U.S. Army Corps of Engineers

Baltimore District

Baltimore Metropolitan
Coastal Storm Risk Management Feasibility Study

APPENDIX B

Hydrology and

Hydraulic Analysis

FINAL REPORT

May 2024

1 Contents

1. Study Overview

1.1 Study Area

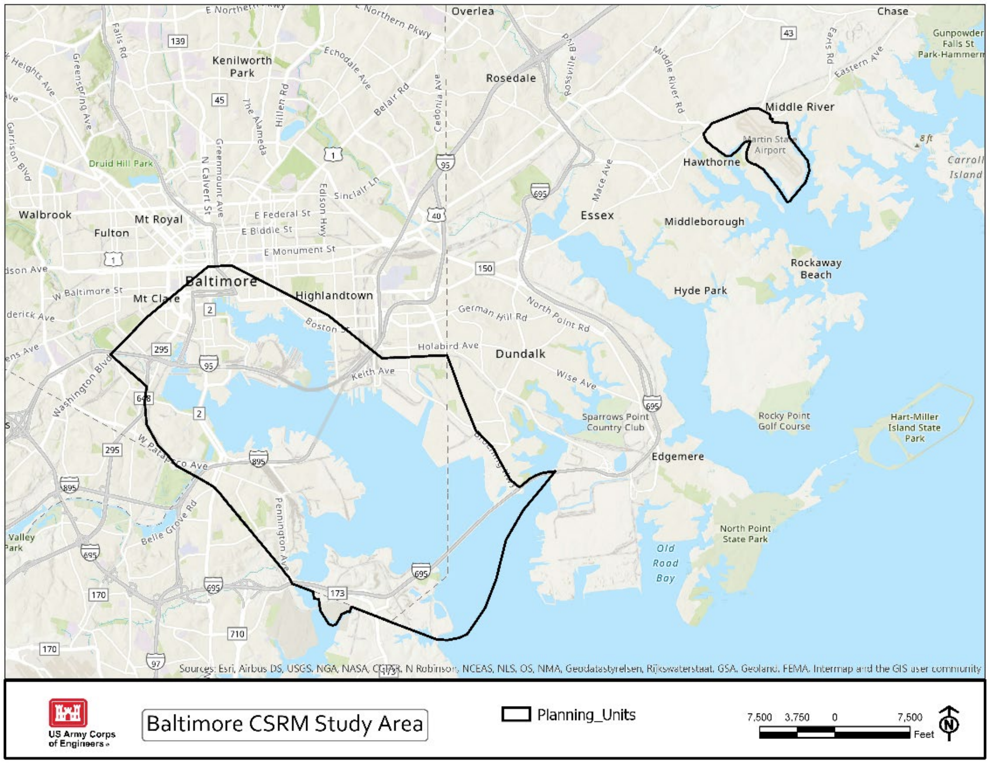


Figure 1 Location of BALTIMORE Coastal Study Area

The Baltimore Coastal Storm Risk Management Feasibility Study (hereinafter referred to as Baltimore Coastal study) area is located within the Downtown Baltimore Inner Harbor area and area around Martin State Airport, as shown in Figure 1. The study area is along the Inner Harbor and Middle River within the Upper Chesapeake (HUC 0206) watershed, which encompasses Baltimore City and County and a large portion of the Chesapeake Bay watershed. It is situated within the Inner Harbor area where natural land subsidence, low-lying topography, tidal influence, and sea level changes have contributed to localized flooding. Downtown Baltimore and Martin State Airport have been impacted by numerous major tropical and extratropical events, most notably by Hurricane Able (September 1952), Hurricane Hazel (November 1954), Hurricane Connie (August 1955), Tropical Storm Agnes (June 1972), Tropical Storm David (September 1979), Hurricane Isabel (September 2003), Tropical Storm Ernesto (September 2006), Tropical Storm Hanna (September 2008), and Hurricane Irene (August 2011). Hurricane Isabel in 2003 resulted in extreme water levels and caused millions of dollars of damage to residences, businesses, and critical infrastructure. High storm surges occurred along the Chesapeake Bay and its tributaries. Over 570 homes and 15 businesses were declared uninhabitable from flooding. The goal of this study is to reduce coastal flood risk to populations, properties, infrastructure, and environmental and cultural resources, considering future climate and sea level change scenarios.

The study evaluates project alternatives to assess flooding risks induced by coastal storms for the Baltimore metropolitan area surrounding the City and County of Baltimore. Specifically, it will address flooding issues near the Inner Harbor area and around Martin State Airport.

1.2 North Atlantic Coast Comprehensive Study

The North Atlantic Coast Comprehensive Study (NACCS) (2015) report detailed the results of a two-year long study by the U.S. Army Corps of Engineers which addressed coastal storm and flood risk to vulnerable populations, property, ecosystems, and infrastructure affected by Hurricane Sandy in the North Atlantic Region. The purpose of the study was to identify flood risk and then plan and implement strategies to reduce the risk now and in the future. The study also determined the magnitude and uncertainty of existing and future forcing conditions. The study's conclusions included a recommendation to use its findings to assess coastal engineering projects for coastal storm risk management and resiliency for the areas in the region from Virginia to Maine. Figure 2 shows the extent of the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) mesh covering the study area.

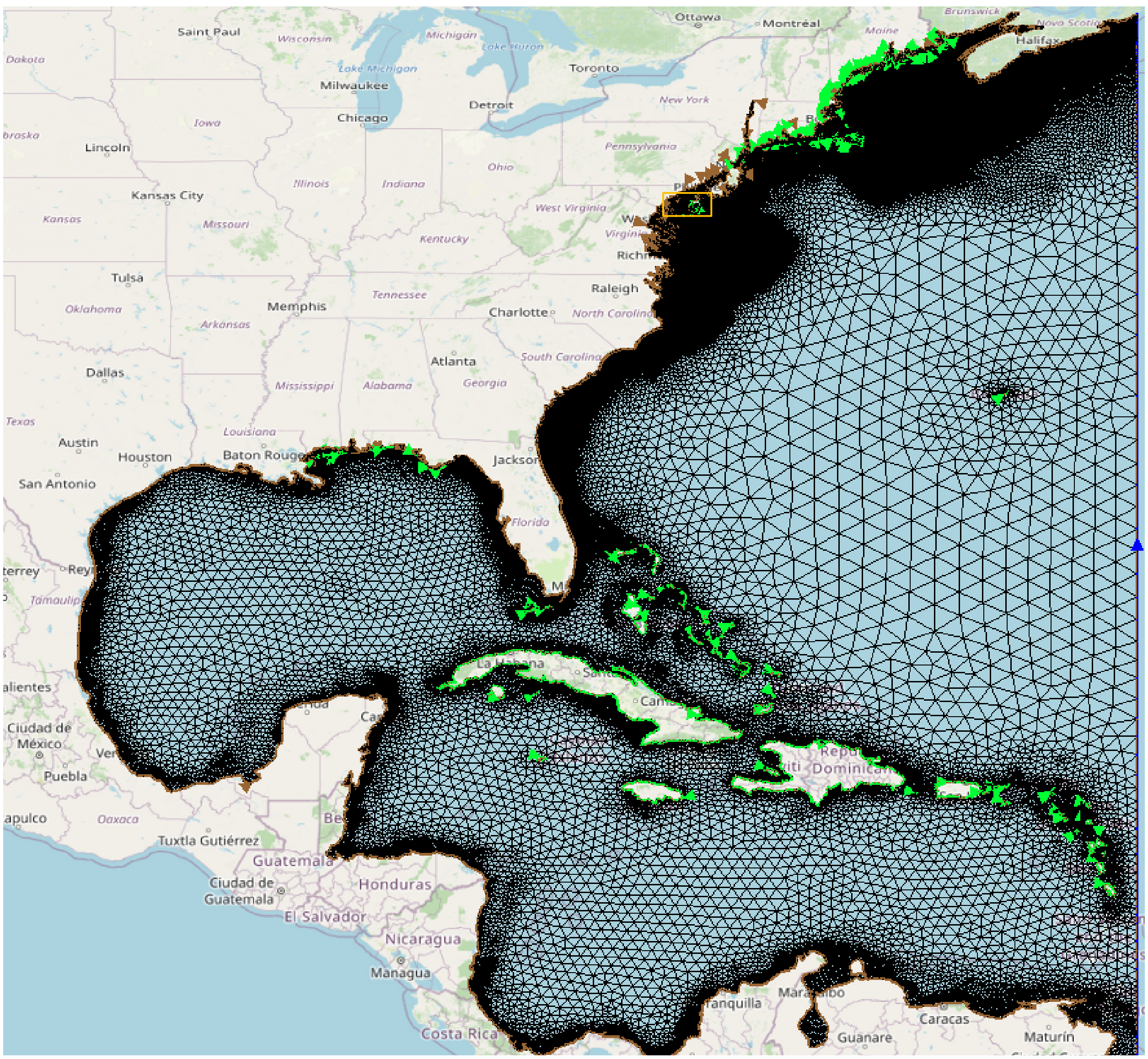


Figure 2 ADCIRC Model Mesh for the NACCS Study

The NACCS included high-fidelity coastal numerical modeling of coastal hazards for the North Atlantic coast region including the Baltimore Coastal Study area. Figure 3 shows the ADCIRC model mesh for the study area. Storm surge and wave modeling results from these efforts in the Baltimore Coastal study area were considered for this study.

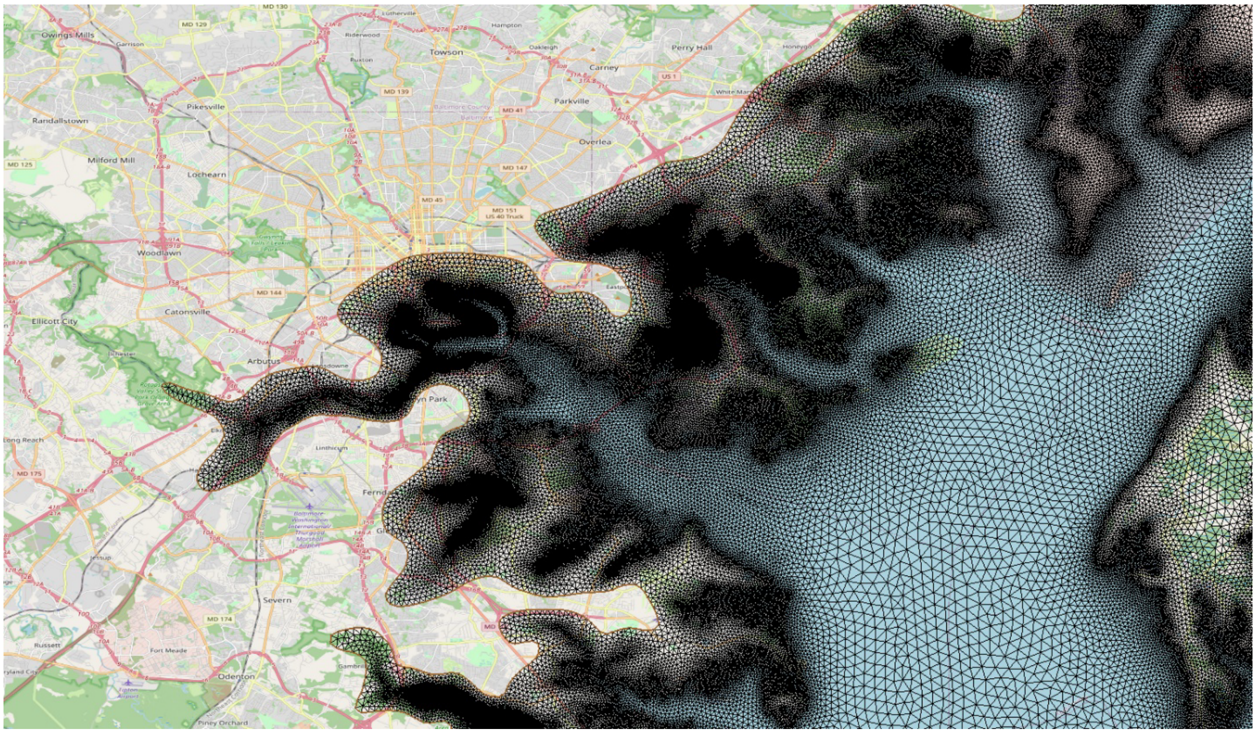


Figure 3 ADCIRC Mesh within Baltimore Coastal Study Area

Many of the coastal projects have been using the NACCS study Water Surface Elevation (WSEL) data as part of the coastal storm risk management studies, but it is evident that in the inland bay areas, many areas have high bias when superimposing coastal storm surge, tidal influence, and sea level rise, yielding a greater level of uncertainty as to the accuracy of the existing modeling. The Baltimore Study has a bias with the majority of save points that have a combined bias of less than 0.3m, which is considered an acceptable level of bias according to the CHL Report.

Figure 4 shows bias for the NACCS model in the Baltimore Harbor area. Besides having low bias for the NACCS in the study area, the NACCS WSEL is comparable against that of the FEMA flood hazard study for Baltimore study area. The following section provides some background information on the 2008 FEMA study for the City and County of Baltimore.

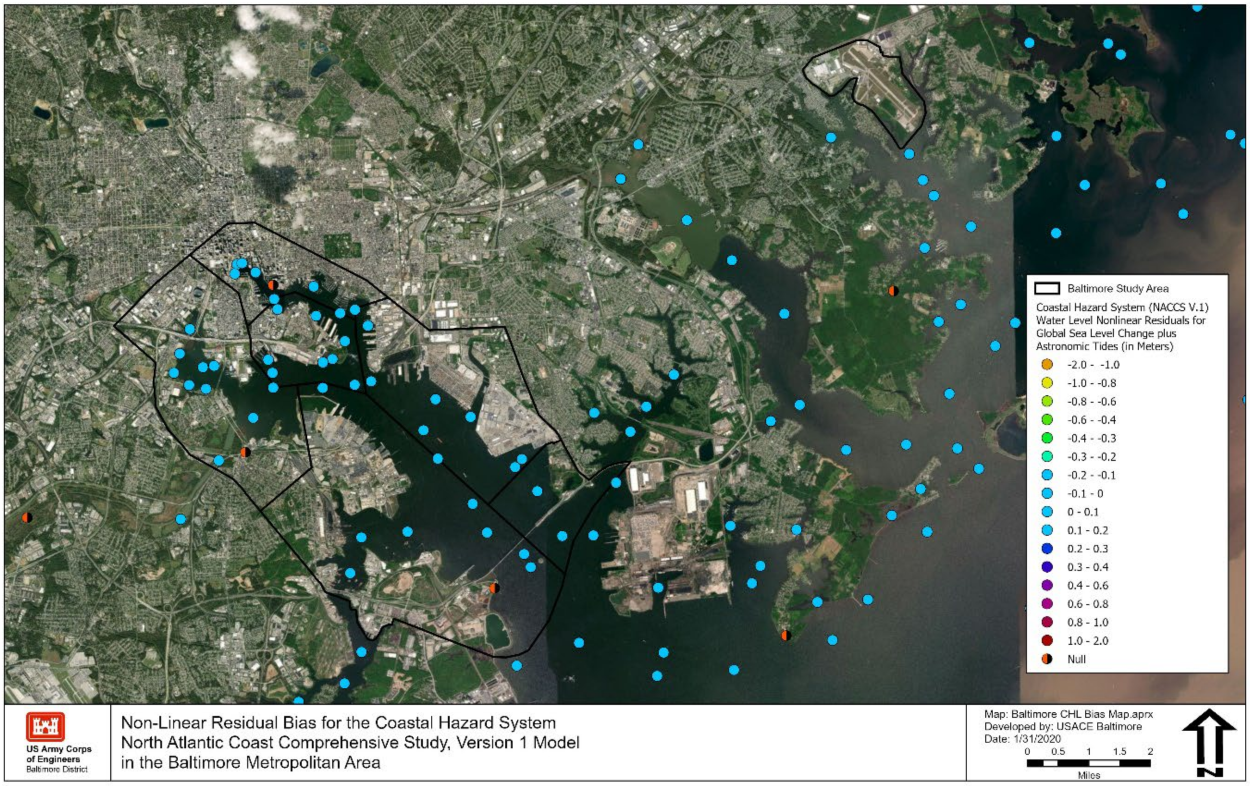


Figure 4 Bias for NACCS Study in Baltimore, Maryland

1.3 FEMA's Coastal Modeling

An analysis was performed to establish peak water surface elevation for coastal flooding in the City of Baltimore. FEMA initiated this study in 2008 to update the coastal storm surge elevations within the states of Virginia, Maryland, and Delaware, and the District of Columbia including the Atlantic Ocean, Chesapeake Bay including its tributaries, and the Delaware Bay. FEMA's Flood Insurance Study is based on a 2012 USACE coastal Analysis performed at ERDC. The ADCIRC was dynamically coupled to the unstructured numerical wave model Simulating WAves Nearshore (unSWAN) to calculate the contribution of waves to total storm surge. The modeling system validation consisted of a comprehensive tidal calibration followed by a validation using carefully reconstructed wind and pressure fields from three major flood events - Hurricane Isabel (2003), Hurricane Ernesto (2006), and extra tropical storm Ida (2009). Model performance was assessed by quantitative comparison of model output to wind, wave, water surface level and high-water mark observations.

FEMA study of the 1% annual chance WSEL (2012) along Baltimore's Inner Harbor varies from 7 to 10 feet NAVD 88. As per FEMA flood hazard data, most of the Inner Harbor area has a WSEL (2012) of 8 feet NAVD 88.

The NACCS WSEL with adjustment for Sea Level Rise (SLR) is between 8 and 8.3 feet NAVD 88. Table 1a shows NACCS WSEL for 2020 with SLR adjustment:

Table 1a Tidal Datum for NOAA Gage 8574680, Baltimore, MD

Flood Frequency	Expected Storm Surge Water Surface Elevation in Year 1992 (NACCS)	SLR Scenario	Expected Storm Surge Water Surface Elevation in Year 2020 (includes Sea Level Rise)
100-year	7.6	Low	8.0
100-year	7.6	Intermediate	8.1
100-year	7.6	High	8.3

The FEMA study was based on 2012 AdCIRC modeling. Therefore, WSEL from FEMA study reflects 2012 WSEL. SLC rate can be applied to bring the FEMA WSEL to 2020. SLC rate of 0.0094 ft/year would show a difference of 0.07 ft between 2012 and 2020 WSEL, which is negligible.

The NACCS study data compares very well against that of the FEMA study flood hazard data. This increases the level of confidence in the NACCS modeling data. In addition, the majority of save points from the NACCS study have a combined bias of less than 0.3m, which is considered an acceptable level of bias according to the CHL Report.

We did perform a brief sensitivity analysis of various WSEL for the Baltimore Study area and results are shown in the following map (Figure 5):

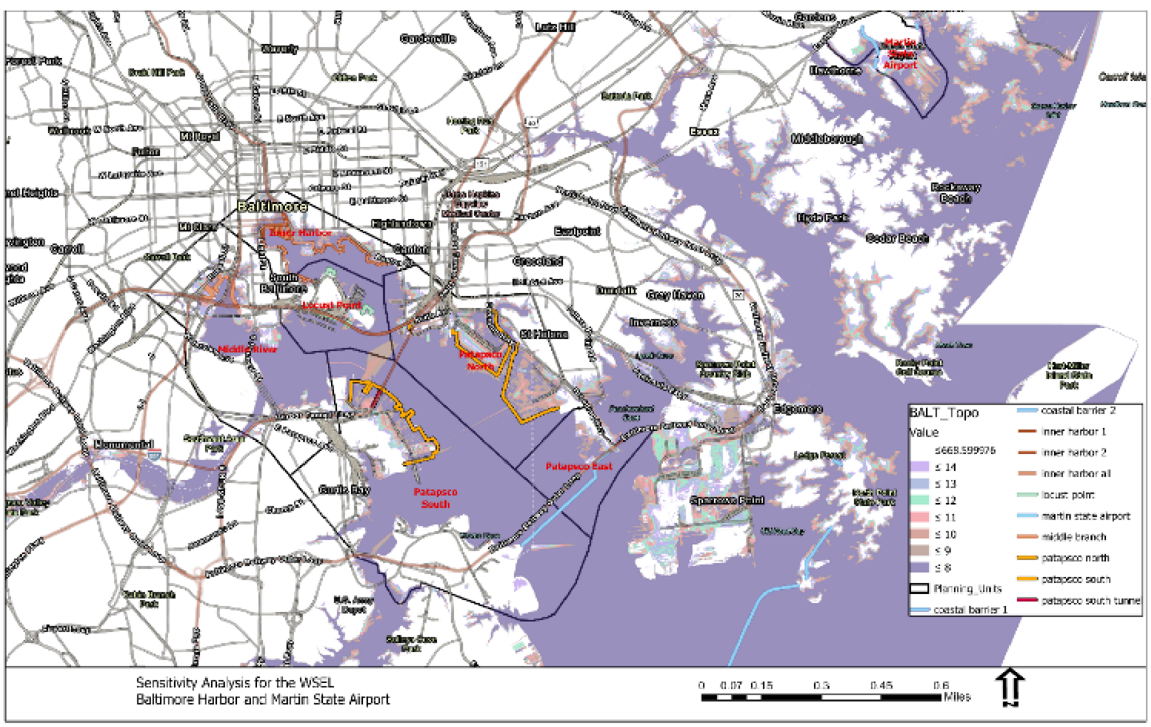


Figure 5 Sensitivity Analysis of the WSEL

The goal of this sensitivity analysis was to examine how inundation extent changes with increases or decreases in WSEL. The exercise identified risk of flooding associated with a range of WSELs.

As Dr. Norberto Nadal of ERDC indicated in our February 3rd, 2020, conference call, USACE was not likely going to see much improvement for the bias if refined modeling was done for the Baltimore area. The bias would remain around 0.3 meters, which is the model tolerance. Hence, further refinement would not be cost effective. Based on these facts, no additional modeling refinements would be warranted as the risk for the study would be minimal.

2. NACCS Modeling and Results

Coastal flooding is primarily caused by rainfall, storm-induced water levels, and waves. For the northeastern U.S. Atlantic coastline, tides can have a significant influence on the degree of flooding given their large amplitudes. For the Baltimore coastal area, tropical cyclones (TCs) and extratropical cyclones (XCs) have historically caused significant coastal flooding. The analysis conducted as part of this study for the quantification of coastal storm hazards focuses on the probabilistic characterization of storm forcing and responses for the study area.

Water levels and wave heights were needed as input for the various types of coastal engineering and planning analyses performed in the study. The NACCS was used as the primary source of water level information. The NACCS characterized the probabilistic tropical and extratropical storm climatology of the coastal areas defined by the extent of Hurricane Sandy's storm surge. This work, carried out by the Engineer Research and Development Center (ERDC) included rigorous regional statistical analysis and detailed high-fidelity numerical hydrodynamic modeling for the North Atlantic region to quantify coastal storm wave, wind, and storm-driven water level extremes. The NACCS modeling efforts included the latest atmospheric, wave, and storm surge modeling and extremal statistical analysis techniques. Products from this work were incorporated into the Coastal Hazards System (CHS) database, a data storage and mining system web tool, and include simulated winds, waves, and water levels for approximately 1,050 synthetic tropical events and 100 historical extratropical events computed at over 3 million computational locations. These storms span the range of practical storm probabilities for the region. For a detailed description of this modeling and the results, the reader is referred to the following USACE documents—"Coastal Storm Hazards from Virginia to Maine 2015" and "North Atlantic Coast Comprehensive Study (NACCS) Coastal Storm Model Simulations: Waves and Water Levels 2015"—which can be found at http://www.nad.usace.army.mil/CompStudy/. The CHS contains output at approximately 19,000 save points or data access points within the NACCS study area from Virginia to Maine. An example image of the save points that are provided in CHS is provided in Figure 6.

The Generation 2 Coastal Risk Model (G2CRM) is being used to assess the economic performance of alternative protective measures. The G2CRM requires as input a description of the environmental forcing in terms of expected storm surge hydrographs and associated wave information if available. The data applied for the Baltimore study were developed from the NACCS. The NACCS produced storm tracks that cover the probability space of potential storms. These tracks allow for selection of relevant storms for study sites. The study applied any storm with a track within a 200 km radius circle of the project site. This resulted in the selection of 291 tropical storms and 100 extra-tropical storms for the project. The storm recurrence rates developed within the NACCS dataset give the relative probability listed in the storms excel file used as input for G2CRM. These rates are used to randomly select the occurrence of a given storm. A rate of 0.015 storms per month was applied from June to November for the Tropical season and 0.1689 storms per month was applied for the extratropical season. A poison distribution is applied using these rates to populate the storm events in each life cycle. The Datum conversions for the tide and surge were calculated based on the NACCS CHS conversion data available for Save Points and applied within the metadata files to transform water levels to the NAVD88 datum used for the asset inventory. Additional engineering input for G2CRM model is available in the economics appendix (Appendix E).

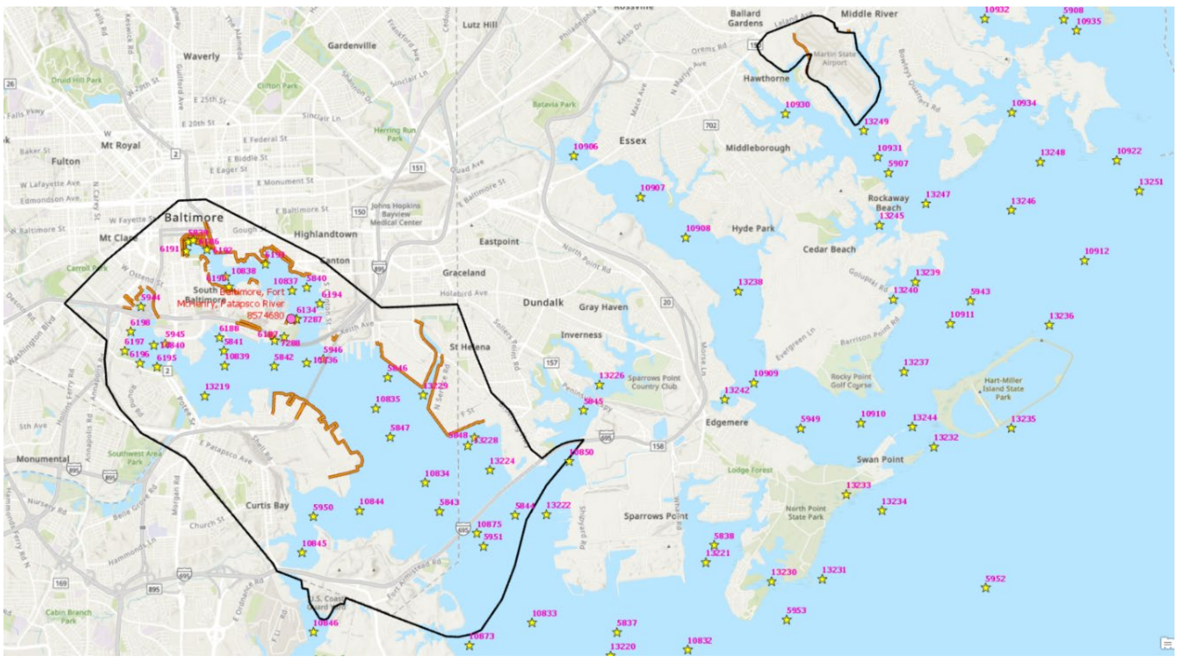


Figure 6 Save Point Locations Surrounding the Baltimore Metro Study Area

2.1 Tidal Regime

Baltimore Harbor experiences semi-diurnal tides (two low and two high tides per day) with one high and low tide typically of greater magnitude than the other due to a slight diurnal shift. NOAA installed this tide gage (Station 8575680) in September of 1989. The mean tide range in the Harbor is 1.14 feet and the diurnal range is 1.66 feet. The tides, which are created by the gravitational pull of the moon, the sun, and the earth's rotations, are responsible for most of the water levels observed. Occasionally, abnormally high or low water levels occur as a result of changes in atmospheric pressure, storm surge, the magnitude and direction of wind and/or waves, and other meteorological anomalies. Table 1b provides the tidal datums for Baltimore at Station 8575680. In Baltimore, the highest water level observed was 8.15 feet MLLW (7.31 feet NAVD88), which was during Hurricane Isabel on September 19, 2003.

Table 1b Tidal Datum for NOAA Gage 8574680, Baltimore, MD

Datums for NOAA Tide Gage 8574680, Baltimore

Station: 8574680, Baltimore, MD
Status: Accepted (Oct 6 2011)
Units: Feet
Control Station:
T.M.: 75
Epoch: 1983-2001

Datum	Description	Elevation in MLLW	Elevation in feet, NAVD88
MHHW	Mean Higher-High Water	1.66	0.82
MHW	Mean High Water	1.37	0.53
MTL	Mean Tide Level	0.79	-0.05
MSL	Mean Sea Level	0.81	-0.03
DTL	Mean Diurnal Tide Level	0.83	-0.01
MLW	Mean Low Water	0.22	-0.62
MLLW	Mean Lower-Low Water	0	-0.84
NAVD88	North American Vertical Datum of 1988	0.84	0
STND	Station Datum	-4.1	-4.94
GT	Great Diurnal Range	1.66	0.82
MN	Mean Range of Tide	1.14	0.3
Max Tide	Highest Observed Tide	8.15	7.31
Max Tide Date & Time	Highest Observed Tide Date & Time	9/19/2003 12:06	9/19/2003 12:06
Min Tide	Lowest Observed Tide	-5.1	-5.94
Min Tide Date & Time	Lowest Observed Tide Date & Time	1/24/1908 21:00	1/24/1908 21:00
HAT	Highest Astronomical Tide	2.22	1.38
HAT Date & Time	HAT Date and Time	7/2/2004 11:06	7/2/2004 11:06
LAT	Lowest Astronomical Tide	-0.65	-1.49

2.2 Wave Conditions

The Inner Harbor area of Baltimore's shoreline is sheltered from long period waves of the Chesapeake Bay. Therefore, waves in the Inner Harbor area are fetch limited, driven by winds blowing just over the length of the Inner Harbor. The proposed floodwalls around the Ft. McHenry Tunnel and the Baltimore Harbor Tunnels are located in areas of relatively shallow waters where waves are depth limited. Ground elevations in the area around flood walls are approximately 8 feet NAVD88. During a storm surge event, the 100-year depth of flooding is anticipated to be 2.2 feet (10.2-8). Therefore, the maximum 100-year wave height could be 2.2 x 0.78 = 1.7 feet. Note that this is the maximum wave height, but the maximum added to the water surface is half of that because of amplitude.

Waves are not computed for many of the Save Points within the Baltimore Harbor area. Extreme wave conditions estimated through NACCS modeling efforts at save point 13228, note that the wave height listed below are based on the save point's location in open water and do not reflect the condition near the LOP as depicted in the above computation. Data for the save point is shown below:

NACCS Save Point 13228		
AEP values	**Wave Height (feet)**	**Wave Period (Seconds)**
100%	2.3	2.9
50%	2.6	3.0
20%	3.0	3.2
10%	3.4	3.3
5%	3.8	3.4
2%	4.3	3.6
1%	4.8	3.7
0.50%	5.3	3.9
0.20%	5.9	4.1
0.10%	6.3	4.2
0.05%	6.8	4.4
0.02%	7.6	4.5
0.01%	8.2	4.6

2.3 Water Surface Elevations

As indicated earlier, the NACCS water levels were used as input to the G2CRM economic model for evaluating damages in the future without- and with-project alternatives. Also, water levels and wave heights were used in designing the structural alternatives. For the Baltimore Study area, water levels and wave heights were selected from save points 5944 and 13228 for

Figure 7a NACCS Save Points Selected for Inner Harbor and Martin State Airport

Baltimore Harbor structural alternatives and save point 10930 for Martin State Airport structural alternatives design. Locations of these save points are shown in figure 7a and 7b.

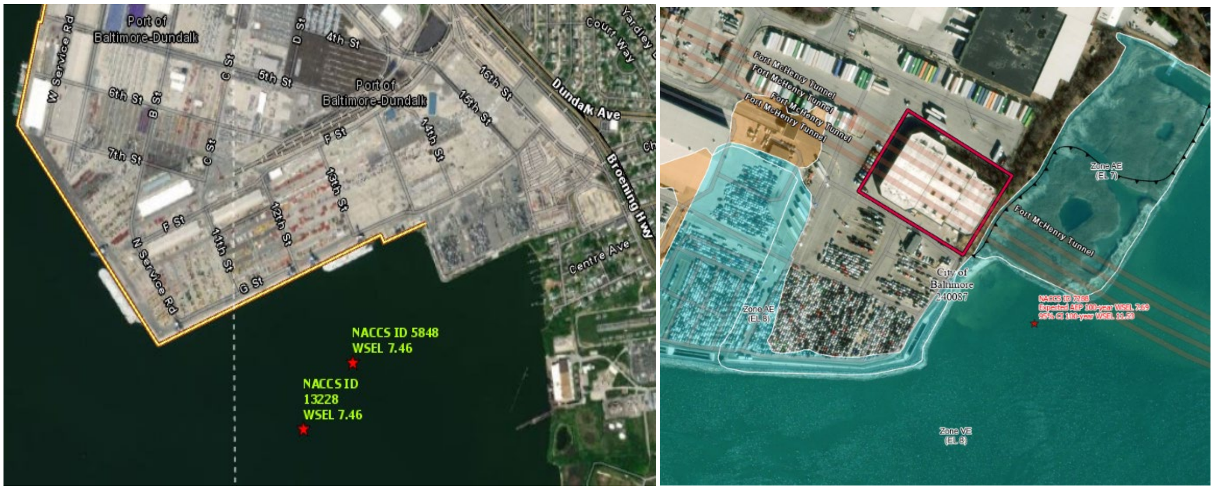


Figure 7b NACCS Save Points Selected for Inner Harbor near Port of Baltimore

The NACCS model mesh is well-defined in this area and water level output was able to be applied directly to the study area without the need for transformation. This save point was considered most representative for the entirety of the study area. The CHS contains water levels in meters, relative to Mean Sea Level, at annual recurrence intervals from 1 year to 10,000 years at four confidence limits (CL). These water levels at save points 5944, 7288, 10930 and 13228 are shown in Figure 8a and 8b.

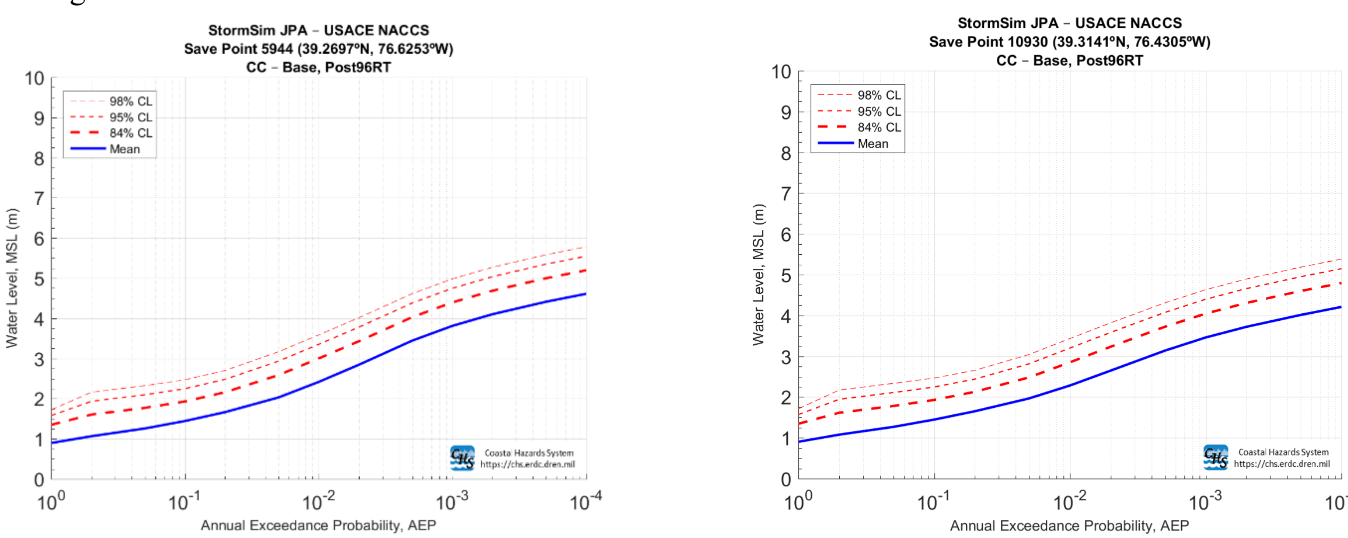
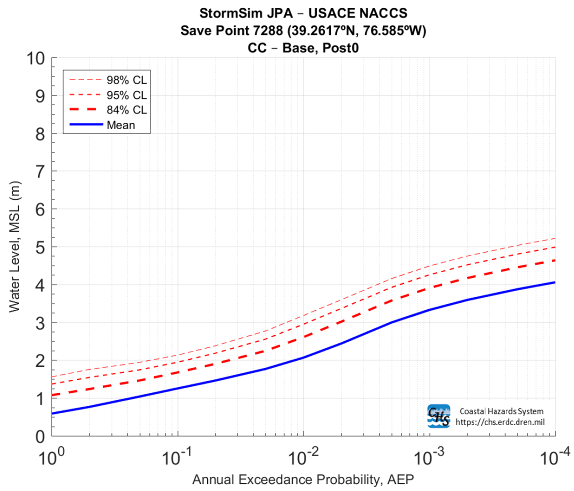


Figure 8a NACCS AEP WSEL for Save Points 5944 and 10930



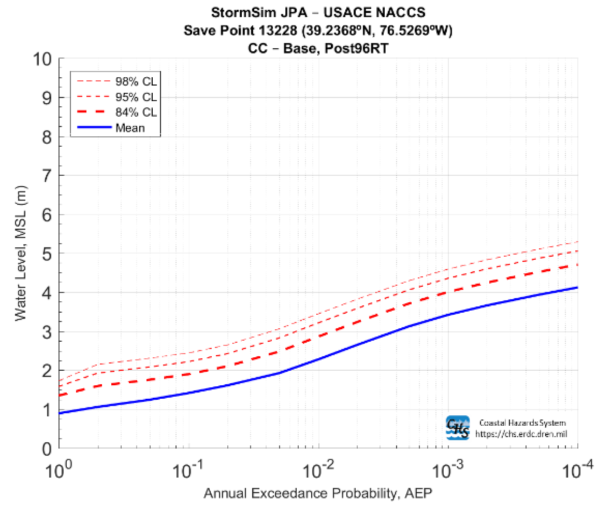


Figure 8b NACCS AEP WSEL for Save Points 7288 and 13228

The water levels were converted to feet, NAVD88 and are provided in Tables 1a, 1b, 2a and 2b. Because economic analyses compute the National Economic Development (NED) Plan utilizing benefits at the mean level, the mean, or expected value, water levels from save points 5944, 13228 and 10930 were used for evaluating damages in the study area. However, Figures 8a and 8b; and Tables 2a, 2b, 2c and 2d express the epistemic uncertainty of the water level response as confidence limits.

Table 2a Annual Exceedance Probability Water Level

NACCS Save Point 5944	Annual Exceedance Probability (1 in x) [Water Level in feet, NAVD 88]												
	1	2	5	10	20	50	100	200	500	1,000	2,000	5,000	10,000
Confidence Limit 84 for AEP	4.43	5.26	5.81	6.33	7.09	8.48	9.84	11.25	13.22	14.43	15.38	16.39	17.04
Confidence Limit 90 for AEP*	4.85	5.76	6.28	6.78	7.55	9.00	10.39	11.80	13.76	14.97	15.92	16.94	17.59
Confidence Limit 95 for AEP	5.19	6.34	6.88	7.38	8.14	9.62	11.00	12.40	14.37	15.58	16.53	17.54	18.19
Confidence Limit 98 for AEP	5.66	7.08	7.62	8.10	8.86	10.39	11.76	13.17	15.14	16.34	17.30	18.31	18.96
Expected Value AEP	2.94	3.49	4.13	4.74	5.46	6.66	7.94	9.33	11.30	12.51	13.46	14.47	15.12

*Computed based on CHS data

Table 2b Annual Exceedance Probability Water Level

NACCS Save Point 7288	Annual Exceedance Probability (1 in x) [Water Level in feet, NAVD 88]												
	1	2	5	10	20	50	100	200	500	1,000	2,000	5,000	10,000
Confidence Limit 84 for AEP	4.40	5.23	5.76	6.25	6.96	8.25	9.59	10.94	12.70	13.79	14.66	15.61	16.24
Confidence Limit 90 for AEP*	4.82	5.73	6.23	6.70	7.42	8.76	10.13	11.48	13.24	14.33	15.21	16.16	16.78
Confidence Limit 95 for AEP	5.16	6.31	6.83	7.30	8.01	9.39	10.74	12.09	13.85	14.94	15.82	16.77	17.39
Confidence Limit 98 for AEP	5.64	7.04	7.57	8.03	8.74	10.15	11.51	12.86	14.62	15.71	16.58	17.53	18.16
Expected Value AEP	2.91	3.46	4.08	4.66	5.34	6.43	7.68	9.02	10.79	11.87	12.75	13.70	14.32

*Computed based on CHS data

Table 2c Annual Exceedance Probability Water Level

NACCS Save Point 13228	Annual Exceedance Probability (1 in x) [Water Level in feet, NAVD 88]												
	1	2	5	10	20	50	100	200	500	1,000	2,000	5,000	10,000
Confidence Limit 84 for AEP	4.40	5.21	5.73	6.20	6.88	8.11	9.36	10.59	12.15	13.12	13.91	14.80	15.42
Confidence Limit 90 for AEP*	4.83	5.71	6.21	6.65	7.33	8.62	9.90	11.13	12.69	13.66	14.45	15.34	15.96
Confidence Limit 95 for AEP	5.17	6.29	6.81	7.25	7.93	9.25	10.51	11.74	13.30	14.27	15.06	15.95	16.57
Confidence Limit 98 for AEP	5.64	7.03	7.55	7.98	8.66	10.01	11.28	12.51	14.06	15.03	15.83	16.72	17.34
Expected Value AEP	2.91	3.45	4.05	4.61	5.26	6.29	7.44	8.67	10.23	11.20	11.99	12.88	13.50

*Computed based on CHS data

Table 1d Annual Exceedance Probability Water Level

NACCS Save Point 10930	Annual Exceedance Probability (1 in x) [Water Level in feet, NAVD88]												
	1	2	5	10	20	50	100	200	500	1,000	2,000	5,000	10,000
Confidence Limit 84 for AEP	4.41	5.30	5.84	6.33	6.99	8.14	9.35	10.61	12.21	13.27	14.13	15.08	15.73
Confidence Limit 90 for AEP*	4.82	5.80	6.32	6.77	7.43	8.62	9.88	11.15	12.76	13.82	14.68	15.63	16.27
Confidence Limit 95 for AEP	5.15	6.38	6.92	7.37	8.01	9.23	10.50	11.76	13.36	14.43	15.28	16.24	16.88
Confidence Limit 98 for AEP	5.62	7.12	7.66	8.08	8.71	9.98	11.27	12.53	14.13	15.19	16.06	17.00	17.65
Expected Value AEP	2.96	3.54	4.16	4.75	5.42	6.45	7.48	8.69	10.29	11.35	12.21	13.16	13.81

*Computed based on CHS data

As only the upper confidence limits are shown it is assumed that the distributions of annual exceedance probability are symmetrical. The annual exceedance probability water levels at higher confidence limits are presented to show the range of uncertainty.

2.4 Overtopping and Wall Height Design Elevation

All of the NACCS save points within the Baltimore Harbor area, including the closest save point from the floodwall--save point 7288--are located in deeper water and not near the proposed floodwalls. Several mitigating circumstances exist that would preclude most of the floodwalls from experiencing significant wave action as discussed below:

- The FEMA floodplain map (Figure 9) shows all of the floodwalls are outside FEMA's designated 100-year floodplain.

Figure 9 FEMA Flood Hazard Around Inner Harbor Area

- The floodwalls protecting the tunnel entrances are approximately 1,000+ feet from the shoreline (except for the I-895 south entrance where it is 300+ feet from the shoreline) with the I-95 and I-895 tunnel entrances. Most of the surrounding ground is at least at elevation 8 feet NAVD88 (Figure 10a).

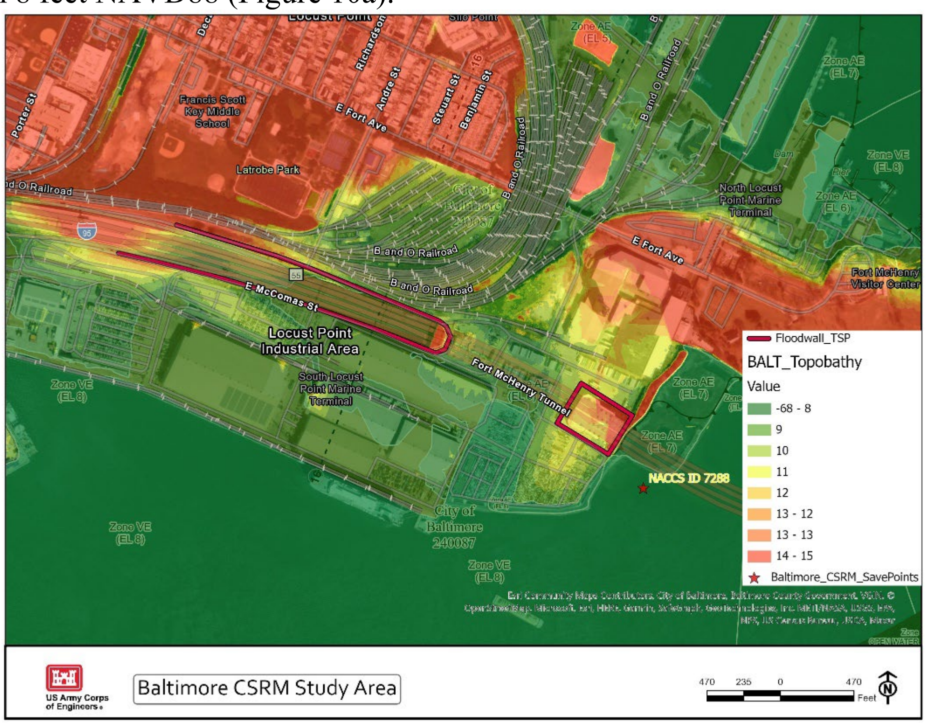


Figure 10a Topography around I-95 Tunnel

The following aerial picture (Figure 10b) from Google Earth shows that most of the wave energy will be blocked by buildings and other structures prior to potentially impacting the LOP of the tunnel entrances, thereby minimizing wave forces.

Figure 10b Aerial Picture Showing Building Around Floodwall

- As per the 2010 Maryland Transportation Authority (MDTA) Study for "Flooding Preparedness for the Fort McHenry and Baltimore Harbor Tunnels," there are existing pump systems capacities of 90 cfs for the Ft. McHenry Tunnel and 13 cfs for the Baltimore Harbor Tunnels. As per their documentation, the existing pump systems were designed to handle up to 500-year rainfall events.

  The 2010 study was performed by Jacobs with support from Parsons Brinckerhoff (now WSP Global), Century Engineering and Athavale, Lystad & Associates. The study analyzed the performance of the drainage system at the Ft. McHenry Tunnel and Baltimore Harbor Tunnel for storm flows of various intensities up to the 500-year rainfall events. The analysis showed that the existing drainage system is adequate for current NOAA-predicted 500-year rainfall events. The drainage system has additional reserve capacity for larger (unusual) events according to the design documentation.

  As part of the study, the capacity of the installed pumps was checked, and it was found that they will maintain their design discharge flow against the pressure of a 12-foot storm surge. This report included analysis of the following storm drainage system elements:

    - Storm water collection system
    - Portal pump station pump capacity
    - Portal pump station storage capacity

The study assumes that the drainage system and all pumps are fully functional at the time of the storm. We are designing floodwalls for the 100-year flood event and the existing pump capacity is adequate for up to the 500-year rainfall event.

As shown in Table 3 below, the 90% Confidence Limit for the 100-year Storm Surge Water Surface Elevation (WSEL) is 10.2 feet NAVD88 for save point 7288. Ground elevation in the area around flood walls is approximately 8 feet NAVD88. During a storm surge event, the 100-year depth of flooding is anticipated to be 2.2 feet (10.2'-8'). Using breaking criteria (per EM 1110-2-1420), the breaking wave height is 0.78 times the depth of flooding. Therefore, the 100-year wave height could be 2.2 x 0.78 = 1.7 feet. One wave amplitude (half of the wave height) is added to WSEL above the flood height. Based on this information, the required flood wall height is computed as follows:

Table 3 Wave Height Computation

Wall Height Computation				
90% CI 100-yr Storm Surge WSEL		10.2	ft	NAVD88
Depth of Water @Floodwall	=10.2-8.0 (GR Elevation)	2.2	ft	ft
Breaking Wave Height (As Per EM 1110-2-1420)	=0.78*Depth of WTR	1.7	ft	ft
Wave amplitude	=Wave Height/2	0.86	ft	ft
Intermediate SLC Through 2080	USACE Curve	1.55	ft	ft
Required Wall Height	Storm Surge + SLC + Breaking Wave	12.6	ft	NAVD88

Based on computations using the Franco and Franco (1999) equations and wave information discussed above, there is no overtopping (See Attachment -1 for additional information on overtopping computations), or chance of overtopping is minimal. Any of the potential overtopping for a flooding event resulting from any extreme situation, should be mitigated by the existing pumps. Therefore, the Floodwall Wall Height will remain as originally proposed for the Agency Decision Milestone at 12.5 feet NAVD88. Also note that there are several existing structures along the shoreline that should provide additional "sheltering" to dissipate the wave energies against the line of protection. While these structures are not able to be modeled, it is anticipated that they will provide an additional impediment to the wave energy. As such, 12.5 ft flood wall elevation is justified.

With the Martin State Airport being a critical infrastructure, PDT considered having 500-year level protection, but the PDT decided it was not feasible considering the project site constraints. We used same wall height for both the Inner Harbor area and Martin State Airport floodwall. Martin State Airport alternatives were screen out from the recommended plan.

2.5 Validation of G2CRM Model

During the Agency Technical Review (ATR) of the final Integrated Feasibility Report and Environmental Assessment (IFR/EA), a discrepancy in the computed frequency curves between CHS data and G2CRM output was discovered. The discrepancy in the frequency curve was partially due to Extra Tropical Storm inputs not utilized in G2CRM modeling efforts. In addition, there are differences in methodology how G2CRM computes frequency curve and how CHS computes frequency curve for the NACCS data. This differences in methodology have also contributed toward the discrepancies. The frequency curve discrepancies for G2CRM model resulted in lower storm surge elevations than that of CHS and underestimated damages calculated computations.

To match the G2CRM computed AEP values to that of the CHS data, the vertical conversion from Mean Lower Water (MLLW) to Mean Sea Level (MSL) was adjusted by adding 1.18 feet to the previous -0.81 value used in the H5 metadata file (G2CRM inputs). After the adjustments for the vertical conversion, the G2CRM model was re-run and frequency curve was computed again. It was also verified that the G2CRM inputs included extratropical storms data and the correct save points. Based on G2CRM computed Frequency curve data, the following plot (Figure 11) was prepared along with CHS adCIRC 50% Confidence WSEL:

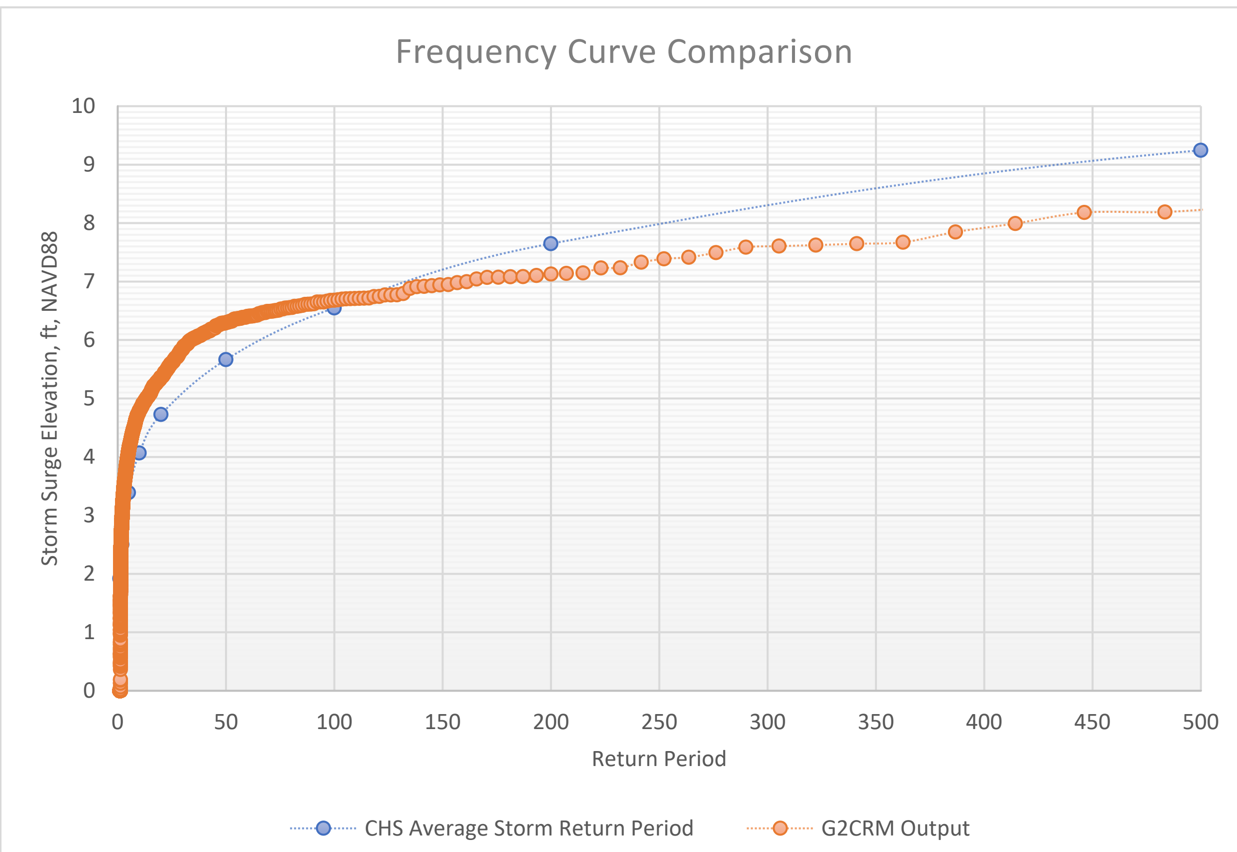


Figure 11. Frequency Curve Comparison

The storm surge WSEL computed with G2CRM matches very well with that of CHS for the 100-year storm event. However, it is within a foot of other flood frequencies.

3 Climate Change

3.1 Introduction

Engineering and Construction Bulletin (ECB) 2018-14 requires USACE studies to provide a qualitative description of climate change impacts to inland hydrology and/or sea level change assessments as necessary. The objective of this ECB is to enhance USACE climate preparedness and resilience by incorporating relevant information about observed and expected climate change impacts in hydrologic analyses for new, and existing USACE projects.

ECB 2018-14 requires at a minimum, a qualitative assessment of potential climate change threats and impacts that may be relevant to the recommended plan for the Baltimore Coastal Study. The Baltimore Coastal Study included a large portion of study within city and county of Baltimore. The primary focus for the study is within the Inner Harbor area, and the Martin State Airport area.

3.2 Literature Review

As required by ECB 2018-14, a hydrologic literature review was conducted to summarize peer reviewed literature on current climate and observed climate trends and projected climate trends in the project area. The literature review includes sources specific to Maryland, and the surrounding northeast United States:

1) *Recent US Climate Change and Hydrology Literature Applicable to US Army Corpsof Engineers Missions: Mid-Atlantic Region 02 (USACE, May 2015*)
2) *Climate Change Indicators in the United States (U.S. Environmental ProtectionAgency, 2019)*
3) *Climate Science Special Report: Fourth National Climate Assessment, Volume I(Carter, et al., 2014)*
4) *NOAA State Climate Summaries for Maryland (Jennifer Runkle and Kenneth E. Kunkel, 2017)*

The literature focuses on the following climate variables, which are consistent with those identified for the project: precipitation, temperature, and streamflow.

A summary of the USACE peer-reviewed climate literature is available for the mid-Atlantic Region 02 and is referenced as one of the primary sources of information in this literature review. This USACE report summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports and characterizes climate threats to the USACE business line (USACE, 2015). The project watershed falls within the Mid-Atlantic region, which is also referred to as Water Resources Region 02 (2-digit hydrologic unit code).

3.3 Scope of Qualitative Analysis

ECB 2018-14 stipulates that for project areas at elevations less than or equal to 50 feet NAVD88, a determination should be made as to whether Sea Level Change (SLC) will affect flooding by increasing (or decreasing) water surface elevation of the project area. The entire project area is affected by coastal flooding from the Chesapeake Bay and area elevation is well below 50 feet NAVD88. Therefore, a SLC assessment is necessary for the Baltimore Coastal Study.
The climate assessment for SLC follows the USACE guidance of Engineer Regulation (ER) 1100-2-8162, "Incorporating Sea Level Change in Civil Works Programs," and Engineer Technical Letter (ETL) 1100-2-1, "Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation." ER 1100-2-8162 and EP 1100-2-1 provide guidance for incorporating the direct and indirect physical effects of projected future SLC across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining the federal projects. Planning studies and engineering designs over the project life cycle, for both existing and proposed projects, will consider alternatives that are formulated and evaluated for the entire range of possible future rates of SLC.

A qualitative analysis will provide the necessary information to support the assessment of climate change risk and uncertainties for the Baltimore Coastal Study. The study is primarily focused on coastal flood risk reduction. Therefore, riverine hydrology is briefly reviewed as part of this qualitative assessment in section 3.6. The relevant climate variables identified for this study are temperature, precipitation, and relative sea level rise.

According to the Fourth National Climate Assessment (4th NCA) report on Region 2, the Chesapeake Bay watershed, which includes the Baltimore Coastal Study area, is experiencing stronger and more frequent storms, an increase in heavy precipitation events, increasing bay water temperatures, and a rise in sea level. These trends vary throughout the watershed and over time but are expected to continue over the next century.

The Maryland climate is changing. The region has warmed by more than two degrees (F) in the last century, hot days and heavy rainstorms are more frequent. In the coming decades, changing climate is likely to increase tidal flooding, cause more heavy rainstorms and sewer overflows, and increased risks to human health.

Our climate is changing because the earth is warming. People have increased the amount of carbon dioxide in the air by 40 percent since the late 1700s. Other heat-trapping greenhouse gases are also increasing. These gases have warmed the surface and lower atmosphere of our planet about one degree during the last 50 years. Evaporation increases as the atmosphere warms, which increases humidity, average rainfall, and the frequency of heavy rainstorms in many places—but contributes to drought in others.

Greenhouse gases are also changing the world's oceans and ice cover. Carbon dioxide reacts with water to form carbonic acid, so the oceans are becoming more acidic. The surface of the ocean has warmed about one degree during the last 80 years. Warming is causing snow to melt earlier in spring, and mountain glaciers are retreating. Even the great ice sheets on Greenland and Antarctica are shrinking. Thus, the sea level is rising at an increasing rate.

3.4 Temperature Trends

According to the Third National Climate Assessment, climate change is expected to intensify current, observed trends in temperature and precipitation in the U.S., including the northeast region (Carter, et al., 2014). The Baltimore CSRM project is located at the Baltimore Harbor and Martin State Airport, approximately 50 miles northeast of Washington DC.

Maryland's climate is generally moist with a rather large seasonal range of temperatures. Due to Maryland's mid-latitude location, the jet stream is often in the vicinity, particularly in the late fall, winter, and spring. In addition, Maryland's location on the East Coast of the North American continent exposes it both to the cold winter and warm summer air masses of the continental interior and the moderate and moist air masses of the western Atlantic Ocean. In winter, the contrast between frigid air masses of the continental interior and the relatively warm Atlantic Ocean provides the energy for occasional intense storms commonly known as nor'easters. As a result of these varying influences, Maryland's climate is characterized by moderately cold and occasionally snowy winters and warm, humid summer.

Average annual temperature has risen by more than 1.5°F in Maryland since the beginning of the 20th century (Figure 12). Historically unprecedented warming is projected by the end of the 21st

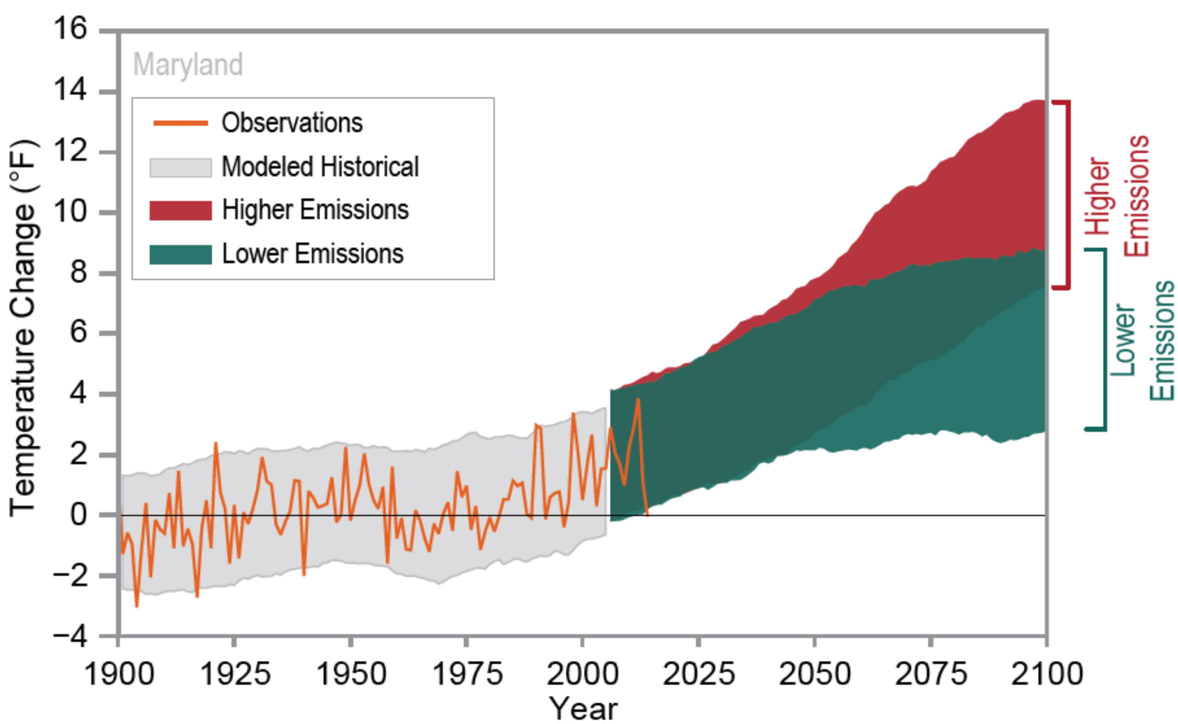


Figure 12 Observed and Projected Temperature Change for Maryland (Source: NOAA)

century under a higher emissions pathway. Heat waves are projected to be more intense while cold waves
are projected to be less intense (Runkle & Kunkel, 2017).

3.5 Precipitation

According to NOAA's Maryland State Summaries, average annual precipitation varies from around 50 inches in the extreme west to around 40 inches just to the east of the Appalachian Mountains. The wettest period was the 1970s, with the wettest 5-year period being 1971–1975, while the driest period was the 1960s, with the driest five-year period being 1962–1966. Annual mean precipitation has been above average for the last two decades. The annual number of extreme precipitation events (days with more than 2 inches) averaged 2.5 days per year during 2005–2014 compared to 1.8 days per year during 1950–2004.

Maryland is susceptible to several extreme weather types including tropical storms and hurricanes, severe thunderstorms, tornadoes, nor'easters, blizzards and ice storms, flooding, drought, and heat and cold waves. Hurricane Irene in 2011 caused considerable wind damage along the coast. Hurricane Sandy in 2012 caused damage from wind and a storm surge of 4–5 feet, which destroyed a large portion of Ocean City's fishing pier and caused widespread flooding in Crisfield and other low-lying areas of the lower Eastern Shore. On June 29, 2012, a derecho (a widespread, long-lived line of thunderstorms with very strong winds) moved through the Ohio Valley and the Mid-Atlantic states; Maryland and Washington, D.C. were two of the hardest hit areas. One-third of Maryland residents and one-quarter of D.C. residents were left without power after the storm, with some outages lasting longer than a week. Mountainous terrain in the narrow, western portion of the state, and the dense urbanized areas of the state are each highly vulnerable to flash flooding. During August 12–13, 2014, torrential rains of up to 6–10 inches occurred resulting in flooding along the coastal plain from Baltimore into New Jersey. This event resulted in the second highest calendar day precipitation total (6.3 inches on August 13) since 1933. Most recently, an extreme precipitation event occurred on July 30, 2016, impacting Ellicott City with 6 inches of rain in several hours and causing two fatalities.

Average annual precipitation is projected to increase in Maryland over the 21st century, particularly during winter and spring (Figure 13). This is part of a large-scale pattern of projected increases in precipitation over northern and central portions of North America. More frequent intense rainfall events are projected, potentially increasing flooding events in urban areas. The 100-year rain-storm event, as defined by historical data, is expected to occur every 20 to 50 years

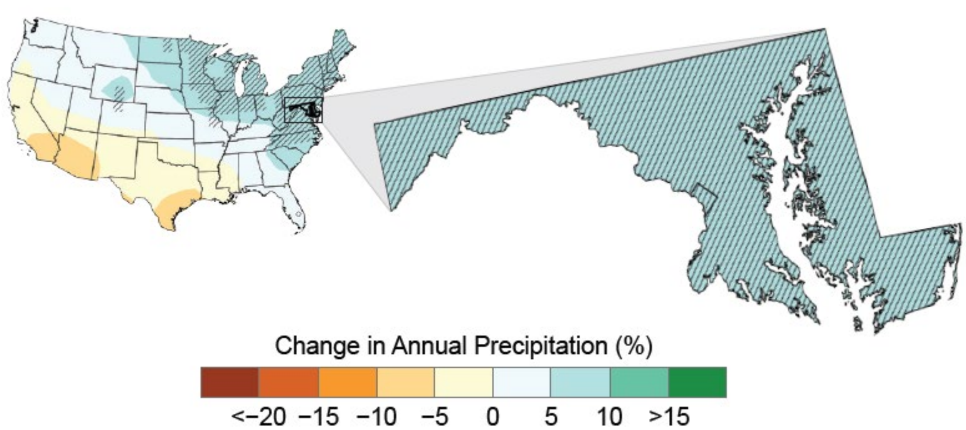


Figure 13 Projected Change in Annual Precipitation (Source: NOAA)

by the end of the century. Increasing and more intense extreme precipitation events will likely expand the flood hazard areas (areas that will be inundated by a flood event).

3.6 Streamflow Trends

Studies of trends and non-stationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which include the Mid-Atlantic Region. Xu et al. (2013) investigated trends for multiple stream gages in the Mid-Atlantic Region. No statistically significant ($p < 0.05$) trends in either annual streamflow or baseflow were identified for any of the stations in the Mid-Atlantic Region. These results are supported by Kalra et al. (2008) who analyzed historical streamflow (1952 – 2001) for over 600 flow stations throughout the U.S., including a large number in the Mid-Atlantic Region. None of the stations in the region exhibited statistically significant ($p < 0.05$) trends, in either direction, for annual or seasonal streamflow. (USACE, 2015).

3.7 Sea Level Rise

Sea Level Rise (SLR) has been a persistent trend for decades in the United States and elsewhere in the world. SLR will likely continue beyond the end of this century. The USACE has developed two web-based SLC tools: Sea Level Change Curve Calculator and the Sea Level Tracker. Both tools provide a consistent and reproducible methods to visualize the dynamic nature and variability of coastal water levels at tide gauges, allowing comparison to the USACE projected SLC scenarios, and support simple exploration of how SLC has or will intersect with local elevation thresholds related to infrastructure (e.g., roads, power generating facilities, dunes), and buildings. Taken together, decision-makers can align various SLR scenarios with existing and planned engineering efforts, estimating when and how the sea level may impact critical infrastructure and planned development activities (USACE, 2018b).

Both the Sea Level Change Curve Calculator and the Sea Level Tracker are designed to help with the application of the guidance found in ER 1100-2-8162 and EP 1100-2-1. The tools use equations in the regulation to produce tables and graphs for the following three SLC scenarios:

- Low estimate, which is based on historic trend and represents the minimum expected SLC.
- Intermediate estimate.
- High estimate, representing the maximum expected SLC.

The calculator accepts user input—including project start date, selection of an appropriate NOAA long-term tide gauge, and project life span—to calculate projected SLCs for the respective project. The Sea Level Tracker has more functionality for quantifying and visualizing observed water levels and SLC trends and projections against existing threshold elevations for critical infrastructure and other local elevations of interest (USACE, 2018b). The start date used by the calculator is 1992, which corresponds to the midpoint of the current National Tidal Datum Epoch of 1983-2001.

3.7.1 Historic and Existing Condition Sea-Level Change

The nearest NOAA tide gauge located approximately 2 miles northeast of Baltimore Harbor. The relative sea level trend is 3.22 mm/year +/- 0.13 mm/year with a 95%

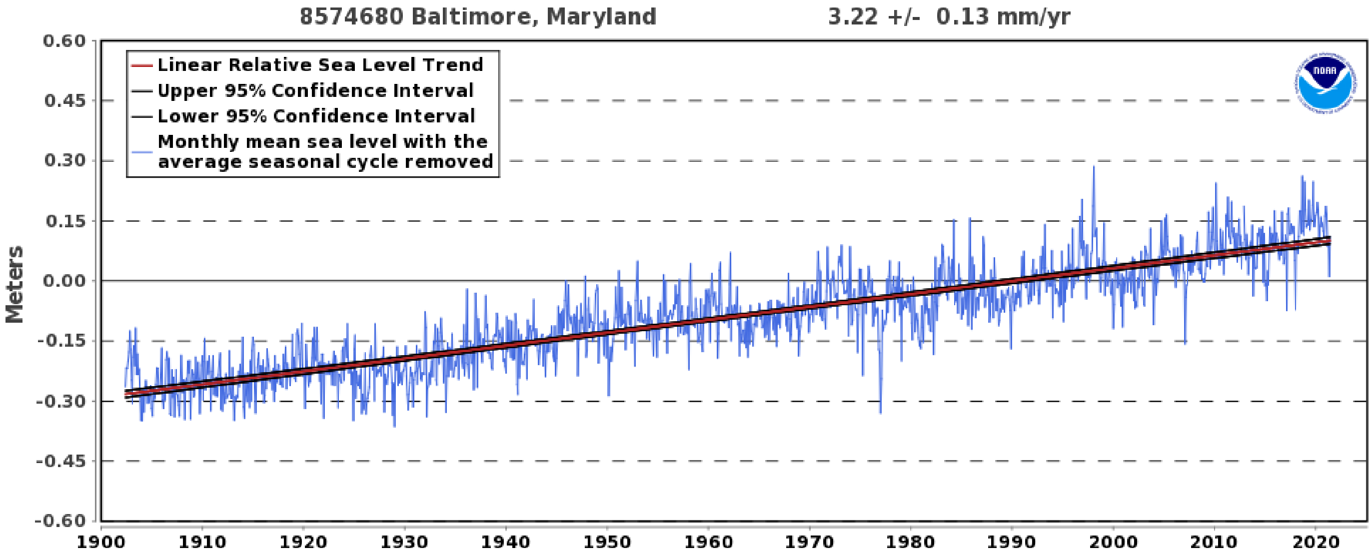


Figure 84 The relative sea level trend from Baltimore, MD

confidence interval. This trend is based on monthly mean sea level data from 1897 to 2021 which is equivalent to a change of 1.2 feet in 100 years (NOAA, 2021). Figure 14 shows historical SLR trend for NOAA tide gauge near Baltimore Harbor.

3.7.2 Potential Impacts to the Project from Sea-Level Change

The following analysis evaluates potential effects on recommended plan for the Baltimore coastal study. For this analysis, the following years are evaluated:

- 2031 (beginning of the Baltimore Coastal planning horizon at the start of construction)
- 2080 (50 years into the future, representing the Baltimore Coastal future without project (FWO) condition)
- 2130 (100 years into the future, representing the end of the Baltimore coastal project life cycle)

Climate for which the project is designed can change over the planning life cycle of that project and may affect its performance, or impact operation and maintenance activities. Given these factors, the USACE guidance from ECB 2018-14, suggests that the project life cycle should be up to 100 years. For most projects, the project life cycle starts when construction is complete which typically corresponds to the time when the project starts accruing benefits. For some cases, however, the project life cycle starts before construction completion, typically because these projects start getting benefits during construction.

For the Baltimore Coastal study, the project life cycle begins in 2031, when construction is planned to be completed. The 2080 and 2130 conditions could ultimately affect flooding due to SLC and local storm water runoff from Gunpowder-Patapsco watershed. Hence, SLC considerations may result in an increase in hydraulic loading impacts on floodwalls/levees under future conditions. The magnitude of those impacts will depend on how soon the sea rises to a level that impacts project performance.

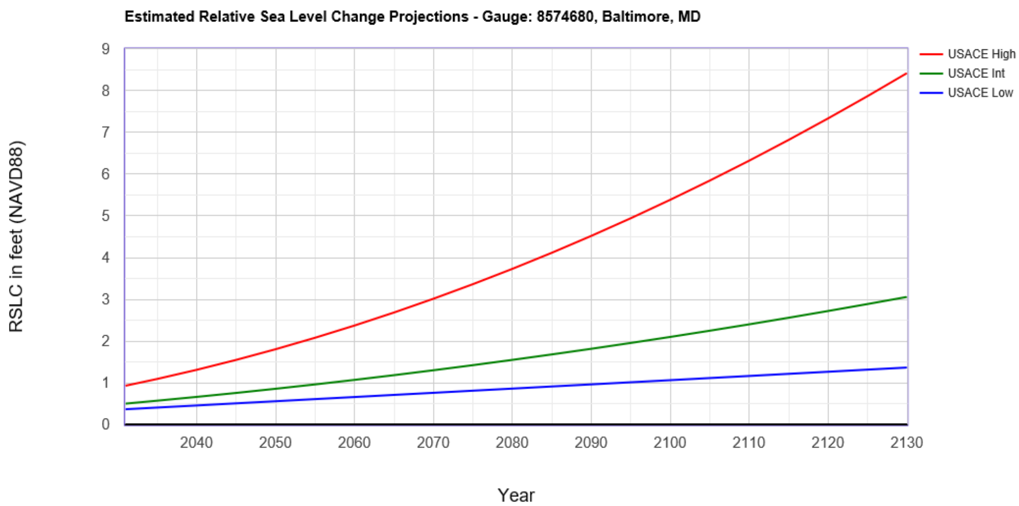


Figure 15a Sea Level Change Projections for Baltimore MD

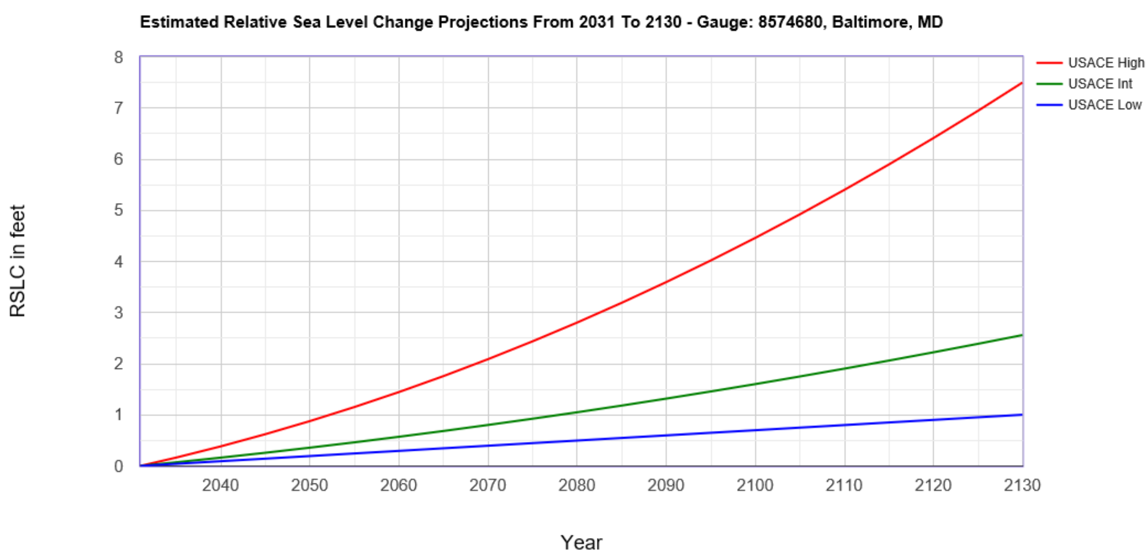


Figure 15b Relative Sea Level Change Projections for Baltimore MD from 2031 to 2130

Sea levels relative water surface elevation level are expected to rise, depending on the projected rates of rise for low, intermediate, and high scenarios. Figure 15a shows the estimated relative SLC in feet NAVD88 from 1992 to 2130, calculated with the USACE Sea Level Change Curve Calculator, at the Baltimore Shores NOAA gauges which is closest to the project sites. Figure 15b shows relative SLC in feet from 2031 to 2130 how SLC will likely change.

Table 4 shows estimated USACE Low, Intermediate, and High SLC projections at Baltimore Shores, in feet relative to NAVD88, from years 2031 to 2130. The USACE Sea level rise calculator is available at https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html

Table 4 Estimated USACE Low, Intermediate, and High Scenarios

Baltimore CSRM
Gauge Status: Active and compliant tide gauge
Epoch: 1983 to 2001
8574680, Baltimore, MD
NOAA's 2006 Published Rate: 0.01010 feet/yr
All values are expressed in feet relative to NAVD88

Year	USACE Low	USACE Int	USACE High
2031	0.36	0.50	0.93
2035	0.41	0.57	1.09
2040	0.46	0.66	1.31
2045	0.51	0.76	1.55
2050	0.56	0.86	1.80
2055	0.61	0.96	2.08
2060	0.66	1.07	2.37
2065	0.71	1.18	2.68
2070	0.76	1.30	3.01
2075	0.81	1.42	3.36
2080	0.86	1.55	3.73
2085	0.91	1.68	4.12
2090	0.96	1.81	4.52
2095	1.01	1.95	4.94
2100	1.06	2.10	5.39
2105	1.11	2.25	5.85
2110	1.16	2.40	6.32
2115	1.21	2.56	6.82
2120	1.26	2.72	7.34
2125	1.31	2.89	7.87
2130	1.36	3.06	8.43

3.7.3 Sensitivity of Sea-Level Changes

USACE Guidance document ER 1100-2-8162 require evaluation of alternative plans and designs are to these rates of future local mean SLC. This section evaluates how the sensitivity of SLC affects project performance if structural alternatives are built as planned. The structural alternative planned will experience overtopping when WSEL increases above 12.5 feet NAVD88 and the area behind the protected structure will experience flooding. The following table 5 shows how the proposed alternatives are sensitive to SLC changes:

Table 5 USACE Sea Level Change Scenarios and their impact of Project Performance for Inner Harbor Area

Year		1992	2031	2031	2031	2080	2080	2080	2130	2130	2130
USACE Sea Level Rise Scenarios		None	Low	Medium	High	Low	Medium	High	Low	Medium	High
Sea Level Rise, ft		0	0.36	0.5	0.93	0.86	1.55	3.73	1.36	3.06	8.43
Recurrence Interval	Percent Chance Exceedance	Water Surface Elevations plus Sea Level Rise, ft (Wall Height 12.5 ft)									
5000	0.02	17.5	17.9	18.0	18.5	18.4	19.1	21.3	18.9	20.6	26.0
2000	0.05	16.5	16.9	17.0	17.5	17.4	18.1	20.3	17.9	19.6	25.0
1000	0.1	15.6	15.9	16.1	16.5	16.4	17.1	19.3	16.9	18.6	24.0
500	0.2	14.4	14.7	14.9	15.3	15.2	15.9	18.1	15.7	17.4	22.8
200	0.5	12.4	12.8	12.9	13.3	13.3	14.0	16.1	13.8	15.5	20.8
100	1	11.0	11.4	11.5	11.9	11.9	12.5	14.7	12.4	14.1	19.4
50	2	9.6	10.0	10.1	10.6	10.5	11.2	13.4	11.0	12.7	18.1
20	5	8.1	8.5	8.6	9.1	9.0	9.7	11.9	9.5	11.2	16.6
10	10	7.4	7.7	7.9	8.3	8.2	8.9	11.1	8.7	10.4	15.8
5	20	6.9	7.2	7.4	7.8	7.7	8.4	10.6	8.2	9.9	15.3
2	50	6.3	6.7	6.8	7.3	7.2	7.9	10.1	7.7	9.4	14.8
1	100	5.2	5.5	5.7	6.1	6.0	6.7	8.9	6.5	8.2	13.6

Pink: Flooding will occur during these conditions (WSEL greater than or equal to 12.5 feet NAVD88)

Green: No flooding will occur during these conditions (WSEL less than 12.5 feet NAVD88)

3.8 Climate Hydrology

It is expected that increased air temperatures and frequencies of drought, particularly in the summer months, will result in increased stream water temperatures, potentially affecting dissolved oxygen levels. Higher average and extreme temperatures combined with an increased annual rainfall in the region may lead to higher peak flows as well as more frequent low flows (USACE, 2015c).

3.8.1 Climate Hydrology Assessment tool (CHAT)

The Climate Hydrology Assessment tool (CHAT) [USACE, 2016a] allows users to access data concerning past (observed) changes as well as potential future (projected) changes to relevant hydrologic inputs. The qualitative analysis required by this ECB includes consideration of both past (observed) changes as well as potential future (projected) changes to relevant hydrologic inputs. A first-order statistical analysis of the potential impacts to particular hydrologic elements of the study can be very useful in considering future without project conditions (FWOP) and the potential direction of climate change.

Baltimore CSRM Study area is located within HUC 02060003 – Gunpowder-Patapsco watershed as shown in Figure 16.

Figure 96 HUC 8 Watershed Boundary for the Baltimore Study Area

Climate Hydrology Assessment Tool was used to analyze HUC 02060003 – Gunpowder-Patapsco watershed. Spatially downscaled, hydrologically simulated and routed and statistically aggregated CMIP5 GCM outputs for the stream segment associated with the Gunpowder-Patapsco watershed is displayed in Figure 17. Streamflow is representative of the cumulative flow from all upstream segments as well as the local runoff contributions to the aligned stream segment for the Gunpowder-Patapsco watershed. Simulated flows are unregulated.

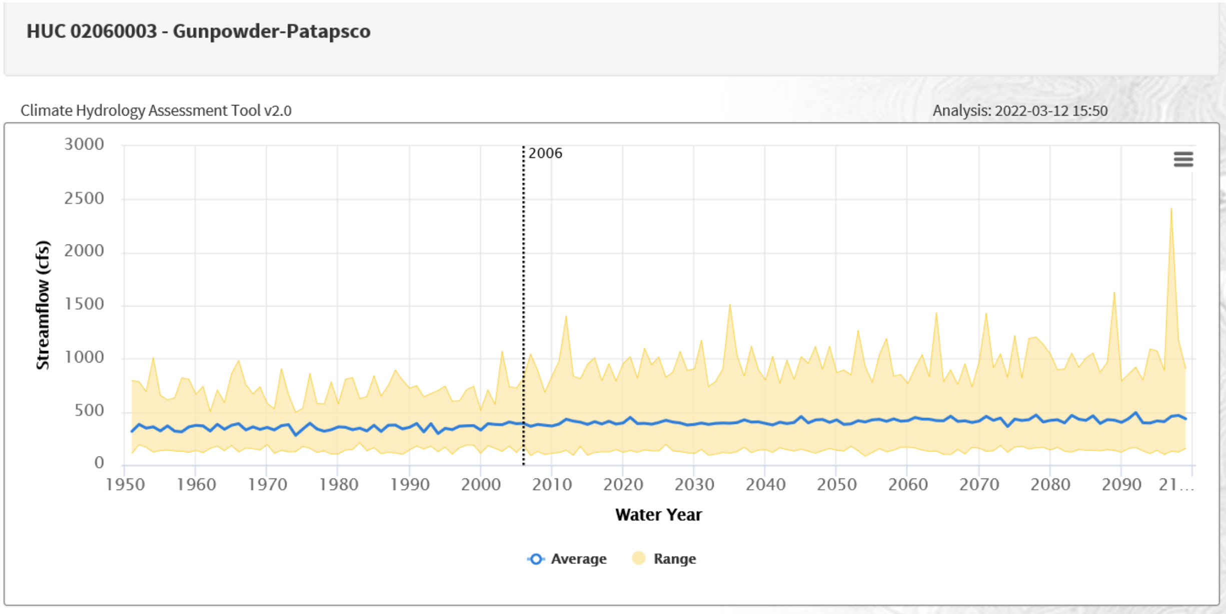


Figure 17 Annual Max of Average Monthly Streamflow: Range and Mean for Gunpowder-Patapsco Watershed

Figure 18 shows trendline for simulated historical data (i.e., water years 1951-2005) and projected future data (i.e., 2006-2099) and presents the results of several statistical tests for monotonic trends in the data displayed.

Linear regression models are separately fitted to simulated historic and projected future streamflows and are shown in Figure 18. Model slope, intercept, adjusted R-square, and three tests for monotonic trends are calculated for each of the two subsets of data (i.e., water years 1951-2005 and water years 2006-2099). The trends can be directly compared as a proxy for future climate impacts. Please note, the trendlines for simulated historical values and projected future values will not be continuous because the trends are calculated separately and may have different magnitudes.

HUC 02060003 - Gunpowder-Patapsco

Climate Hydrology Assessment Tool v2.0

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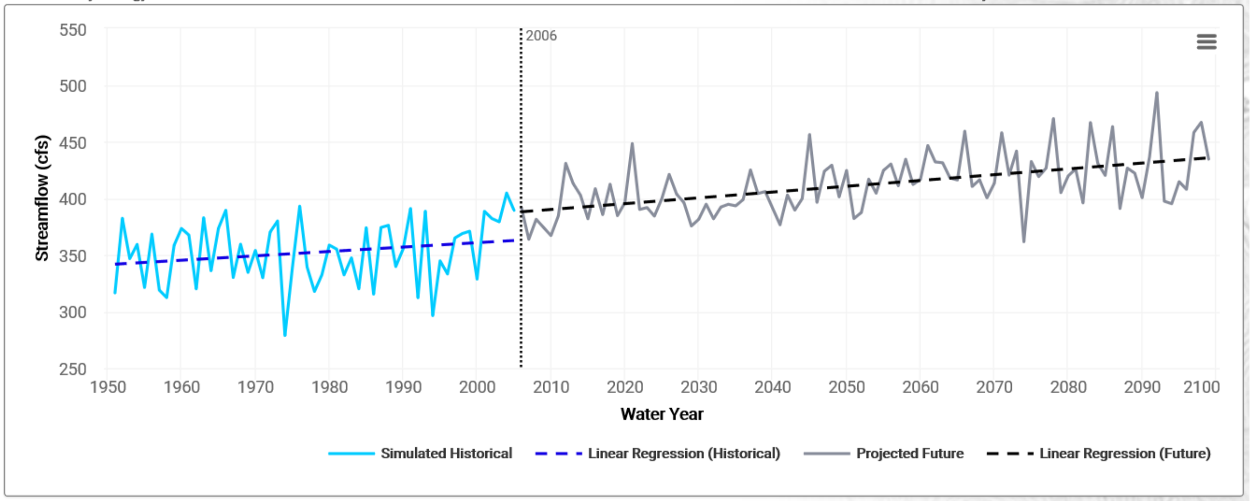


Trend Lines

Simulated Historical (1951 to 2005)

REGRESSION LINE
Flow = -412.98 + 0*water year

ADJUSTED R-SQUARED
0.03

Projected Future (2006 to 2099)

REGRESSION LINE
Flow = -638.22 + 1*water year

ADJUSTED R-SQUARED
0.28

Statistical Significance Tests (Historical)

The p-value is for the linear regression fit drawn; a smaller p-value indicates greater statistical significance. There is no recommended threshold for statistical significance, but typically 0.05 is associated with a 5% risk of a Type I error or false positive.

Test	p-value
t-Test	0.10811
Mann-Kendall	0.074124
Spearman Rank-Order	0.090314

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Statistical Signficance Tests (Future)

The p-value is for the linear regression fit drawn; a smaller p-value indicates greater statistical significance. There is no recommended threshold for statistical significance, but typically 0.05 is associated with a 5% risk of a Type I error or false positive.

Test	p-value
t-Test	2.0153e-08
Mann-Kendall	< 2.2e-16
Spearman Rank-Order	6.1158e-09

- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Figure 18 Stream Flow Trend for Gunpowder-Patapsco Watershed

With the information available, there is not enough evidence to suggest a trend in the simulated, historical data. The statistically significant change in projected, future stream flows suggests changes in the future without project condition due to climate change.

3.8.2 Non-stationarity Detection Tool

The current guidance for detecting nonstationarities is the USACE ETL 1100-2-3, "Guidance for Detection of Nonstationarities in Annual Maximum Discharges." Provides technical guidance on detecting nonstationarities in the flow record which may continue to impact flow into the future and should be considered in the Future without (FWO) project conditions.

The Nonstationarity Detection Tool (NSD) was developed to support ETL 1100-2-3. The USACE Responses to Climate Change (RCC) Program developed the tool to enable users to detect abrupt and slowly varying changes (nonstationarities) in observed, annual instantaneous peak discharges at USGS streamflow gauges with over 30 years of record. The tool allows users to conduct monotonic trend analysis on the data and any resulting subsets of stationary flow records identified.

Nonstationarities are identified when the statistical characteristics of a hydrologic data series are not constant through time. The NSD, however, is not a substitute for engineering judgment. Engineers are advised to use their judgment to consider the resilience of the system when incorporating the range of results in the hydrologic study or design results (USACE, 2016d)

It is up to the tool's user to determine which, if any, of the statistically significant nonstationarities identified by the NSD may be used to segment the data for hydrologic analysis. The user assesses the relative "strength" of any nonstationarities detected to identify "strong" nonstationarities for use in further analyses. The tool applies several methods that assess nonstationarities in time series datasets driven by changes in the mean, variance/standard deviation, and in the distributional properties of the dataset.

The NSD was utilized for the Gwynns Falls USGS gage 01589300 at Villa Nova, MD in accordance with ECB 2018-14. The tool analyzes whether the assumption of stationarity, which is the assumption that statistical characteristics of time-series data are constant over the period of record, is valid for a given hydrologic time-series data set. Similar to the CHAT analysis, the Gwynns Falls gage was selected because it is closest to the project site.

Figure 19 shows the results from the tool applied to the period of record available at the Gwynns Falls USGS gage 01589300: 1956-1988 and 1997-2020. The tool's default sensitivity parameters were applied to evaluate the stationarity of the streamflow record. The statistical methods collectively identified nonstationarities in 1970. The nonstationarity was identified using the Cramer-Von-Mises (CPM), LePage (CPM), Pettitt, Mann-Whitney (CPM) Method.

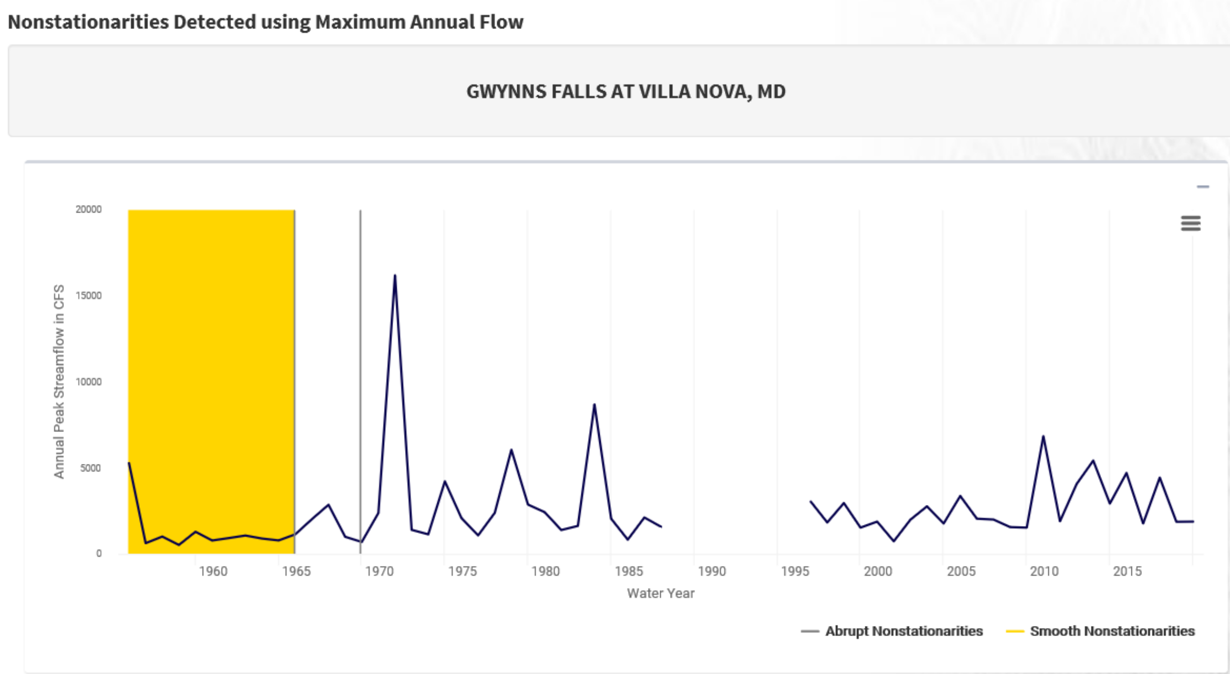
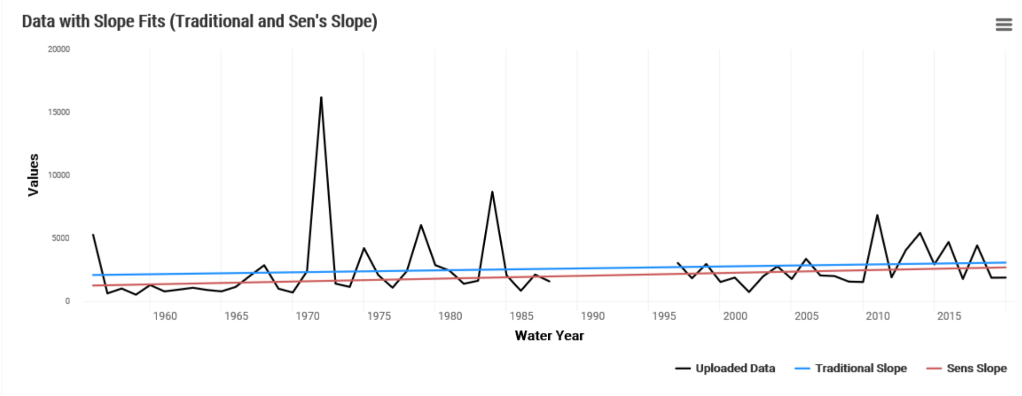


Figure 19 Non-Stationarities for Gwynns Falls

A "strong" nonstationarity is one for which there is a consensus among a minimum of three nonstationarity detection methods (more than one test flagging a nonstationarity targeted at the same statistical property), robustness in detection of changes in statistical properties (tests flagging nonstationarities targeted at different statistical properties), and relatively large change in the magnitude of a dataset's statistical properties (mean or standard deviation).

Based on these criteria, there is strong evidence of statistical non-homogeneity in the 1970 event to warrant consideration within the decision-making process.

A monotonic trend analysis is conducted to identify statistically significant trends in peak streamflow. Detected nonstationarities are used to subdivide the period of record into stationary subsets, each of which are tested for the presence of monotonic trends.



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Positive	15	-28004
Sen's Slope	Positive	22	-42731

Trend Hypothesis Test

Test	P-Value
t-Test	0.35399
Mann-Kendall	0.0011011
Spearman Rank-Order	0.0010593

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically significant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Figure 20 Monotonic trend analysis results.

Figure 20 shows a monotonic trend analysis using the Mann-Kendall Test and Spearman Rank Order test for time period 1956-2020. Statistically significant trend in annual peak streamflow was detected for the period of record using both the Mann-Kendall Test and Spearman Rank Order test.

3.9 Climate Risk

The study area is most vulnerable to sea level rise, increases in precipitation frequency and intensity, and increases in air temperature. Per guidance in ECB 2018-14, Table 5 identifies risks resulting from changing climate conditions in the future. Table 6 the major project feature, the trigger event (climate variable that causes the risk), the hazard (resulting dangerous environmental condition), the harms (potential damage to the project or changed project output), and a qualitative assessment of the likelihood and uncertainty of this harm. Note that not all impacts of climate change will result in increased risk.

Project benefits may change as a result of climate change due to sea level change. In addition, project benefits may be impacted by climate change due to SLC. Changes to benefits due to climate change may occur due to increases in flooding produced by sea level rise, or flooding produced by a combination of precipitation and sea level rise. There may be positive impacts to the project from increased air temperatures.

Table 6 Climate Risk Summary

Feature or Measure	Trigger	Hazard	Harm	Qualitative Likelihood
Floodwall	Increased sea level	Increased water levels and wave heights seaward of the floodwall	Increased SLR may increase frequency and magnitude of water level and wave loading on floodwall. Risk reduction level decreases while residual risk increases.	Likely
Closure Structures	Increased sea level	Increased water levels and wave heights seaward of closure structures	Increased SLR may increase frequency of structure closure, increasing operational costs. Frequency and magnitude of water level and wave loading may increase. Risk reduction level decreases while residual risk increases.	Likely
Pump Station	Increased sea level	Increased water levels to pump	Increased O&M costs associated with running pumps for a longer duration and with higher head differentials.	Likely
Pump Station, Elevated Gravity Inlet Piping	Increased extreme precipitation	Future flood volumes may be larger than present	Larger flood volumes may not be adequately captured by elevated gravity inlet piping and pumps. Water that cannot be pumped from interior may reduce project benefits or cause nuisance flooding. Current pump size may be able to handle increased water levels at a higher energy cost (longer pumping duration)	Somewhat Likely
Pump Station, Elevated Gravity Inlet Piping	Increased air temperatures	Increased evapotranspiration or drought	Decrease in flow volumes entering the elevated gravity inlet piping and through the pump station	Likely

4 Coastal Storm Damage Reduction Measures Considered

Proposed structural alternatives are considered in two areas i) Baltimore's Inner Harbor area, and ii) Martin State Airport. These alternatives involve floodwall, and road raisings. The following figure shows structural alternatives considered and their locations. Details on these structural alternatives are shown in Civil Engineering appendix.

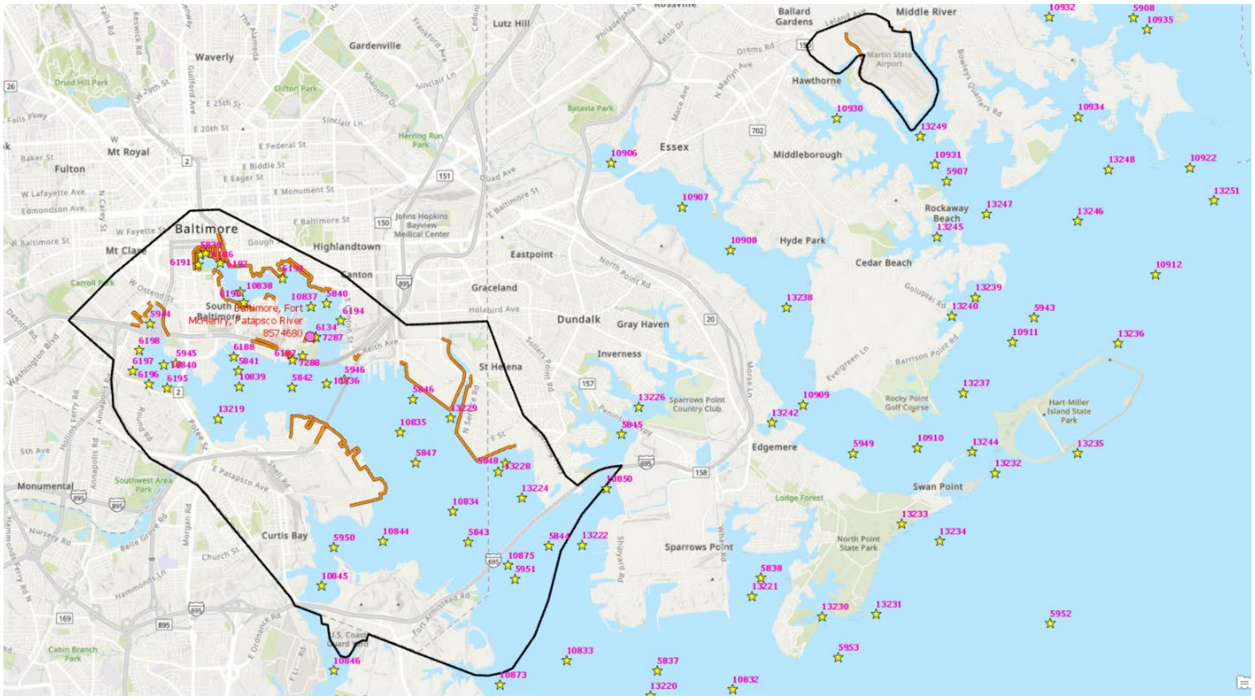


Figure 21 Structural Alternatives Considered

In accordance with ER 1105-2-101, Risk Assessment for Flood Risk Management Studies, the flood risk management performance of each alternative was estimated as its ability to manage the flood hazard for the full range of possible events. The flood hazard was defined using the 2080 90-percent confidence limit annual exceedance probability water levels presented in Table 6. This flood hazard does not include wave effects such as runup and overtopping. The performance of each alternative is reported using two metrics, Annual Exceedance Probability (AEP) and Long-Term Exceedance Probability (LTEP). AEP represents the probability of any event equaling or exceeding the level of protection provided by each alternative in any given year. LTEP describes the probability of flooding over a specified period. LTEP accounts for the repeated annual exposure to flood risk over time. Table 7 presents the AEPs and the LTEPs over 10, 30, and 50 years for each alternative.

Table 7 – Performance of alternatives described by 90% Confidence Limit AEP and LTEP

Alternatives	AEP		LTEP		
	Mean	90% Assurance	10-yr Period	30-yr Period	50-yr Period
Floodwalls in Inner Harbor (Elevation 12.5 feet NAVD88)	0.0013	0.0057	0.0126	0.0374	0.0615
20-year Flood (non-Structural) Elevation 7.0 feet NAVD88	0.0481	0.7143	0.3890	0.7719	0.9149
50-year Flood (non-Structural) Elevation 8.2 feet NAVD88	0.0172	0.1190	0.1596	0.4065	0.5809

Note: AEP's correspond to 2080 90% confidence limit water levels. The Intermediate SLC scenario was used to approximate 2080 water levels.

5 Performance of the Selected Plan

The recommended plan was evaluated further to define its performance, sensitivity to alternate sea level change scenarios, and detail residual risks.

Currently, the Baltimore Inner Harbor area is vulnerable to coastal flooding when water levels exceed approximately elevation 8 feet NAVD88. The proposed floodwall and closure structure system would manage and reduce risk up to elevation 12.5 feet NAVD88 for I-95 and I-895 tunnels. The proposed flood will mitigate flooding for the tunnel and remaining Baltimore Harbor Area will not be affected by the proposed floodwall. With the proposed project, the Baltimore Harbor area would be subject to a 1 in 176 chance of being flooded by storm surge alone in any year but a 1 in 16 chance in 50 years. This likelihood of flooding does not include the effects of wave overtopping or interior flooding that might occur with the flood barriers closed. Wave overtopping of floodwall is discussed in Sections 2.4 and any increases in interior water levels are proposed to be mitigated through pumping.

Potential flooding from greater events, with water levels exceeding 12.5 feet NAVD88, will remain a possibility. However, a taller floodwall would require adding considerable length to tie into higher ground. The probability of water levels exceeding the floodwall crest at elevation 12.5 feet NAVD88 will increase over time due to sea level rise. The relative sea level rates considered a low rate based on an extrapolation of the historic rate, and intermediate and high rates which include future acceleration of the eustatic sea level change rate. The USACE intermediate Sea Level Change scenario was considered in the feasibility level design for the recommended plan.

The recommended plan design accounts for 1.55ft of relative sea level rise based upon the middle of the current tidal epoch – year 1992, shown as green line in Figure 22. If actual SLC trend follows High curve, then the project may experience overtopping earlier than 2080. If the trend follows "High SLC" scenario then in year 2062 the project start seeing overtopping, and project will start failing to function as designed. However, the current trend shows slightly higher than "intermediate SLC" as shown in the following figure 22 below:

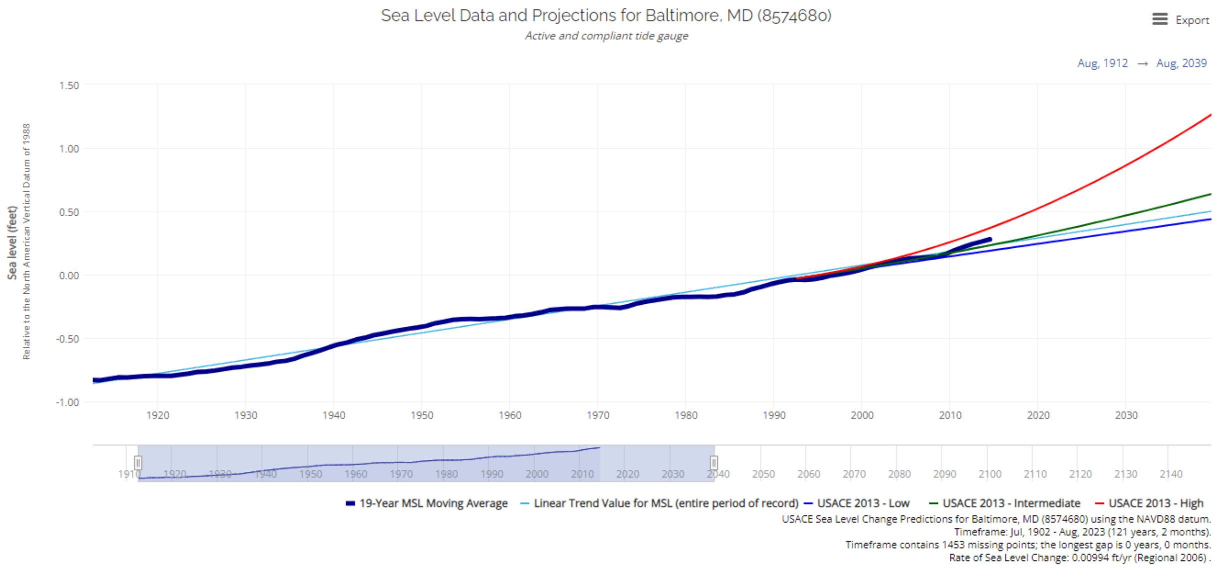


Figure 22 Current Sea Level Trend

The levels of residual risk are considered to be low and tolerable.

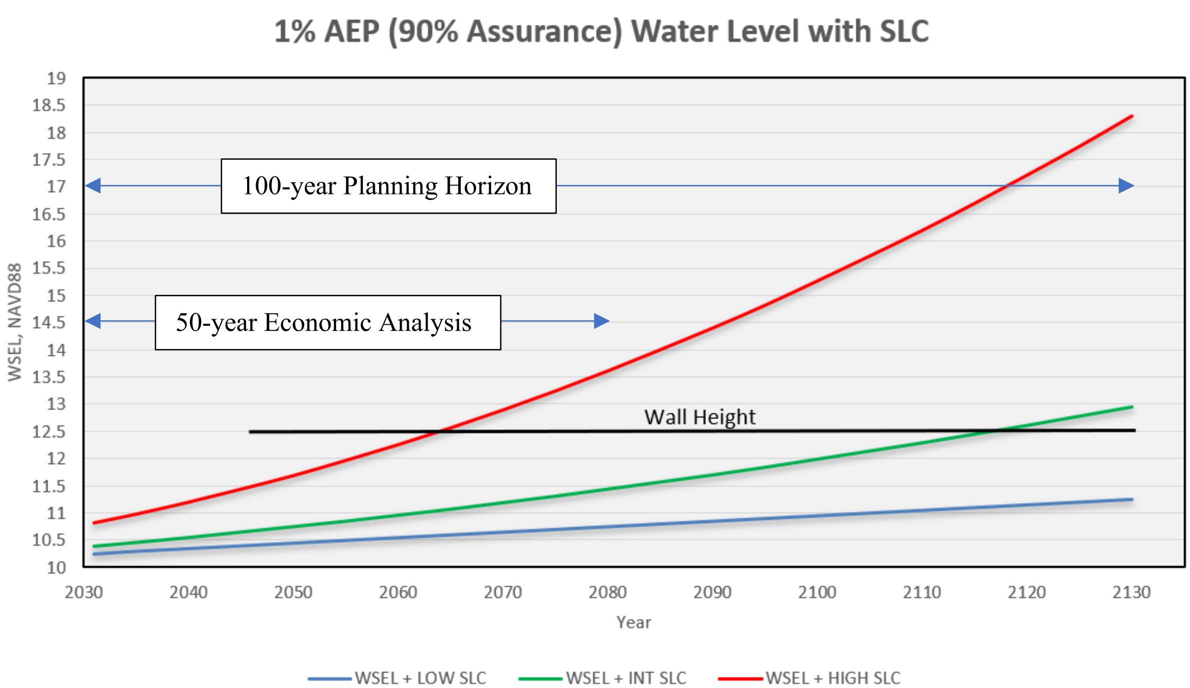


Figure 23 SLC Scenarios & Project Design Level

6 Summary and Conclusion

The Hydrology and Hydraulic Section reviewed available water level and wave data and recommended water levels to be used for the formulation and design of plan alternatives and as input to the economic analysis for the Tentatively Selected Plan. The water levels provided were extracted from the NACCS study and adjusted for anticipated changes due to sea level rise.

The Model water surface elevations were computed for SLR through 2080 and 2130.

For designing structural alternatives of the study, we used 12.5 feet NAVD88 as the wall height for all floodwalls in the Inner Harbor area. The wall height is designed based on the NACCS 100-year WSEL with 90% confidence level, wave height and intermediate SLC curve through year 2080. Results from overtopping analysis shows depth over wall crest is negligible. However, one wave amplitude (half of the wave height) is added to abet free flow above the flood wall height due to any potential wave overtopping. With the Martin State Airport being a critical infrastructure, PDT considered having 500-year level protection, but the PDT decided it was not feasible considering the project site constraints. We used the same wall height for both the Inner Harbor area and Martin State Airport floodwall. Martin State Airport alternatives were screened out from the recommended plan.

ATTACHMENT # 1 Overtopping Computation

Franco and Franco (1999) Wave Overtopping

$$\frac{q}{\sqrt{gH_{mo}^3}} = 0.082\exp\left(-3\frac{R_c}{H_{mo}}\frac{1}{\gamma_s\gamma_\beta}\right)$$

$$\gamma_\beta = \begin{cases} \cos\beta & \text{for } 0° \le \beta \le 37° \quad \textit{Long-Crested Waves} \\ 0.79 & \text{for } \beta > 37° \\ & \\ 0.83 & \text{for } 0° \le \beta \le 20° \quad \textit{Short-Crested Waves} \\ 0.83\cos(20° - \beta) & \text{for } \beta > 20° \end{cases}$$

Sharp Crested Weir

$$q = C_d \frac{2}{3}\sqrt{2g}\,\eta^{3/2}$$

$$C_d = 0.611 + 0.08\left(\frac{\eta}{h_w - h_c}\right)$$

Impact Velocity

$$B_J = B_x \sin(-\theta_J)$$

$$v_s = \frac{q}{B_J}$$

Nappe Profile:

Lower Nappe

$$\frac{x_L}{\eta} = \frac{-B - \sqrt{B^2 - 4A(C - y/\eta)}}{2A}$$

Upper Nappe

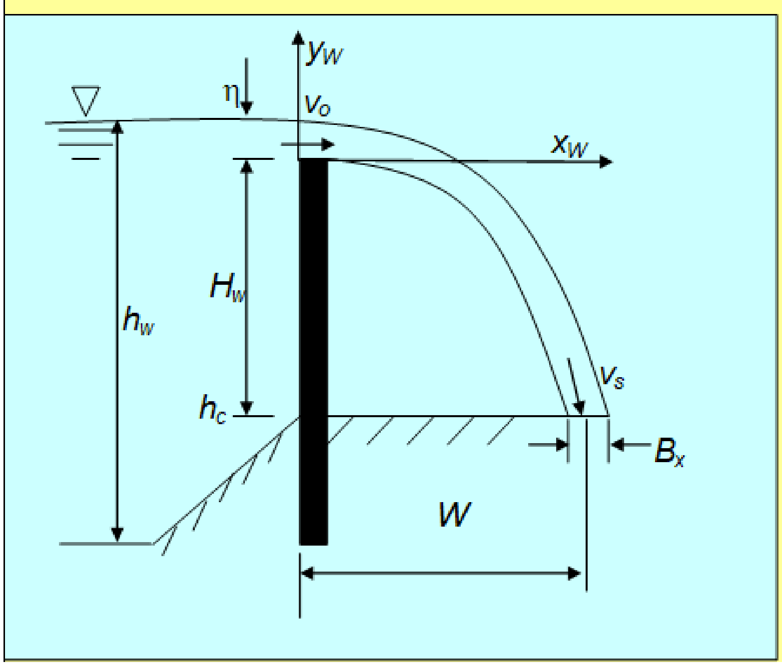
$$\frac{x_U}{\eta} = \frac{-B - \sqrt{B^2 - 4A(C + D - y/\eta)}}{2A}$$

$A = -0.425$

$B = 0.055$

$C = 0.150$

$D = 0.559$



Intersection of nappe with ground:

Horizontal width of nappe

$$B_x = x_U(y = -H) - x_L(y = -H)$$

Horizontal distance from flood side of wall to center of jet impact

$$W = \frac{x_U(y = -H) + x_L(y = -H)}{2}$$

Lower Nappe Angle of Impact

$$\theta_L = \tan^{-1}\left(\frac{2\,A\,x_L}{\eta} + B\right)$$

Upper Nappe Angle of Impact

$$\theta_U = \tan^{-1}\left(\frac{2\,A\,x_U}{\eta} + B\right)$$

Average Nappe Angle

$$\theta_J = \frac{(\theta_L + \theta_U)}{2}$$

ATTACHMENT # 1 Overtopping Computation

Overtopping of Floodwalls

Wave overtopping of floodwalls is computed using Franco and Franco (1999) The sharp-crested weir equation is used for steady flood overtopping.

Legend
User inputs
Intermediate Computations
Final Calculation

Input Wave and Water Level Variables from Input Sheet			
H_{mo} =	1.7	ft	Wave Height for Floodwall Overtopping
T_p =	5.02	s	Wave Period
h_w =	2.2	ft	Total Depth at Levee Toe
h_c =	12.5	ft	Levee Crest Height Above Toe
h_B =	0	ft	Seaward Slope
x_B =	1	ft	Roughness Influence Factor
g =	32.2	ft/s^2	Acceleration of Gravity
□ =	0	deg	Wave Obliquity
	1		CASE
H_B/h_B =	0.6		Breaker Ratio for Breaker Height at xB
H_w =	2.2	ft	Wall Height

Computed Overtopping *q* Due to Wave Overtopping Only			
q =	0.000	ft^3/s/ft	Wave Overtopping Rate for Wall

Does not apply to angles of incidence > 60 degrees

Computed Overflow *q*			
q =	0.0	ft^3/s/ft	Overtopping Rate for Sharp Crested Weir
$x_L(y_W=-H_w)$ =	0.0	ft	Horizontal Location of Lower Nappe at Ground
$x_U(y_W=-H_w)$ =	0.0	ft	Horizontal Location of Upper Nappe at Ground
B_x =	0.0	ft	Nappe Width at Ground
W =	0.0	ft	Horizontal Nappe Distance from Wall
q_L =	0.0	rad	Lower Nappe Angle at Ground
q_U =	0.0	rad	Upper Nappe Angle at Ground
q_J =	0.0	rad	Nappe Angle at Ground
B_J =	0.0	ft	Nappe Width for Streamlines Normal to Ground
v_s =	0.0	ft/s	Impact Velocity