US Army Corps of Engineers®
New York District

Storm Surge Barrier Sub-Appendix

Annex D – Storm Surge Barrier Closure Frequency and Closure Duration Analysis

DRAFT

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

Annex B2.D

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1 Introduction

The framework and preliminary results of the closure frequency and closure duration analysis performed for the New York and New Jersey Harbor and Tributaries Coastal storm Risk Management Study (HATS) is presented herein. The main purpose of this analysis is to evaluate time related parameters of the storm surge barrier (SSB) operations using statistical methods and provide data for risk informed decision-making. This would aid the selection of optimal parameters for the barrier operation and configuration. Results are presented to inform the choice of water level criterion for closure of SSB gates and the expected duration of required closure before storm water levels recede and allow for re-opening the gates.

The current analysis is based on a statistical evaluation of parameters using a Monte-Carlo type approach. The total water level is considered a random variable and is computed as the sum of tidal water level, storm surge, and sea level rise (SLR) prediction. In the computation, tidal water levels and storm events are also selected randomly, while the local mean sea level is computed according to a SLR projection. The evaluation period for this analysis which was mostly conducted to extend up to the preliminary expected end-date of service life (in 2105) for HATS ranges from 2050 to 2110. The current 100-year planning horizon for HATS is understood to be from 2045 to 2145. The barrier closure and opening operations are evaluated for each storm event during the evaluation period and is based on selected thresholds, such as closure elevation.

The results of the statistical analysis include the following parameters:

- Frequency of closures in each year over the evaluation period; the rate of change in frequency depends on the SLR scenario;
- Expected closure duration in each year depending on the SLR scenario;

The statistical results can be used as an input into the risk informed decision-making framework to refine operational SSB gate closure parameters and further inform the need for perimeter flood risk reduction measures aroudn the basin behind the SSB.

The analysis methodology, preliminary results, and conclusions are presented in the following sections.

2 Methodology

2.1 Definitions of key parameters

The analysis assumes the following definitions of the closure criterion and the closure elevation:

- The closure criterion is the forecasted water level for which operation of a storm surge barrier is authorized to reduce flood risk for the region behind it.

- The closure elevation is the observed water level at which the mechanical closure procedure is executed.

The closure elevation is lower than the closure criterion to safely maintain water levels below the threshold criterion within the basin. A rise in basin water levels after closure can result from the following processes (among others): riverine inflow, rainfall, municipal discharges/inflows, wind setup, wave overtopping and atmospheric pressure variations generated by the storm. Variations in closure elevation for a given closure criterion are investigated in this analysis.

The closure criterion is illustrated in Figure 2-1 with the red circle. In the example, the forecasted water level exceeds the closure criterion, therefore, SSB closure is authorized. The closure of the SSB gates occurs when the water level reaches the closure elevation. In the analysis, it is assumed that the closure operation occurs instantly. However, in reality the physical closure of the gates of a SSB would take time and start prior to the water levels reaching the closure elevation. Furthermore, the timing for initiation of the SSB gate closure depends also on many non-hydraulic factors which are omitted from this analysis.

The closure duration is the time interval between gate closure and gate opening. The assumption is that the SSB gates can be opened once the peak(s) of the storm surge has passed and water levels on the flood side of the SSB are falling and are equal to or just below the water levels within the basin. The closure duration is illustrated in Figure 2-1. In the example, the closure duration is shown as the minimum interval during which the gates remain closed. In the analysis, the opening is assumed to occur instantly. However, in reality, the gate opening will also take time.

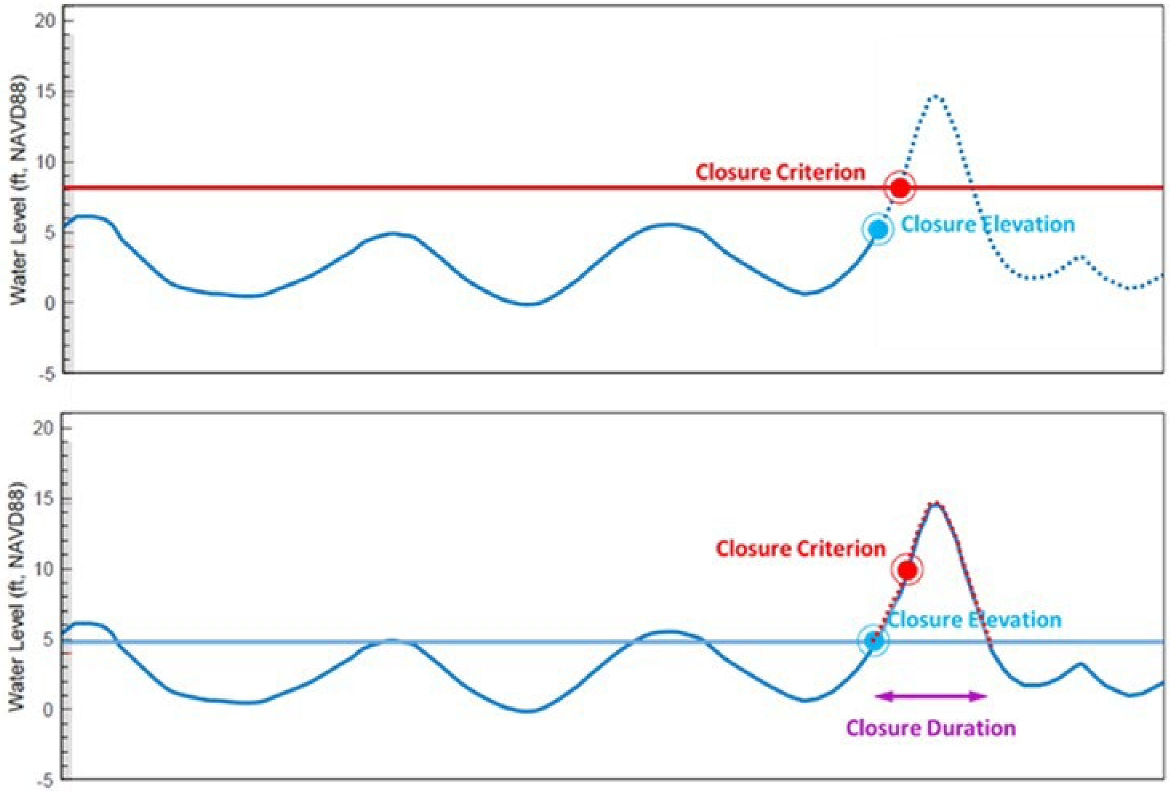

Figure 2-1: Water level and forecasted water level to illustrate the Closure Elevation and Closure Criterion (upper panel). Water level time series post storm to indicated closure duration (lower panel)

2.2 Monte Carlo Analysis Framework

A Monte Carlo (MC) Analysis for a probabilistic analysis of the likelihood and duration of closure was completed for which the framework is described below.

The goal of the Monte Carlo analysis is to use a large population of outcomes to statistically describe various parameters. For this analysis, a large number of synthetic storm hydrographs for both current and future years are generated and for each individual hydrograph the closure criterion is checked. If the closure criteria are met, the closure duration is recorded. A total of 50,000 MC simulations is completed for 10 points in time spanning the years 2010 through 2120. A schematic of this basic outline of the methodology is provided in the graphic below (Figure 2-2).

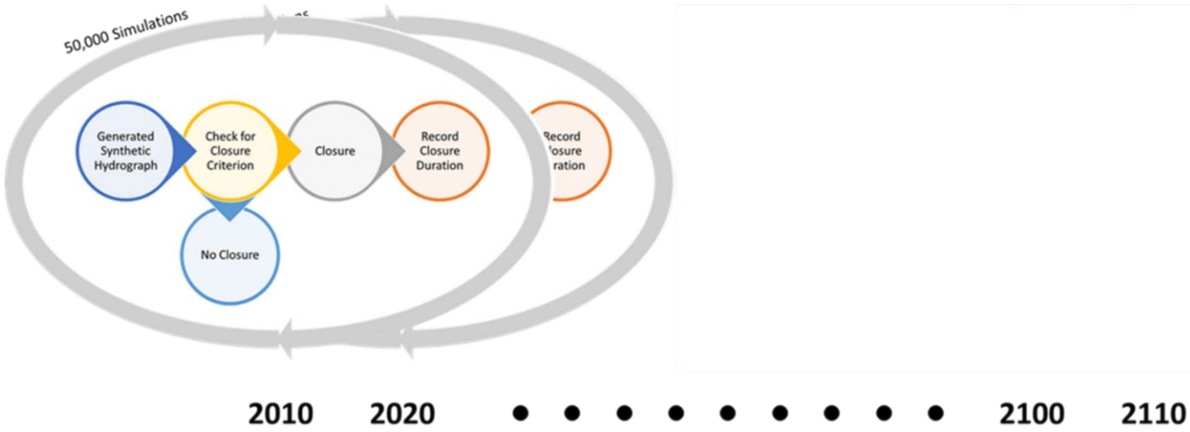

Figure 2-2: Schematic of the Analysis Methodology

The framework for one Monte Carlo simulation is schematically depicted in Figure 2-3 and each simulation uses the following predetermined information:

- Stage Frequency Curve for the SSB,
- A description of recurrence ratios for tropical and extratropical cyclones, and
- A storm hydrograph database.

These parts are briefly described below.

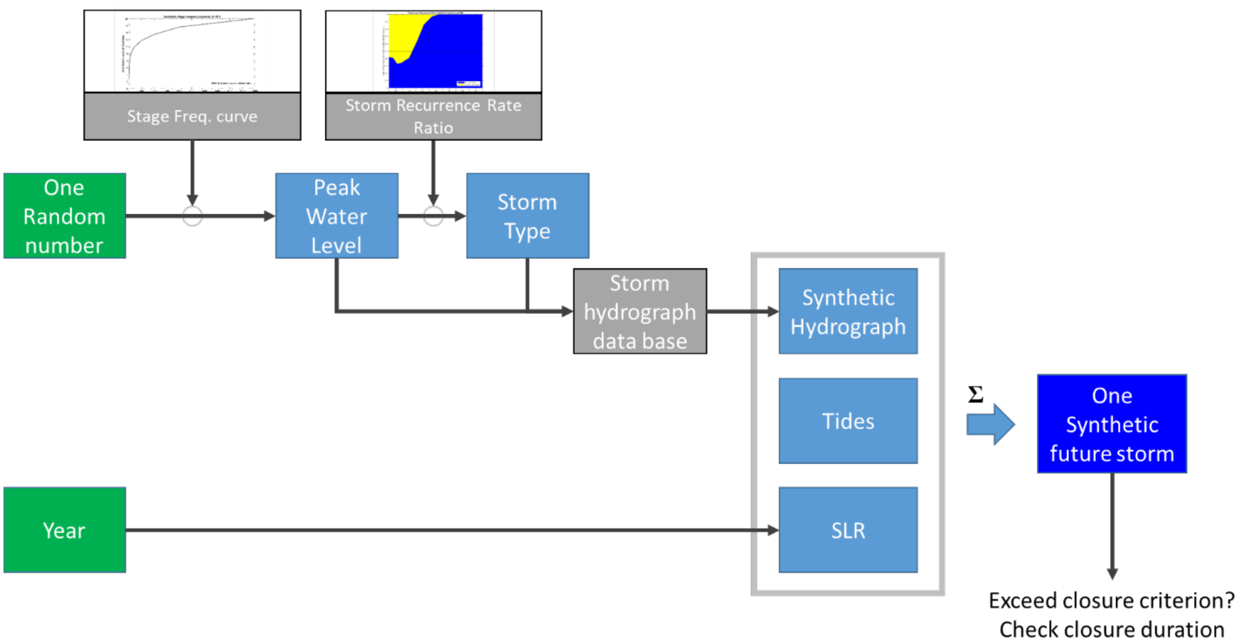

Figure 2-3: Individual Monte Carlo Simulation Framework

2.2.1 Storm Stage Frequency Curve

The North Atlantic Coast Comprehensive Study (NACCS) data sets 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 study and are based on the ADCIRC modeling component of NACCS. The stage frequency curve for The Battery (Save Point ID: 7673 expected values) is used in this analysis (Figure 2-4). The Battery water levels are representative of the water levels within the upper New York Harbor and, for example, can be used to inform closure of the Verrazano Narrows or the Kill van Kull SSBs. The stage frequency curve is obtained from the NACCS simulations for the base conditions (without tides) such that tides can be added in separately in the analysis.

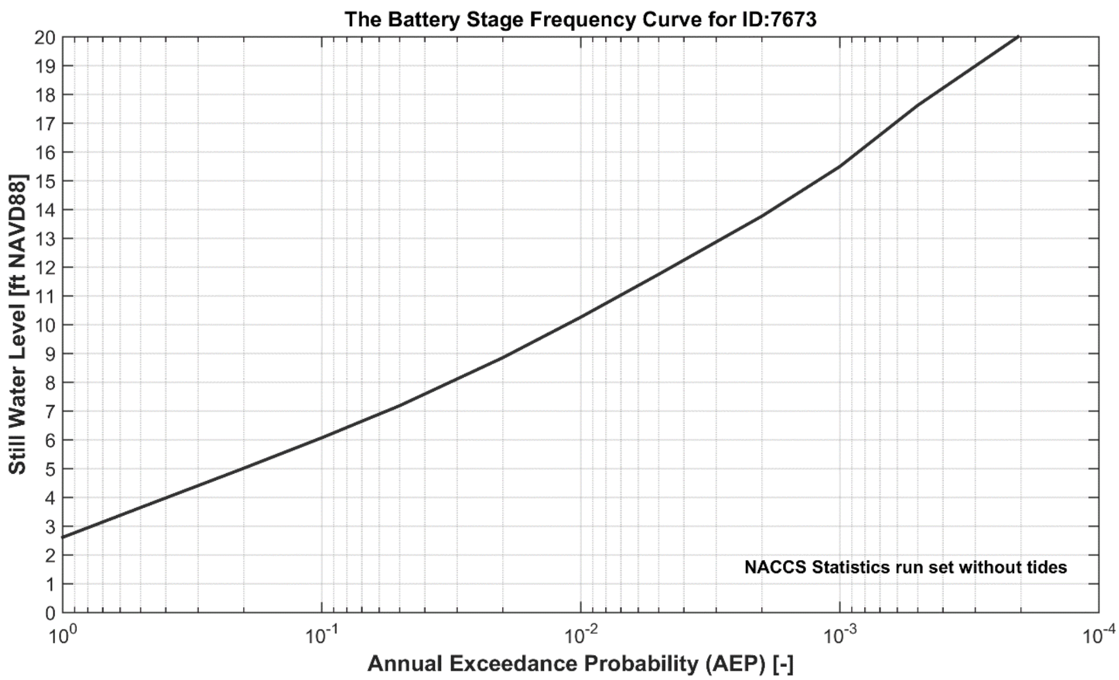

Figure 2-4: Stage Frequency Curve (expected values) for AEP

2.2.2 Storm Recurrence Ratios

The flood hazard for the New York areas is determined by the potential occurrence of both tropical cyclones (TCs) and extratropical cyclones (XCs). The flood hazard curve for The Battery combines the probabilities and responses from both TCs and XCs (NACCS TR-15-5). Although many differences exist between TCs and XCs, for this analysis it is important to highlight two general observations that result from their difference in structure and wind field. First, the peak water levels for high intensity XCs are lower than those generated by high intensity TCs. The speed of forward movement of XCs is generally lower than that of TCs and as a result the storm surge component of the total water level observations lasts longer than for TCs. For the analysis of closure duration, the shape of the storm surge hydrograph (peak storm surge and duration of storm surge) is important and as such, both the TCs and XCs need to be represented within the synthetic data set.

TR-15-5 provides the mean water level hazard curve for both TCs and XCs at The Battery. These curves are then compared to the total water level hazard curve (Figure 2-5) and the contribution of each event type is represented as a ratio to the total water level.

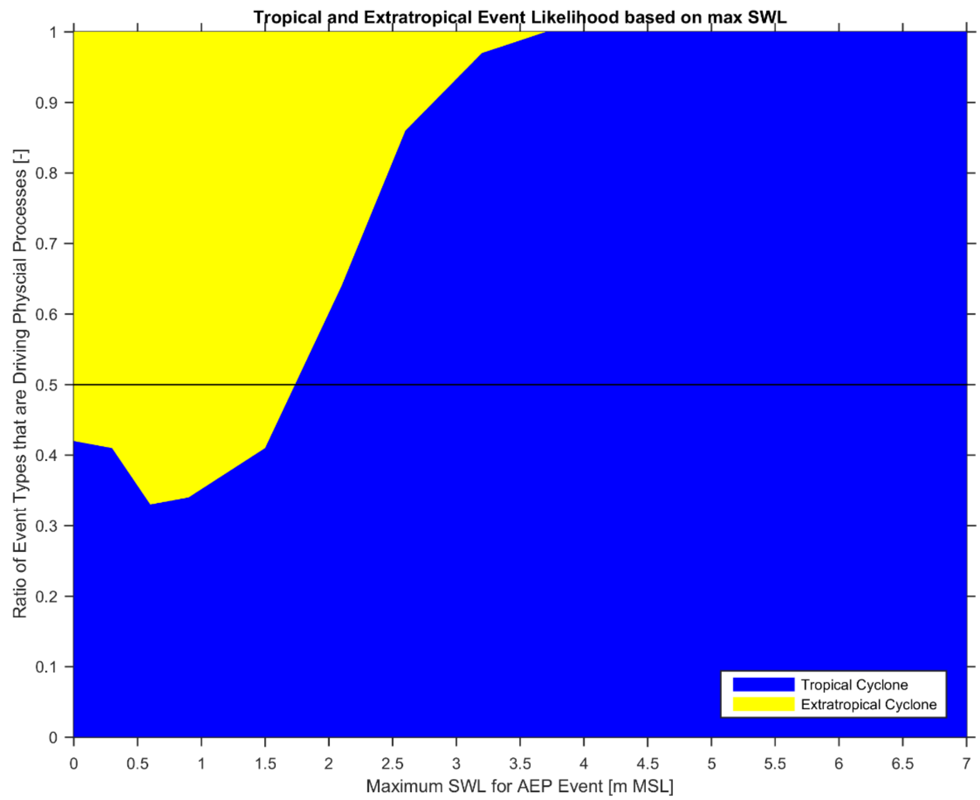

Figure 2-5: Ratio of Event Types (Tropical and Extratropical Cyclones) for maximum Still Water Levels (SWL).

2.2.3 Storm Hydrograph Database

The ADCIRC modeling component of NACCS included a storm suite of 1031 tropical cyclones and 100 historic extra tropical cyclone events. This results in a total of 1131 storm surge hydrographs at The Battery with storm surge as low as 1 ft (0.3m), up to a maximum of 19.2ft (5.8m). However, only a limited number of severe to extreme storms are present within the storm suite and coverage over the full range of the stage frequency curve is needed to complete the analysis. The 1131 storm surge hydrographs are developed by scaling water levels to expand the NACCS set and create a database of synthetic storm surge hydrographs that covers all potential storm surges from 1ft (0.3m) up to the 23ft (7m), on a 0.01m resolution. This storm surge hydrograph database covers all potential events up to and beyond the 0.01% AEP (10,000-year RP). The peak of the hydrograph for each of the 1031 tropical cyclones is scaled up and down with

0.25m, by 0.01m increments, to generate 50 additional hydrographs. The peak of the hydrograph for each of the 100 extratropical cyclones is scaled up and down with 0.50m, by 0.01m increments, to generate 100 additional hydrographs. XC storms 007, 011 and 060 are scaled with higher factors to provide at least three different XC hydrographs in the range between +2.0 and +3.0 meter. The ADCIRC model accuracy for water level is approximately 0.5 meter. Based on this uncertainty (USACE ERDC, 2015), generating synthetic hydrographs by scaling within this range provides for a realistic yet large set of hydrographs. The database used for this analysis includes over 25,000 hydrographs, covers the full range of AEP events up to the 0.01%, and includes both XC and TC event hydrographs. Figure 2-6 below shows the distribution of hydrographs and storm type over the range of potential storm surge water levels between 0.3 m and 7 m. It should be noted that these are hydrographs for storm surge only. Tides are added separately and the methodology is discussed in the following section.

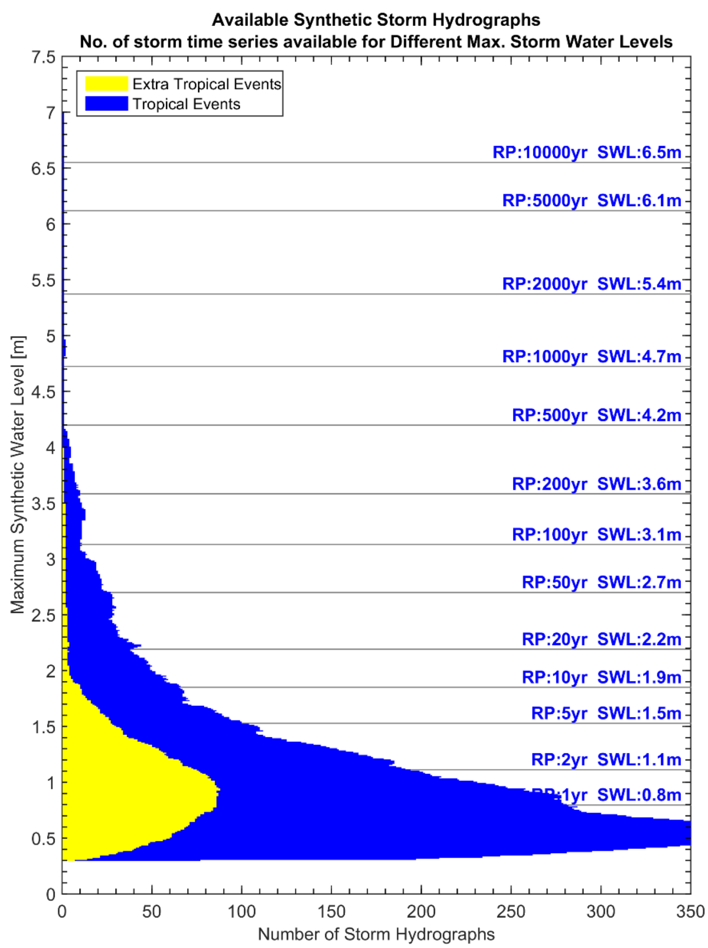

Figure 2-6: Histogram of available synthetic storm hydrographs for storm surge levels between 0.3 and 7m (Tropical shown in blue, Extratropical Cyclones shown in yellow).

2.2.4 Total Water Level Hydrograph

Within the MC analysis a total water level hydrograph is used. The total water level hydrograph consists out of three components: 1) The storm surge hydrograph, 2) Tides and 3) Sea Level Rise.

Storm surge hydrographs were discussed in the preceding section. Tides are added to the total water level signal by using the tidal constituents for The Battery. A tide signal is added by creating a time series of the tide with equal duration of the storm surge hydrograph. By using a random start time for the tide time series, variations in tides and occurrence of the storm surge at high or low water is accounted for in the analysis. Sea Level Rise is added per the USACE intermediate or USACE high scenario (ER 1100-2-8162) depends on the year considered in the analysis and is a simple linear addition. Although wave setup is omitted, in deep waters where the storm surge barriers are located, wave setup is expected to be minimal. In addition, any non-linear effects on surge with sea level rise are excluded from this analysis.

Figure 2-7 shows an illustration of the total water level and its three components for one synthetic storm. The closure elevation is shown as a horizontal dashed line to indicate when the water levels cross this threshold (both upward and downward).

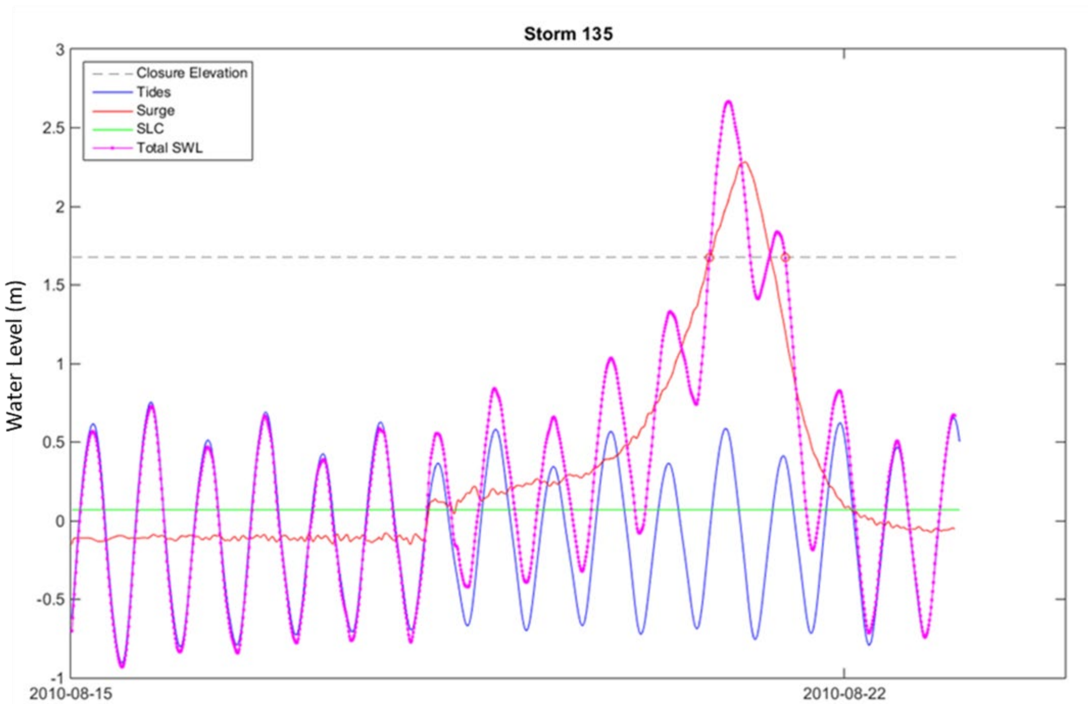

Figure 2-7: Total water level for a synthetic hydrograph based on Storm 135: total water level (in magenta) is the sum of tides (blue), storm surge (red) and Sea Level Change (green)

2.2.5 Monte Carlo Simulations

An algorithm was set up to complete the Monte Carlo Simulations for each year considered for a given parameter set (combination of closure criterion and closure elevation). The MC simulation framework as shown in Figure 2-3 covers the following steps:

- Read input (years to evaluate, closure criterion, closure elevation and USACE SLC scenario).
- Compute storm surge water level using inverse sampling from the cumulative probability function of non-exceedance for storm surge water levels. Generate random number from a uniform distribution between 0 and 1 then map the number to the corresponding storm surge level. This is the storm surge water level for the simulation.
- Compute storm type. A random number between 0 and 1 is drawn to compute the storm type based on the XC and TC distribution (see Figure 2-5) for the selected storm surge water level.
- Pull storm hydrograph from database. A random integer between 1 and n is generated to randomly selected a synthetic hydrograph from the storm surge hydrograph database out of n available storms (based on storm surge water level and storm type).
- Compute tides. A random point in time is selected to generate a time series of tides using the tidal constituents for The Battery (NOAA Station 8518750).
- Compute SLR. Given the input year and USACE SLC scenario this is computed as a single value.
- Compute the total water level time series by summation of the storm surge hydrograph, tides and SLR.
- Check whether the maximum water level of a given time-series exceeds the closure criterion. If closure criterion is exceeded, record the closure duration and other parameters of potential interest. These may include the wind speed at the time of closure, maximum wind speed during closure, wind speed during opening.
- Repeat Steps 2 through 8 N times, where N is a sufficiently large number.
- Sort all results and compute the probability density function and cumulative probability density function. Compute the 50% Confidence Limit (CL) and the 90% CL for the closure duration for the closure criterion and closure elevation.
- Provide graphical and tabular summaries of the results of the simulations.

Test runs were completed that show that the number of simulations N should be over 50,000 to reach a result that bring the estimate for the 90% CL closure duration within 1% of the statistically stationary result. A small sample of 5,000 peak water levels generated during the MC procedure for a single year is shown below in Figure 2-8. Both extratropical (XC) and tropical (TC) events may produce smaller peaks but extreme events (high peaks) are rare and are mostly associated with TCs.

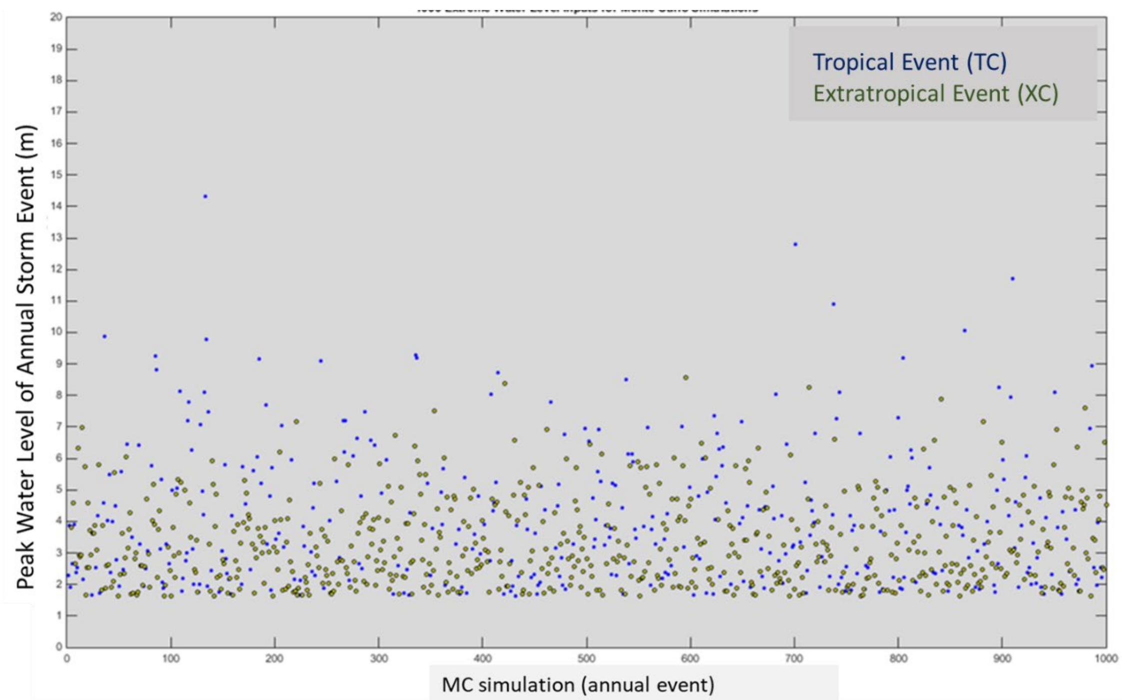

Figure 2-8: Sample of peak water levels used in 5,000 MC Simulations

2.2.6 Limitations and Capabilities

This methodology is set up to assess storm surge barrier closure frequency and closure duration for different hypothetical closure criteria using storm surge hydrographs that are available from the advanced ADCIRC modeling effort that was completed in support of the NACCS. The use of this synthetic data set that includes hydrographs allows for the analysis of the closure duration for a wide range of storm severity which is not possible when one uses the historical record (because the historical record is relatively short and only has a small number of extreme events in it). However, there are still some limitations to this methodology that need to be considered, which include:

- This analysis focuses on the larger storm surge barriers that accommodate deep draft navigation. It is assumed that an operational frequency on the order of once per year is near the upper limit of intended/desired operational frequency. For the smaller storm surge barrier that do not accommodate deep draft navigation an operational frequency exceeding once a year may be feasible. Such details may need to be worked out in a later phase
- The analysis completed based on one ADCIRC output point, located at The Battery. Results will vary throughout the HAT Study region because of the spatial variation in the stage frequency curves for extreme water levels. The selected output point is closest

to and probably most representative of the Verrazano Narrows SSB closure (HATS Alt 3A Basin) or Kill van Kull SSB (NYNJHAT Alt. 3B)

- Potential non-linear response of storm surge and tides with SLR is not included
- The analysis only considers the maximum annual water level and does not include multiple annual storms
- River inflows into the closed basin are not included. However, inclusion of the inflows would serve to increase basin water levels during a closure thereby hastening the occurrence of their equilibrium with falling outside water-levels after the storm peak. Since reaching this point of equilibrium is considered as the criterion for reopening, the effect of the inflows would be to shorten the duration of closure. Therefore, the results of the analysis can be considered conservative in this aspect
- The closure duration is extended to the full duration of double or multi peaked events (which may occur more frequently with high sea level rise), which potentially results in a conservative estimate for the closure duration. One potential alternative in such situations might be to reopen the gate following the first or the highest peak depending on the assessed risk to avoid such long closures.
- For extreme SLR values closure duration may exceed 7 days. ADCIRC time series are too short to properly analyze closure durations of such length. However, the expected frequency through time of such long closure events could still be tracked.

3 Results

Following the Monte Carlo simulations, a total of N event outcomes for each analyzed year are available. For each simulated event, the algorithm records a closure or non-closure as per the preset closure criterion. In the event of a closure, the closure duration as well as other parameters of interest such as the wind speed at closure are recorded. Statistical outcomes are then generated following a probabilistic analysis of this large data set and are presented below.

3.1 Closure Probability

The closure probability for a given closure criterion is calculated by dividing the number of recorded closures by the total number of simulations. For a fixed closure criterion, the closure probability changes over time with SLC, as shown in the stacked bar chart in Figure 3-1. The closures by event type - tropical or extratropical - are tracked separately. This allows calculation of the probability of closure due to XCs (heights of the yellow bars) distinct from the probability of closure due to TCs (heights of the stacked blue bars). Their total height indicates the overall probability of gate closure due to XCs or TCs. The closure probability for a closure criterion of +7.0ft in 2050 is just over 20% on an annual basis. From the MC simulations. the expected mix of tropical or extratropical events responsible for closures is close to 1:1. However, the relative proportion of extratropical storms (XCs) triggering gate closure appears to slowly increase with time. This is because with Sea Level Rise, smaller surge events are able to push the total water level up to the closure criterion, triggering closure. And based on the expected hazard curve presented in Figure 2-5, smaller surge peaks are more likely to occur as part of extratropical events (XCs) which are more numerous than tropical events (TCs) in the study area.

The same information - the combined closure probability, and the proportion of closures in response to events that are tropical in nature (TC ratio) - for selected years (2050, 2100, and 2140) distributed over the project timeline is presented in numeric form in Table 3-1. For a closure criterion of +7.0 ft, this clearly shows the change in total probability of closure from just over 20% in 2050 to over 80% in 2080 with only the SLR. The proportion of TC-induced closures also drop from roughly 56% in 2050 to about 40% in 2140. Similar trends are observed in the tests with higher closure criteria.

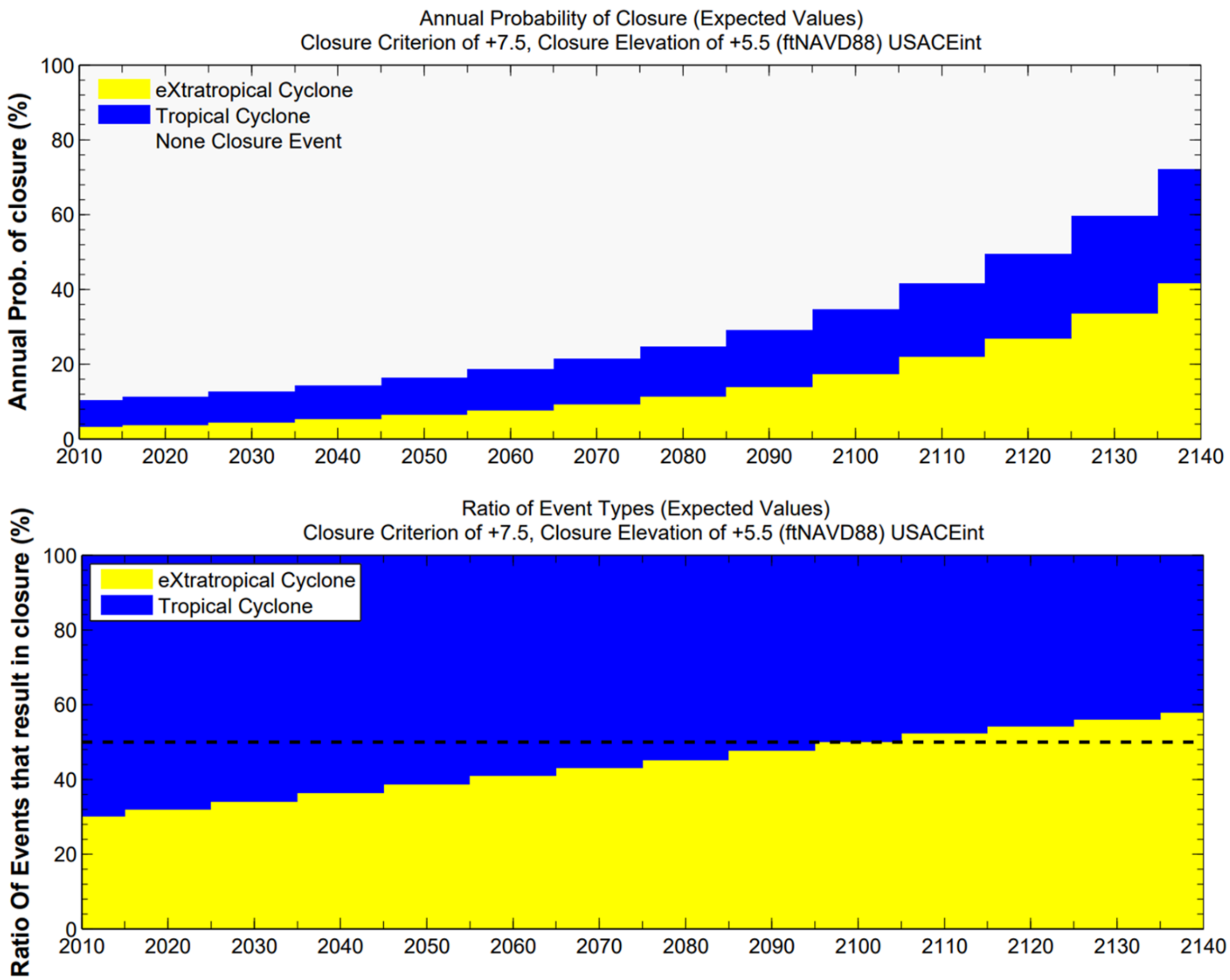

Figure 3-1: Annual Closure Probability over time (upper panel) for a closure criterion of +7 ft NAVD88; Causal ratio (TC/XC) of closure over time (lower panel).

Table 3-1: Combined annual probability of closure and proportion of TC-induced closures for selected years

Closure Criterion	Year	2050	2100	2140
+7.0	Probability of Closure	22.5	46.5	83.5
	TC Ratio	0.56	0.46	0.41
+7.5	Probability of Closure	16.5	35.0	72.0
	TC Ratio	0.61	0.50	0.42
+8.0	Probability of Closure	11.5	25.5	55.0
	TC Ratio	0.68	0.54	0.45
+8.5	Probability of Closure	8.0	19.0	42.0
	TC Ratio	0.74	0.59	0.48
+9.0	Probability of Closure	6.0	13.5	30.5
	TC Ratio	0.81	0.65	0.52

Figure 3-2 shows the change in closure probability with time for several different closure criteria, with the corresponding average recurrence intervals (ARI) indicated as well. The ARI is computed based on the annual exceedance probabilities as they are both statistical measures of the likelihood of occurrence of an event.

Figure 3-2 assumes the USACE Intermediate scenario for Sea Level Rise. Closure frequencies exceeding once a year (i.e., ARI of one year) might be deemed too frequent and hence inoperable, especially for SSBs that would need to accommodate deep draft navigation. Hence evaluating the change in closure probabilities with different closure criteria until the point in time when they reach this conservative limit of operability could help inform the selection of an appropriate closure criterion and suitable adaptation planning. Based on these assumptions, a closure criterion of +7 ft might be manageable under USACE's intermediate SLR scenario up to around 2100, beyond which adjustments to the criterion would be needed. However, a closure criterion of +8.5 ft or + 9 ft would suffice to keep the frequency of operation within this limit of operability through 2150.

Figure 3-3 shows a similar projection of closure probabilities for different closure criteria but assumes the USACE High scenario for Sea Level Rise. In this scenario, closure criteria between +7 ft and +9 ft would be insufficient to provide a functional period of more than 50 years. Even the +9 ft closure criterion would need to be adjusted further upwards around year 2080. The +10 ft closure criterion would be just enough to limit the frequency of operations to less than once per year on average through 2100. However, a closure criterion of well over +12 ft (outside the range of evaluated criteria) would likely be needed for comparable performance through 2150.

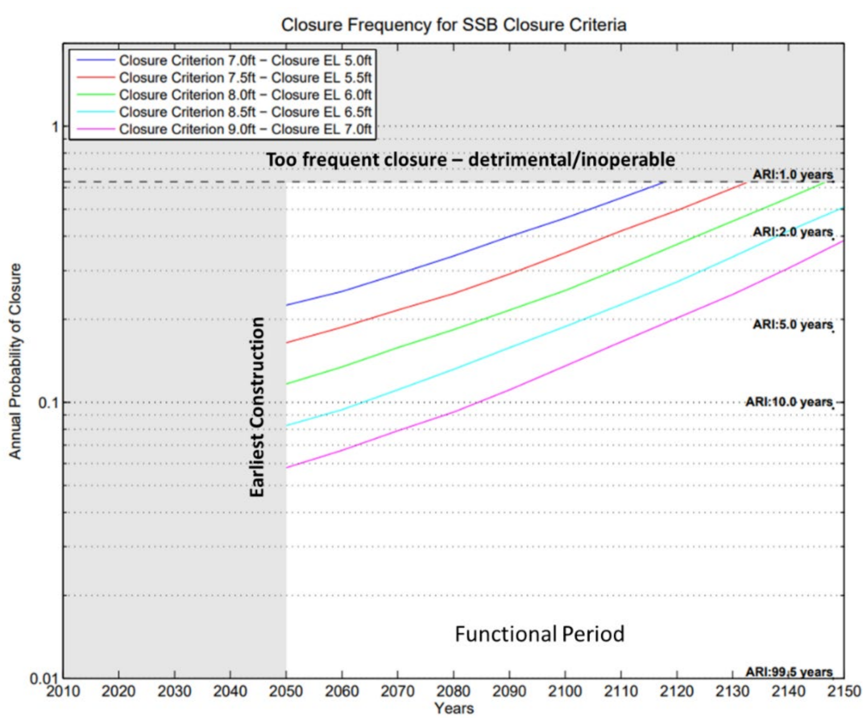

Figure 3-2: Closure probability through time for several different closure criteria, assuming USACE Intermediate SLR projection

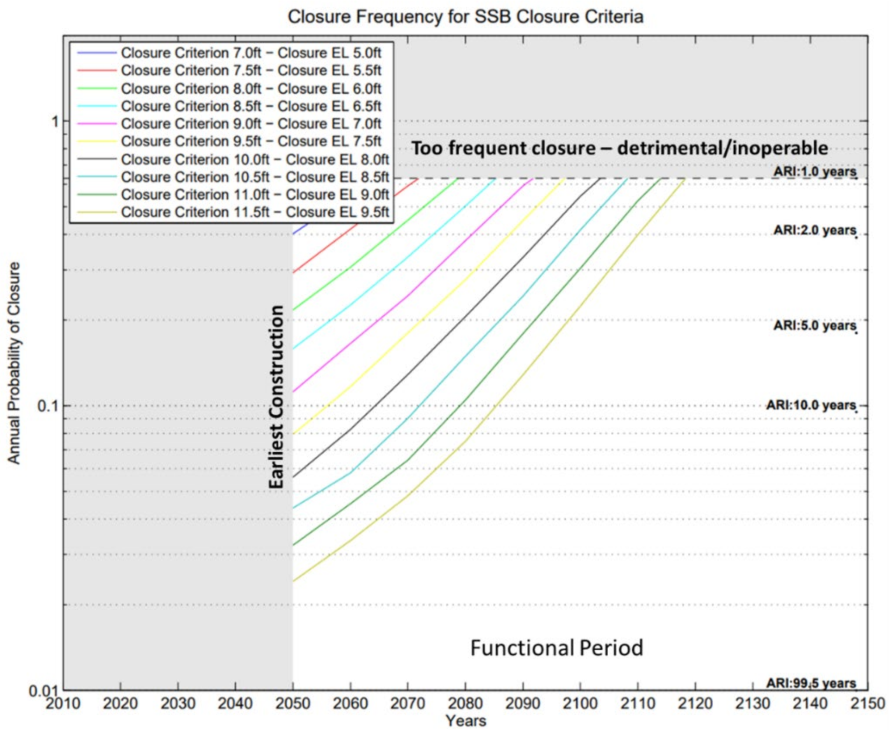

Figure 3-3: Closure probability through time for several different closure criteria, assuming USACE High SLR projection

3.2 Closure Duration

The probability distribution function of the closure duration for any given combination of closure criterion and closure elevation can be obtained from this analysis. Figure 3-4 below shows the cumulative probability distribution curves of closure duration for a closure criterion of 7 ft and closure elevation of 5 ft. The curves change over time as higher mean sea levels due to projected SLR tend to prolong elevated water levels above the closure criterion and hence increase the duration of required closure. Curves based on simulations that span the years 2010 to 2110 are shown in the figure. They can be observed to shift to the right (towards larger durations) over time. The modal value (50th percentile) of the closure duration increases from 5.2 hours to 6.6 hours from year 2010 to 2110. However, there is a large range of possible durations with any closure level at any given time based on the type and intensity of the storm as evidenced by the x-axis range of the curves. The labeled 10th and 90th percentile values on the curves further illustrate this variability. For instance, in 2010, the 10th percentile of the computed closure durations is 2.5 hours, while the 90th percentile is 8 hours. At the 90th percentile a shift can be observed between the years 2060 and 2080 as closure durations shift by almost 6 hours. This is a result of some of the longer simulated closures getting further extended by another full high tide cycle due to sustained high waters under the projected Sea Level Rise by this point in time.

The time-series of just the 10th, 50th and 90th percentile closure durations is shown in Figure 3-5 for different closure elevations in combination with the +7.0 ft NAVD88 closure criterion. Higher closure elevation for a given closure criterion generally results in shorter closure durations. Modal closure durations (50th percentile) for these scenarios range from about 3 to 5 hours in year 2010, and about 4 to 7 hours in year 2110, depending on the closure elevation. Here too, as noted previously with Figure 3-4, the distinct shift in the 90th percentile values of closure duration going from 2060 to 2080 can be observed with all scenarios.

The closure duration as a function of the closure criterion and the closure elevation is further illustrated in Figure 3-6. This shows mapped contours of closure duration over a range of potential closure criteria (shown on the x-axis) and corresponding closure elevations (y-axis). Based on these graphs, it is clear that the duration of closure is mostly controlled by the closure elevation, especially in the earlier years. With higher closure criteria, the set of storms for which closure is initiated is generally skewed toward larger events. This has some effect on the statistical estimates of the closure duration, tending to make them larger. But this effect appears to be smaller than the effect of the closure elevation. An exception to this trend may be noted with the contour graphs of the 90th percentile closure duration estimates for years later than 2060. Here the closure duration statistic appears to respond sharply to the change in closure criterion from 7 to 7.5 ft in the 2080 graph, and 7.5 to 8 ft in the 2110 graph. With the applied SLR projection, the shift in tidal datum at these years causes the low tide immediately following the storm peak to be just large enough to prolong closure by another tidal cycle for a sufficient number of storms to affect the 90th percentile duration statistic.

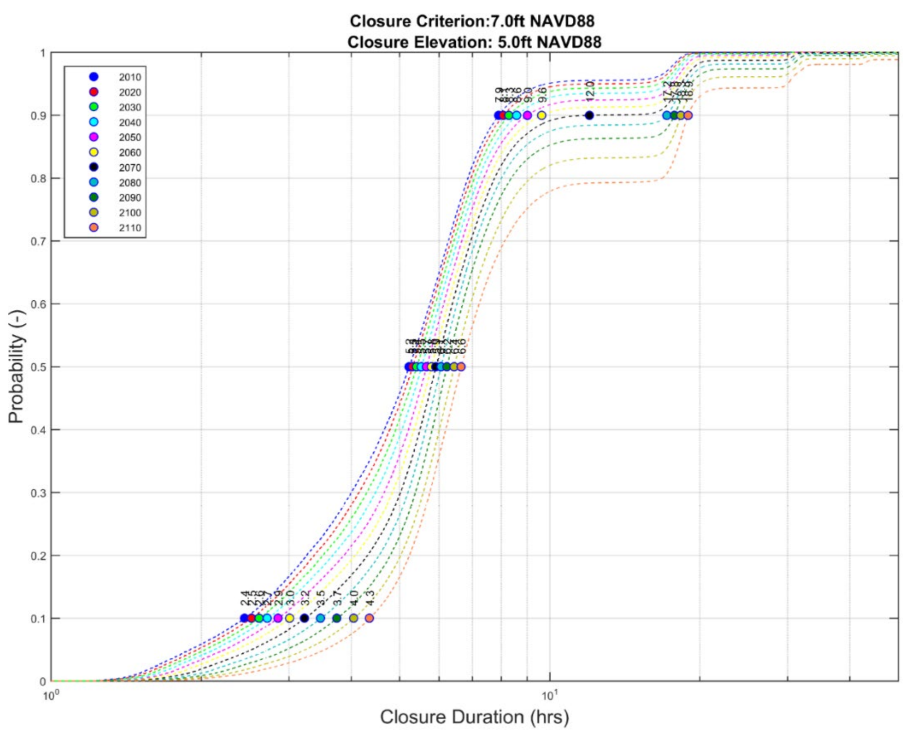

Figure 3-4: Cumulative Distribution Function of the closure duration for years 2010 through 2110 for a closure criterion of +7.0ft and closure elevation of 5.0ft NAVD88

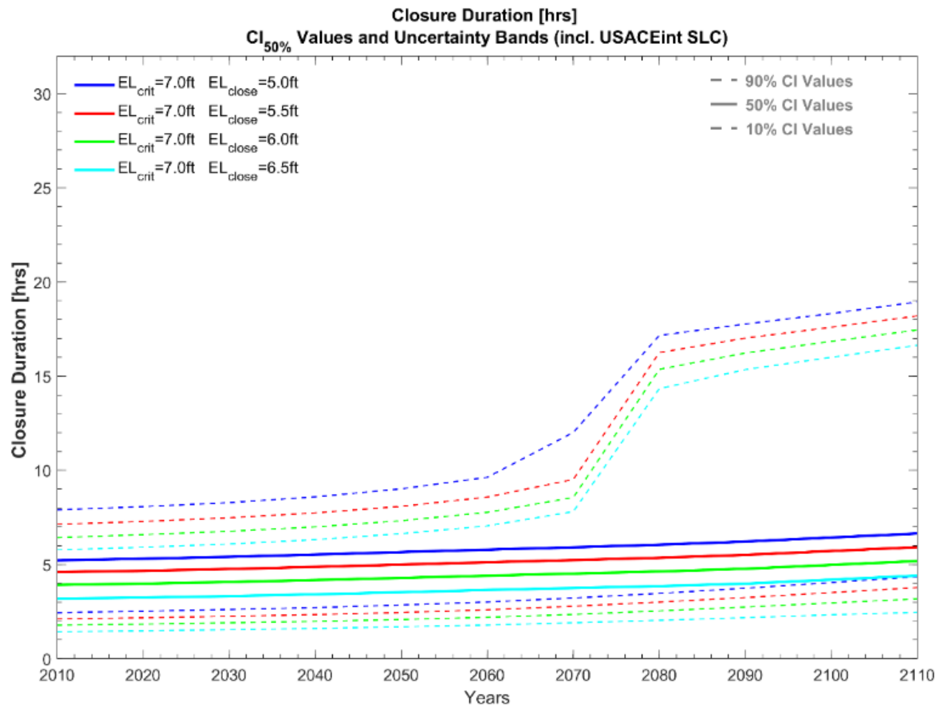

Figure 3-5: Time-series of 10th, 50th, and 90th percentiles of closure duration for a closure criterion of +7.0 ft NAVD88 with several possible closure elevations

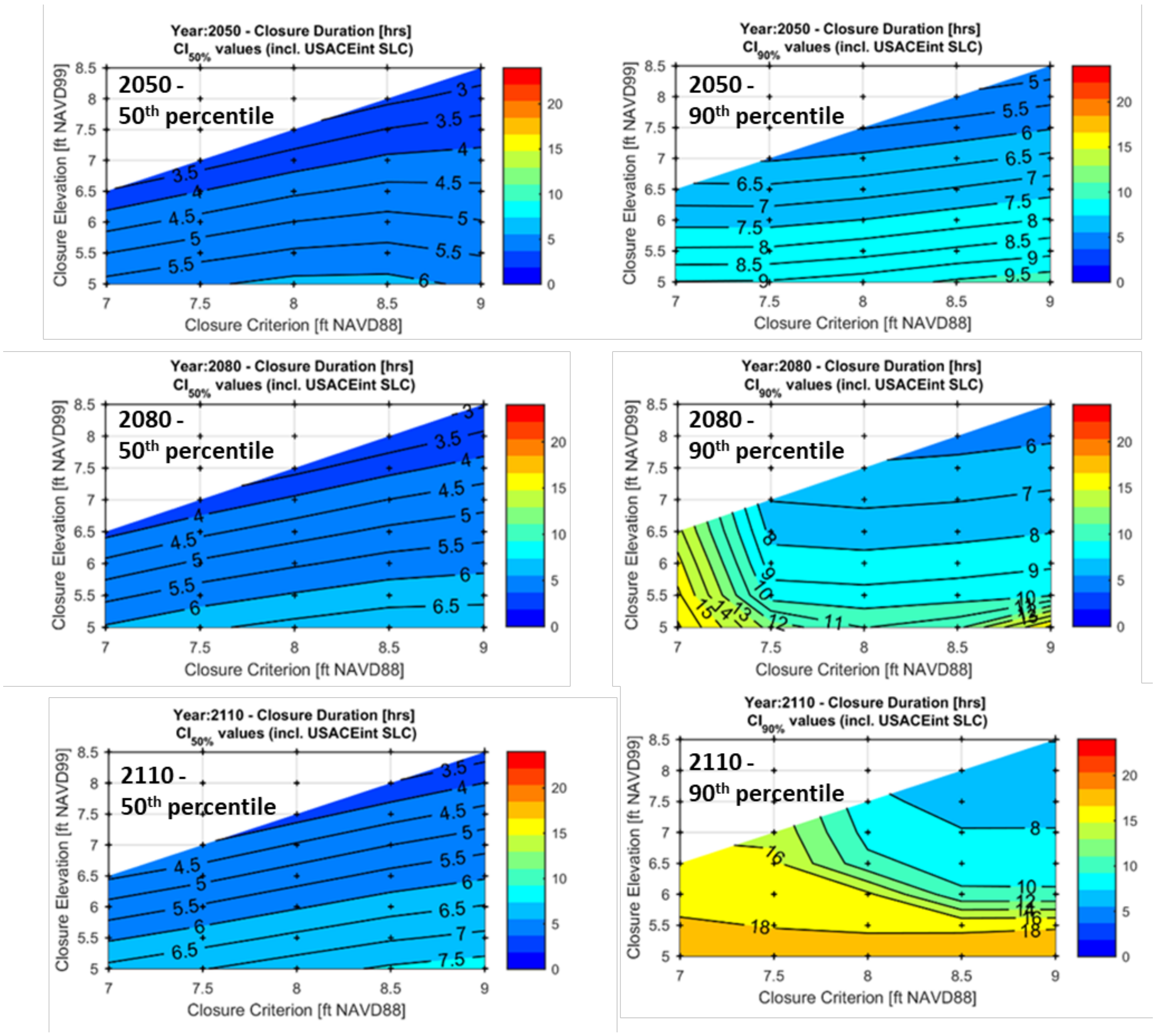

Figure 3-6: Contour maps of estimated closure duration (in hours) over a range of closure criteria and closure elevations. Showing separate maps for 50th and 90th percentile estimates for years 2050, 2080, and 2110.

4 Conclusions

The expected closure probability of SSB gates and the possible duration of closure events were analyzed over the 100-year planning period for the HAT Study. The applied Monte Carlo approach allowed for the separate evaluation of Tropical (TC) and Extratropical (XC) cyclonic events, such that the impact of the typically longer lasting but smaller extratropical events could be properly included in the computed closure duration statistics.

The closure elevation is generally found to have the biggest impact on the closure duration as it directly controls the moment of closure and reopening. However higher closure criteria also generally tend to skew the set of closure events towards larger storms, thereby somewhat affecting the estimated typical closure durations. A secondary effect of the closure criterion on the higher end of the possible range of closure durations was also observed, when in conjunction with projected Sea Level Rise for certain years, the applied criterion led to prolonged closures due to spill-over into the next tidal cycle for some events.

4.1 Further considerations

The presented analysis is limited to hydraulics only. Timing for initiation of the SSB gate closure procedure for any site-specific storm surge gate would depend on many factors not included in this analysis. Further considerations affecting the timing might be storage capacity behind SSB, anticipated inflows, storm damages, navigational considerations, number and size of navigation and auxiliary gates, non-instantaneous (sequenced) gate closure for multi gate SSBs, gate closure time required for safe operation, additional safety factors, etc.

The current analysis is based on only a broad representation of conditions within the extensive HAT Study Area. A more detailed analysis would consider more location-specific inputs.