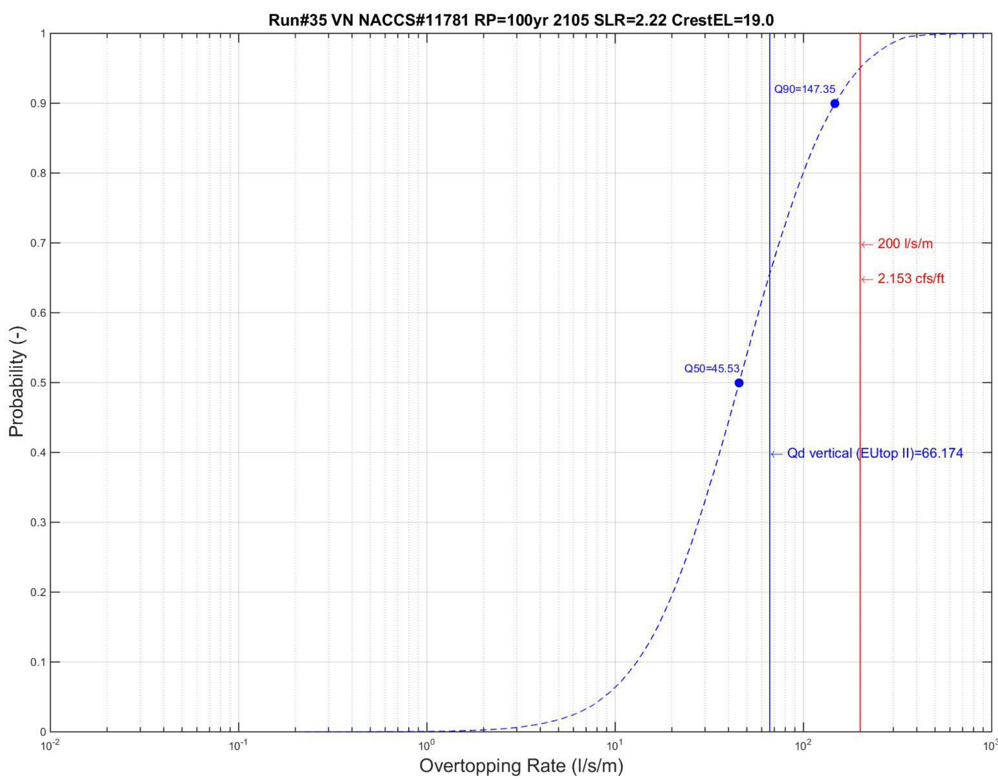

Figure 1-4: Example of graphical output for the Verrazano Narrows Storm Surge Barrier with a crest elevation of +19ft NAVD88 – cumulative distribution function of overtopping discharge rate for the 1% AEP conditions in 2105 using NACCS output point 11781.

For each of the tested crest elevations the 90% CL overtopping rate for the 1% AEP conditions is available. 90% CL overtopping rates can then be plotted against the SSB crest elevation for the year 2105. Figure 1-5 shows 90% CL overtopping rate for the 1% AEP conditions for Verrazano Narrows SSB with crest elevations of +17ft, 18ft, +19ft and +20ft for the year 2105 as red line. It can be seen that a crest elevation of +19ft is sufficient to meet the overtopping criterion in the year 2105. In addition, the figure provides the same information for two other years of interest; year 2055 and year 2155 in blue and green respectively. 1% AEP conditions include the intermediate scenario for SLC. For future years beyond 2105, under the assumption of the intermediate SLC scenario, overtopping rates are expected to exceed the criterion of 200 l/s/m.

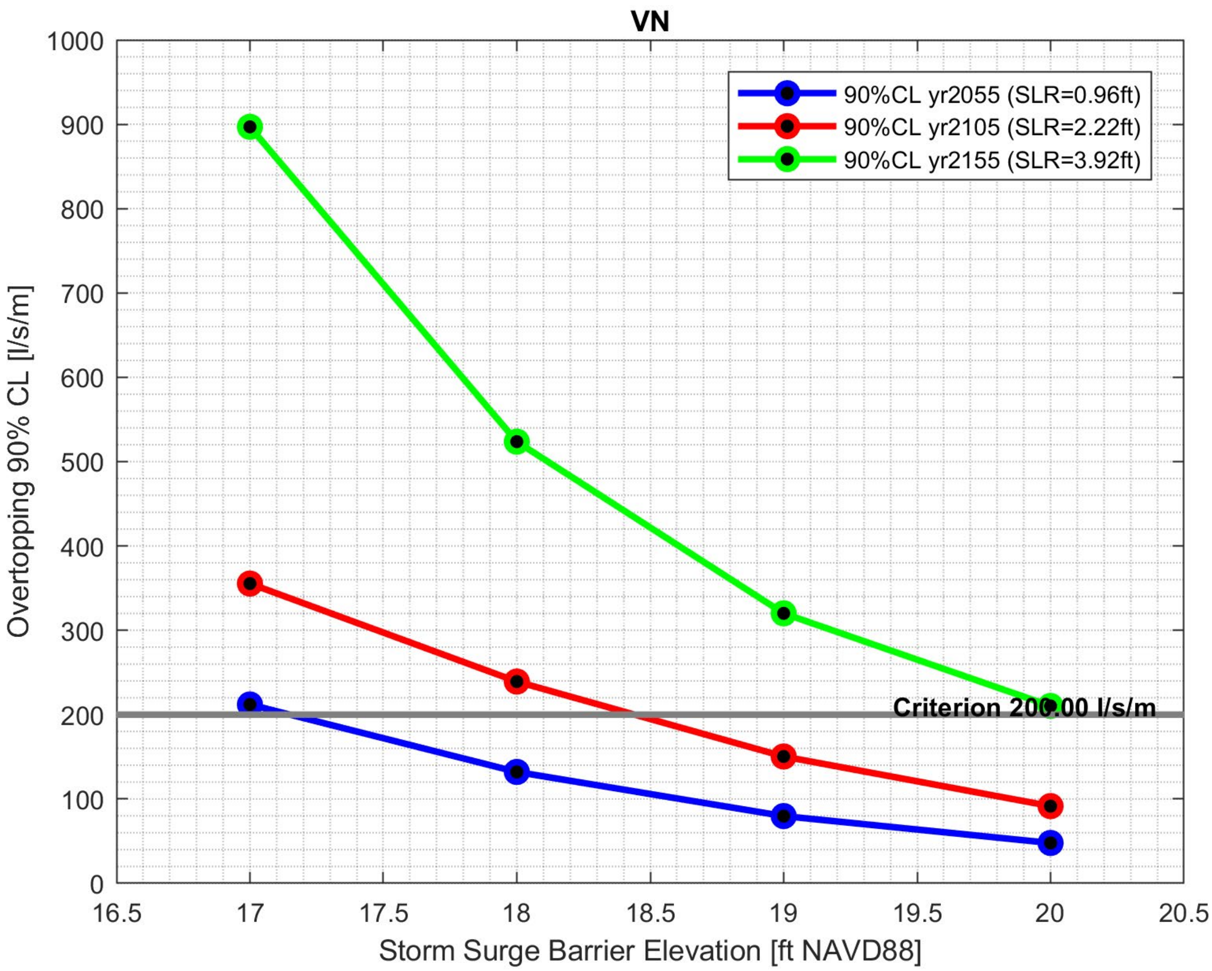

Figure 1-5: 90% CL overtopping rates for the 1% AEP conditions for Verrazano Narrows SSB with crest elevations of +17ft, 18ft, +19ft and +20ft. 90% CL overtopping rates are shown for the years 2055, 2105 and 2155.

1.6.3 Storm Surge Barrier Crest Elevations

For all storm surge barriers, a screening analysis was completed and a SSB crest elevation was established such that the overtopping criterion is met. Crest elevations are set in increments of 1ft which is deemed appropriate and reflective of the level of detail for the feasibility level design of the storm surge barriers. The 50% and 90% CL results from the Monte Carlo Analysis for the 1% AEP conditions in 2105 are summarized in the last two columns of Table 1-8. The 0.2% AEP still water level levels are presented for reference and it can be noted that for the Arthur Kill, Hackensack River, Flushing Creek, Newtown Creek, Gowanus Canal, Sheepshead Bay and Gerritsen Creek storm surge barriers, the 0.2% AEP still water level level in the year 2105 (USACE intermediate Sealevel change) exceeds the storm surge barrier crest elevation.

Table 1-8: Monte Carlo Analysis Overtopping Results 2105 USACE Intermediate Sea Level Change.

Storm Surge Barrier	Interim Report Crest Elevation [ft NAVD88]	Crest Elevation [ft NAVD 88]	Year	AEP Condition	1% AEP SWL	0.2% AEP SWL	Case ID	50% CL Overtopping rate [l/s/m]	90% CL Overtopping rate [l/s/m]
Verrazano Narrows	+22	+19	2105	1%	14.6	18.8	35	46.1	150.4
Throgs Neck	+20	+19	2105	1%	15.4	18.9	43	22.3	113.8
Arthur Kill	+19	+19	2105	1%	16.5	20.8	47	30.9	169.4
Outer Harbor	+46	+29	2105	1%	14.0	17.7	63	102.4	174.3
Kill van Kull	+21	+19	2105	1%	14.2	18.0	52	40.6	127.4
Jamaica Bay	+18	+18	2105	1%	14.5	18.0	39	35.9	138.7
Hackensack River	+18	+19	2105	1%	16.6	19.7	55	19.3	171.6
Flushing Creek	+18	+18	2105	1%	15.3	18.9	266	15.0	117.7
Newtown Creek	+17	+17	2105	1%	14.0	17.8	59	19.0	111.8
Gowanus Canal	+17	+16	2105	1%	13.7	17.4	262	31.7	186.2
Sheepshead Bay	+21	+17	2105	1%	13.7	17.6	270	53.6	190.1
Gerritsen Creek	+18	+17	2105	1%	13.9	17.8	275	23.7	126.8

1.6.1 Overtopping Rates under the High Sea Level Change Scenario

In addition to the established crest elevations based on the intermediate scenario of sea level change up to the year 2105, a sensitivity test is completed to investigate the overtopping rate in the year 2105 under a high sea level change scenario. The high sea level change scenario is based on the New York State projections and values are tabulated in Table 1-9.

Table 1-9: Monte Carlo Analysis Overtopping Results 2105 New York High Sea Level Change.

Storm Surge Barrier	Interim Report Crest Elevation [ft NAVD88]	Crest Elevation [ft NAVD88]	Year	AEP Condition	1% AEP SWL	0.2% AEP SWL	Case ID	50% CL Overtopping rate [l/s/m]	90% CL Overtopping rate [l/s/m]
Verrazano Narrows	+22	+19	2105	1%	19.3	23.4	134	408.5	1278.0
Throgs Neck	+20	+19	2105	1%	20.3	23.8	143	559.2	2114.6
Arthur Kill	+19	+19	2105	1%	20.7	25.0	146	687.6	2470.6
Outer Harbor	+46	+29	2105	1%	18.3	21.9	162	266.8	431.3
Kill van Kull	+21	+19	2105	1%	18.8	22.6	151	353.7	1050.9
Jamaica Bay	+18	+18	2105	1%	18.7	22.2	138	473.2	1612.7
Hackensack River	+18	+19	2105	1%	21.2	24.3	154	1005.3	3193.6
Flushing Creek	+18	+18	2105	1%	20.1	23.7	373	933.5	2925.0
Newtown Creek	+17	+17	2105	1%	18.6	22.4	159	949.7	2882.6
Gowanus Canal	+17	+16	2105	1%	18.3	22.1	374	1075.2	3105.3
Sheepshead Bay	+21	+17	2105	1%	18.0	21.8	375	602.1	1875.9
Gerritsen Creek	+18	+17	2105	1%	18.1	22.0	376	491.0	1995.6

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