100% DRAFT PREDESIGN SUBMITTAL

National Mall and Memorial Parks (NAMA)

Rehabilitate Seawalls and Shoreline – Design Services for Predesign (PD), Schematic Design (SD), and Design-Build (DB) Request for Proposal (RFP)

Climate Change and Natural Hazards

PMIS No. NAMA 318722

August 19, 2022

Rehabilitate Seawalls and Shoreline

National Mall and Memorial Parks

Washington, DC

PMIS Number: NAMA 318722

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1. Introduction

1.1. Project Background

The National Park Service (NPS) is preparing for the rehabilitation of portions of the National Mall (NAMA) Tidal Basin seawall and the entire West Potomac Park seawall. This Project evaluates 6,800 linear feet of seawall that is administered by the NPS through the National Mall and Memorial Parks (Park) and located in the District of Columbia (see Figure 1).

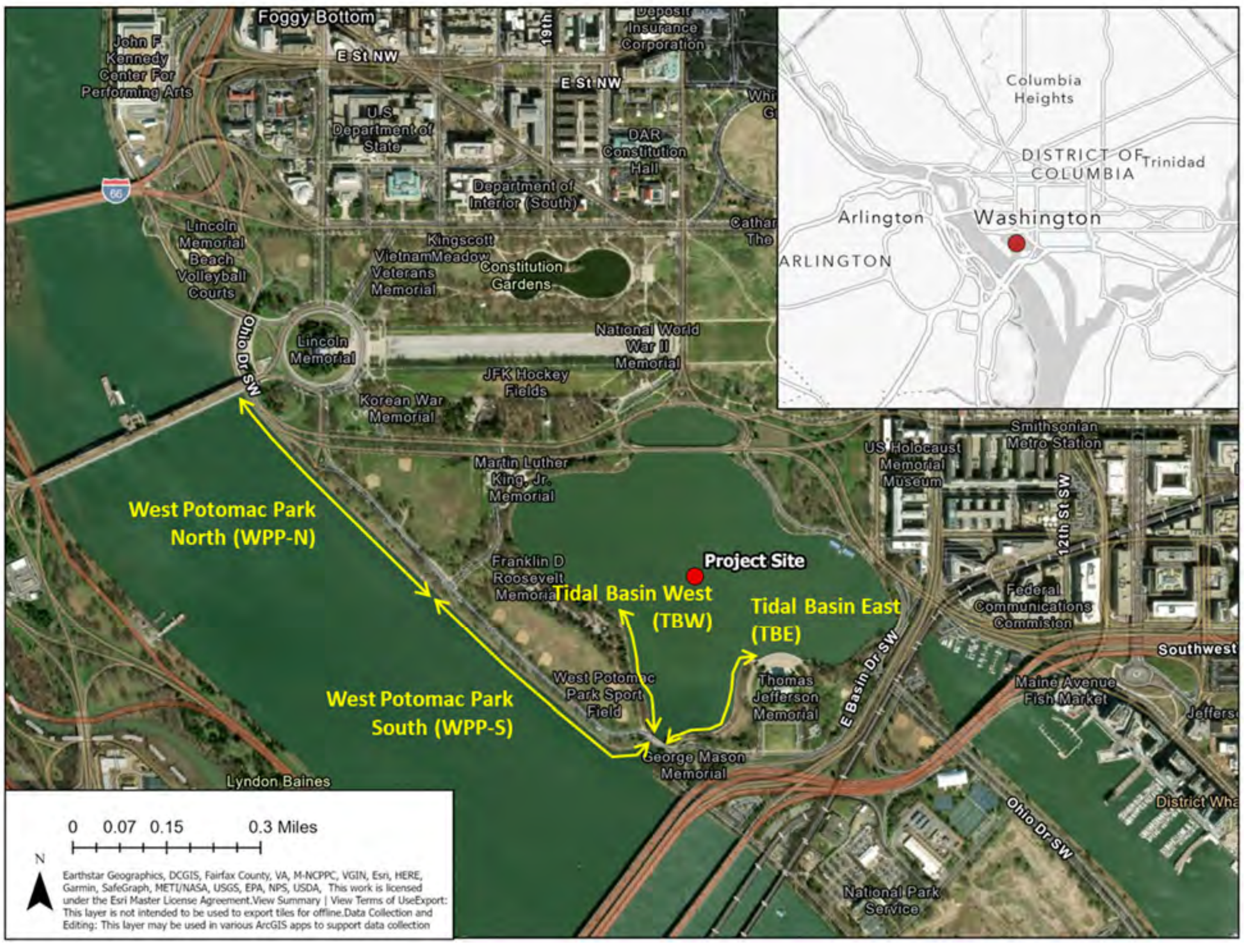


FIGURE 1. PROJECT SITE LOCATION MAP.

In the years since their construction, the seawalls have significantly settled and water levels have risen, leading to overtopping of the seawalls in some sections twice a day during normal tidal conditions. The water does not dissipate in a timely manner due to poor drainage resulting in reduced public access and damage to the cultural landscape and park infrastructure. This negatively impacts visitor use and experience. The frequently flooded areas are littered with large wood debris and other trash from the river that often collides with and damages the seawalls, causing further failure and creating an unsightly appearance. The Tidal Basin and West Potomac Park experience large numbers of visitors every day of the year with peak visitation during the spring with the blooming of the cherry blossoms. The current condition of the seawalls affects visitor use, experience, and safety since the pedestrian trails have degraded creating trip and fall hazards and provide limited accessibility due to standing water, mud, and debris left behind from daily flooding. Significant cost is expended by the NPS staff to remove the debris load after each overtopping event.

The purpose of the proposed project is to restore the historic functional height of the seawalls, restore the cultural landscape, improve visitor experience along the shorelines, minimize soil erosion and safety hazards, and provide some flood protection. The proposed action is primarily needed because the existing structural deficiencies of the seawalls negatively impact the experience and safety of park visitors and allow brackish water to drown out vegetation affecting the landscape.

The NPS proposes to rebuild and elevate the seawalls to re-establish the historic functional height of the walls in such a way as to provide for a sustainable solution that expands the lifecycle of the seawalls and future extensions of the wall to respond to changing climate patterns, including storms of greater intensity and frequency.

1.2. Climate Change and Natural Hazards

This Climate Change and Natural Hazards report is written to support NPS in the planning and designing NAMA Rehab Seawalls and Shoreline Project and to evaluate and respond to existing and projected climate change impacts and natural hazards. This document provides a decision path for dealing with natural hazards and climate change with three stops along the way. The considerations at each “stop” are to support NAMA in management decisions (NPS, 2015):

- **Natural Hazard Checklist:** Identify the most likely natural hazards that may pose a risk to the project. It provides general information to help identify the full range of risks at the Project site.
- **Background Data:** Gather data and make judgments that are independent of the specific hazard identified to provide a foundation for hazard considerations.
- **Specific Hazard Considerations:** Address the risks posed by specific hazards. This will typically involve further data gathering and analysis. This guidance provides sources for such data and questions that should be addressed as facility planning and design decisions are made.

2. Natural Hazard Checklist

The checklist below is a screening tool to be used as the first step of facility planning to determine the most likely natural hazards the Project may confront. For each of the natural hazards listed below, it is indicated whether the hazard is applicable or not given existing data and best professional judgement.

TABLE 1. NATURAL HAZARD CHECK LIST.

Potential Natural Hazard	Risk or secondary hazard	Sources for Site Specific Data	Best Professional Judgment
Earthquake	• Falling objects • Collapsing structures • Inoperability of major building systems • Liquefaction; loss of strength to foundations, silt deposition, standing water • Trigger to other hazards e.g. landslides, debris flows	Details provided in Section 3.	Applicable.
Landslide Avalanche	• Rockfall • Mud or debris slides or flows onto structures • Mud or debris slides or flows from under structures • Snow avalanche	USGS	Not applicable. Hazard does not occur due to geologic setting.
Permafrost	• Melting • Surface collapse • Increased landslide susceptibility	Global Permafrost Zonation Index	Not applicable. Hazard does not occur due to geologic setting.
Cave/Karst (sinkholes)	• Surface collapse • Contamination • Abandoned Mineral Lands (AML) features	USGS	Not applicable. Hazard does not occur due to geologic setting.
Shrink/Swell soils	• Damage to structure • Increased landslide susceptibility	Details provided in Section 3.	Applicable.
Coastal Storm Surge	• Rising Sea Levels • Rising Water - Wind Driven (i.e. hurricane, nor'easter)	Details provided in Section 3.	Applicable.
Tsunami	• Coastal area inundation associated with earthquakes or undersea landslides	USGS	Not applicable. Hazard does not occur due to geologic setting.
Riverine Flood	• Flooding (i.e. snowmelt, rainfall, etc.) • Destruction of infrastructure • Stream channel migration • Stream bank erosion	Details provided in Sections 3.	Applicable.

Potential Natural Hazard	Risk or secondary hazard	Sources for Site Specific Data	Best Professional Judgment
Flash Flood	• Sudden rising water (i.e. dry wash) • Loss of life due to unexpected flooding.	Details provided in Sections 3.	Applicable.
Hurricane	• High wind speed • Flying debris • Storm Surge	Details provided in Sections 3.	Applicable.
Tornado	• Extreme wind speed • Flying debris	FEMA	Applicable. However, hazard has low likelihood of occurrence and does not affect project.
Wildfire	• Fire and Heat • Smoke	USDA Forest Service	Not applicable. Hazard has low likelihood of occurrence and does not affect project.
Volcanic Eruption	• Lava Flows • Fire • Volcanic Secondary Hazards • Toxic gas releases	USGS	Not applicable. Hazard does not occur due to geologic setting.
Hydro-thermal Activity	• Toxic gas release • Explosion • Boiling water • Steam • Surface collapse into void	USDE	Methane gas is applicable. However, hazard has low likelihood of occurrence and does not affect project.
Pest Infestation	• Historic/ Facility Fabric Loss • Vegetation Loss • Fauna Impacts • Infection	USDA Forest Service	Cicadas are applicable. However, hazard has a low likelihood of affecting the Project

3. Hazard Considerations

3.1. NAMA Seawall Description

The area which the Park now occupies was originally a tidal flat of alluvial silt. In 1897, Congress designated the area formerly known as the Potomac Flats, which had been reclaimed with fill dredged from the bottom of the Potomac River starting in 1870, as Potomac Park. The NAMA seawall, built in various stages between 1884 and 1909, was originally a dry-laid, cut-stone masonry wall stacked 6 ft tall on top of a stone riprap foundation, sitting on a "mattress" of woven vegetation, in an excavated trench. Mortar was added to the wall above the level of high tide starting in 1896. Some areas of mortar has since dissolved (Dewberry & Davis, 2011). An illustrative estimation of the original seawall cross-section construction is shown in Figure 2.

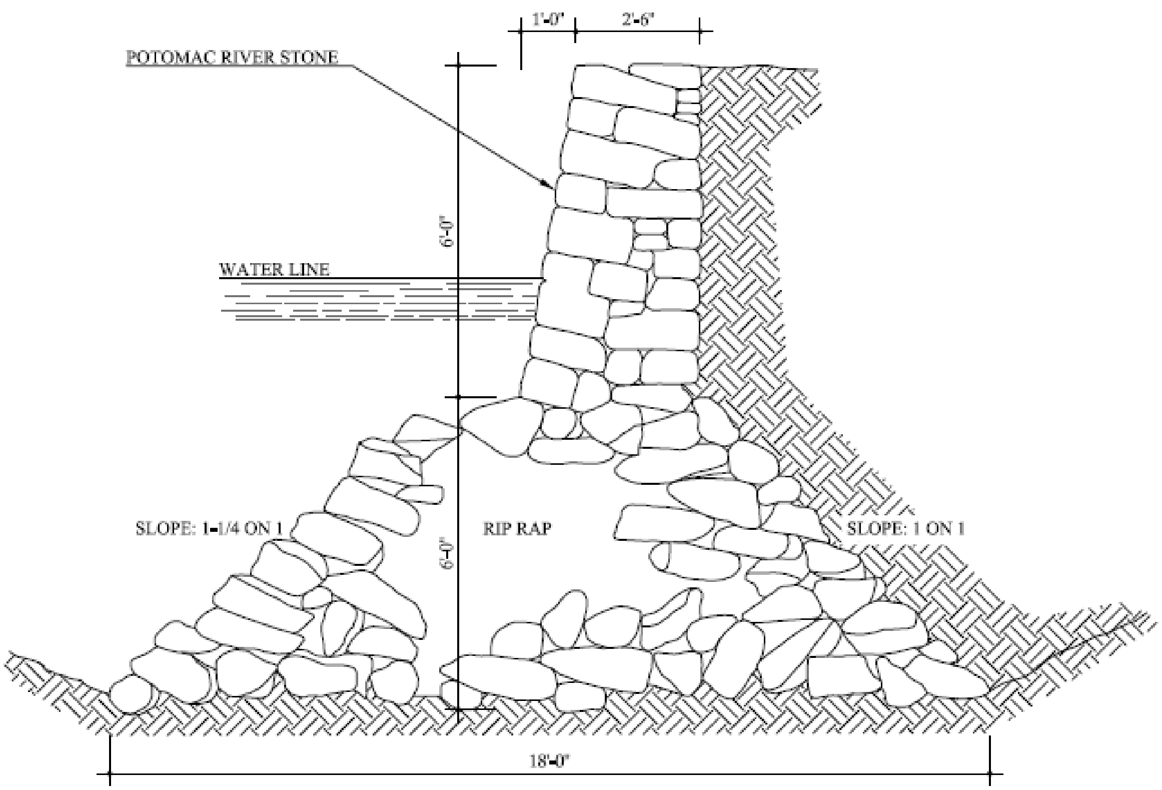


FIGURE 2. TYPICAL SEAWALL CROSS-SECTION (NPS, 2018).

Over time, the seawall has undergone settlement due to primary consolidation of the very thick underlying soil layers of weak soils; possibly as much as 3 ft to 5 ft since the wall was constructed. Settlement or mechanical damage increased leeside erosion accelerating the failure of the wall and the sidewalk (Dewberry & Davis, 2011). Shown in Figure 3, the damage observed during spring 2022, including but not limited to, are:

- Cracking of top of the wall concrete cap.
- Damage of existing asphalt pavement in the form of cracks or potholes.
- Dislodging and/or loss of seawall stone fill.
- Separation between top of wall and the uplands.

- Erosion and undermining of the uplands.
- Grade separation between concrete sidewalk and the uplands.

The observed flooding and overtopping of the existing seawall are associated with settlement and changes in water levels (discussed in section 3.2). The typical seawall cross-section shown in Figure 2 indicates the top of wall elevation at 6 ft above the riprap foundation. At the time of construction, the top of riprap foundation was set at mean low water (MLW). Based on the current tidal epoch (1983-2001), the functional top of wall elevation should be at +4.75 ft NAVD88, where:

+4.75 ft NAVD88 = -1.25 ft (MLW) + 6 ft (wall height); *see section 3.2.1 for water level details*.

As shown in Figure 4, the most current survey taken in spring of 2022 indicates an existing top of wall elevation lower than +4.75 ft NAVD88 along the entire Project length, and a top of wall elevation even lower than mean higher high water (MHHW) at +1.77 ft NAVD88 particularly along Tidal Basin East (Figure 5).

The analysis presented in this report is based on the tidal epoch currently listed by NOAA from 1983 to 2001 (NOAA, 2022), which has not yet been updated to reflect the 2001 to 2022 higher water levels. Thus, the tidal datums are likely higher in 2022 (although not yet listed) due to sea level rise. This is important because the water levels are reaching higher highs and higher lows than the present listed averages (MHHW, MLLW, etc.).

FIGURE 3. EXAMPLES OF EXISTING DAMAGE TO SEAWALL (PHOTOS TAKEN IN SPRING 2022): 1-ASPHALT DAMAGE, 2-CONCRETE CAP DAMAGE, 3-UNEVEN TOP OF WALL, 4-TOP OF WALL SEPARATION FROM UPLANDS, 5-DISLODGING OF SEAWALL STONES.

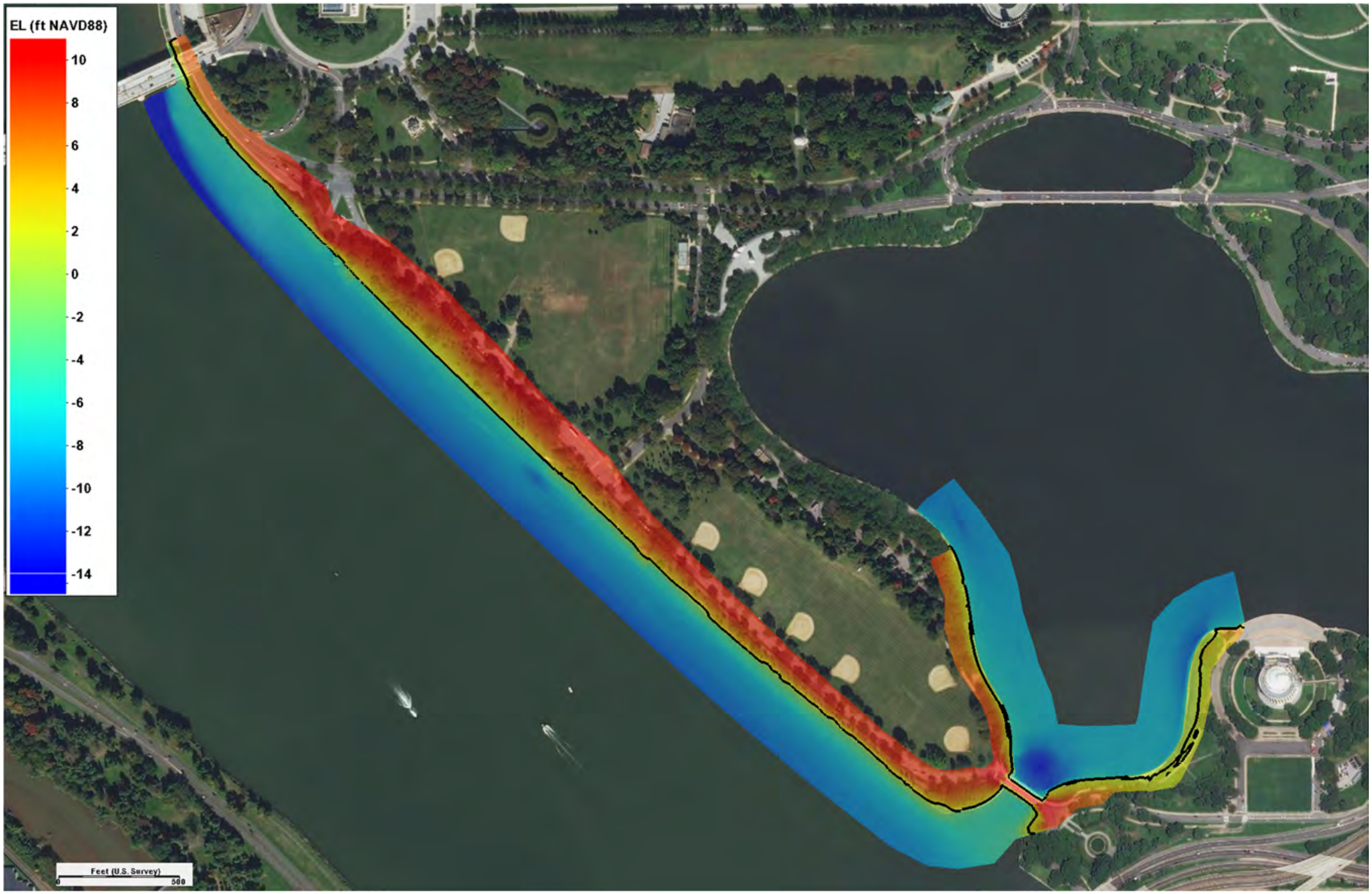


FIGURE 4. PROJECT AREA WITH SPRING 2022 SURVEY EXTENTS AND MHHW (1.77 FT NAVD88) ELEVATION LIMIT SHOWN IN BLACK CONTOUR LINE.

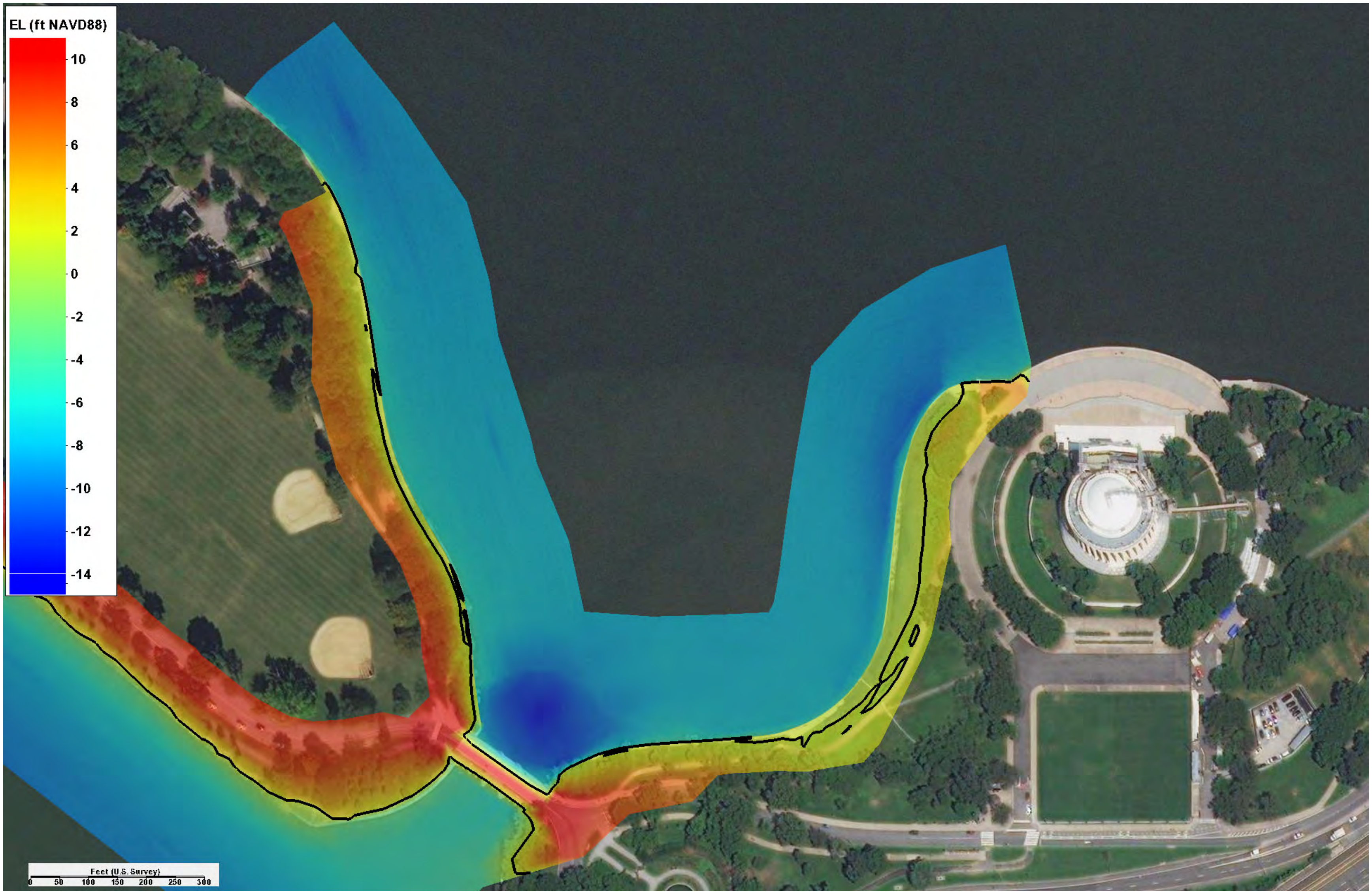


FIGURE 5. TIDAL BASIN WITH SPRING 2022 SURVEY EXTENTS AND MHHW (1.77 FT NAVD88) ELEVATION LIMIT SHOWN IN BLACK CONTOUR LINE.

3.2. Baseline Hazard Risks (Present Conditions)

The impacts of the potential natural hazards are driven by numerous physical factors, discussed in this section, which include wind, water levels, Potomac River processes, waves, and geotechnical conditions.

3.2.1. Data Sources

Baseline hazard risks for the Project site were determined using the nearest available data sources to the site (Figure 6; Table 2), which include water surface elevation, wind speed, and river discharge. Water level and wind speed measurements are available within 3 miles of the Project site. River discharge data was collected from the closest stream gage data upstream of the Project site.

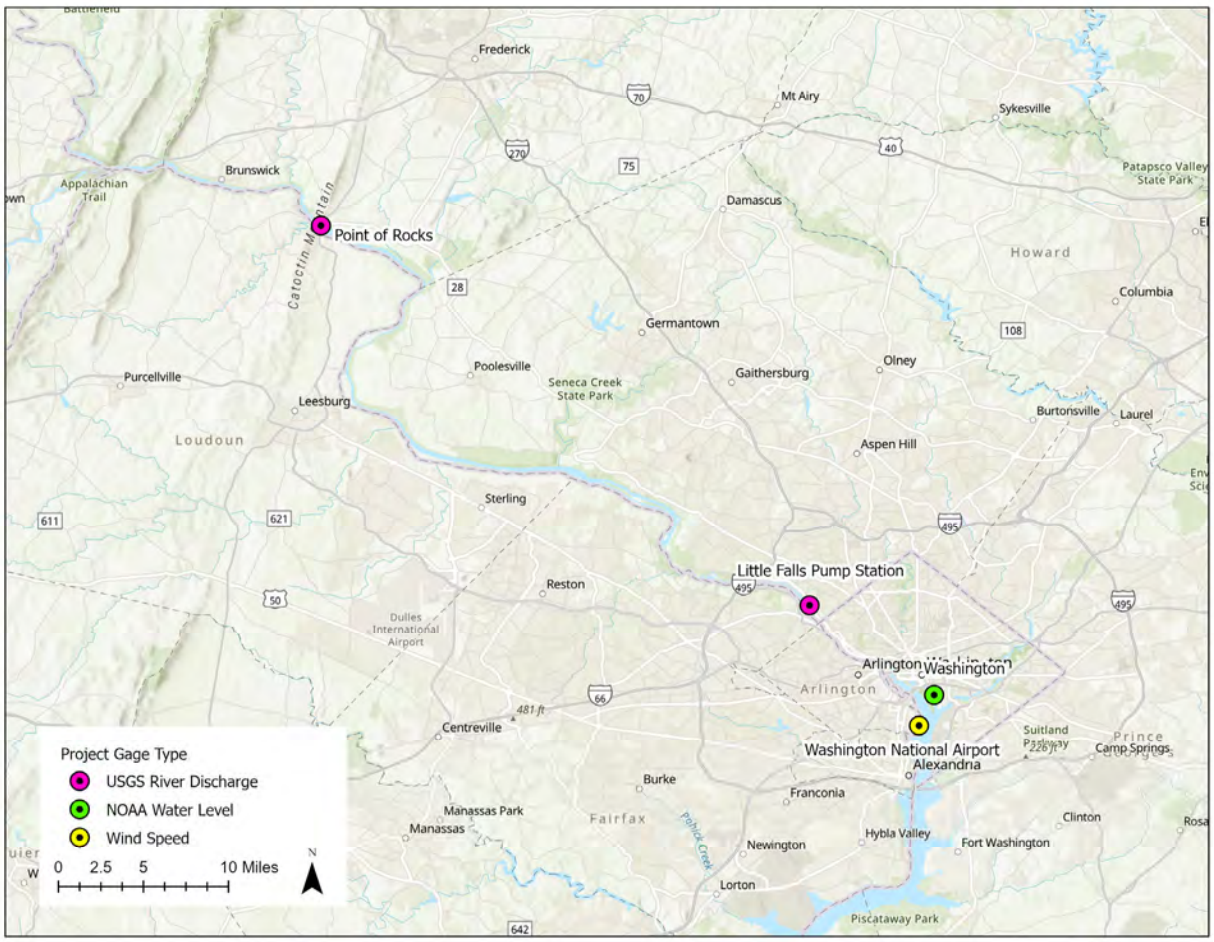


FIGURE 6. DATA SOURCES LOCATION MAP.

TABLE 2. BASELINE HAZARD DATA SOURCES.

Data Type	Source	Gauge ID	Distance from Project	Measurement Frequency	Data Record
Water Level	NOAA CO-OPS	8594900	1.0-1.5 mi	Hourly	1924-1926, 1931-2003, 2004-2022
Wind	Virginia ASOS Network	KDCA (Washington National Airport)	2.2-2.6 mi	Hourly	1938-1945, 1946-1965, 1970-2022
River Discharge	USGS	01638500 Points of Rocks 01646500 Little Falls	49.0 mi 7.0 mi	Daily	1895-2022 1930- 2022
Temperature	Iowa Environmental Mesonet NOAA	DCA Washington/National -	2.0 mi -	Hourly Monthly	1935-2022 1871-2022
Precipitation	NOAA	-	-	Monthly	1871-2022

3.2.2. Wind

Wind conditions near the Project site were evaluated from sustained wind speed data and direction (average of observed values over a 2-minute period), recorded hourly at the Reagan National airport from 1936 to 2022. Figure 8 presents a wind rose as well as the join occurrence of wind speed and wind direction. The predominate wind directions are from the south and northwest.

Extreme wind speeds were calculated based on the largest events observed using the peak over threshold method. Numerous probability distributions were tested against the data and the probability distribution providing the best fit for each direction sector was selected; results are shown in Table 3.

Extreme wind speeds have been reported in Washington, DC such as the June 29, 2012, devastating line of thunderstorms known as a derecho, which moved east-southeast at 60 miles per hour (mph) from Indiana in the early afternoon to the Mid-Atlantic region around midnight significantly impacting Washington, DC (NOAA NWS, 2013). It is assumed that wind speeds associate with the high winds that have affected the Project site have been recorded by the Washington National Airport wind gage.

TABLE 3. EXTREME WIND SPEEDS (2-MINUTE AVERAGE) AT THE PROJECT SITE.

Return Period (yr)	$U_{2\text{-min}}$ (kn)
5	39.9
10	43.2
25	48.7
50	54.3
100	61.6

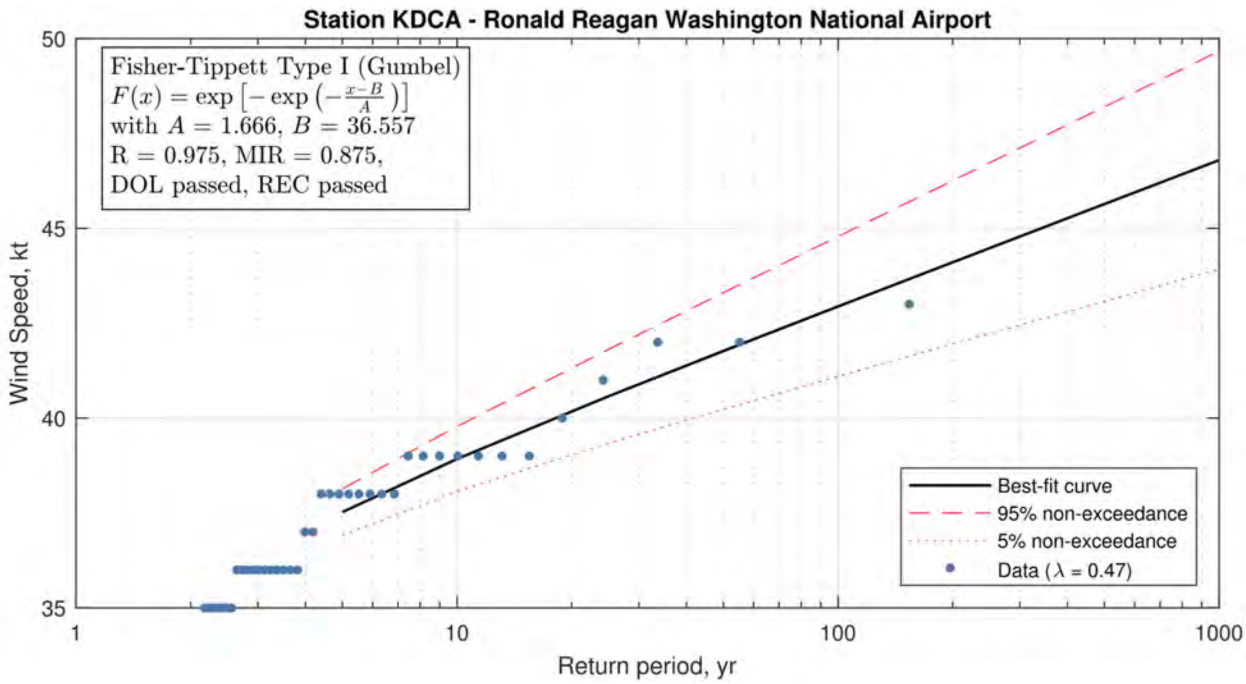
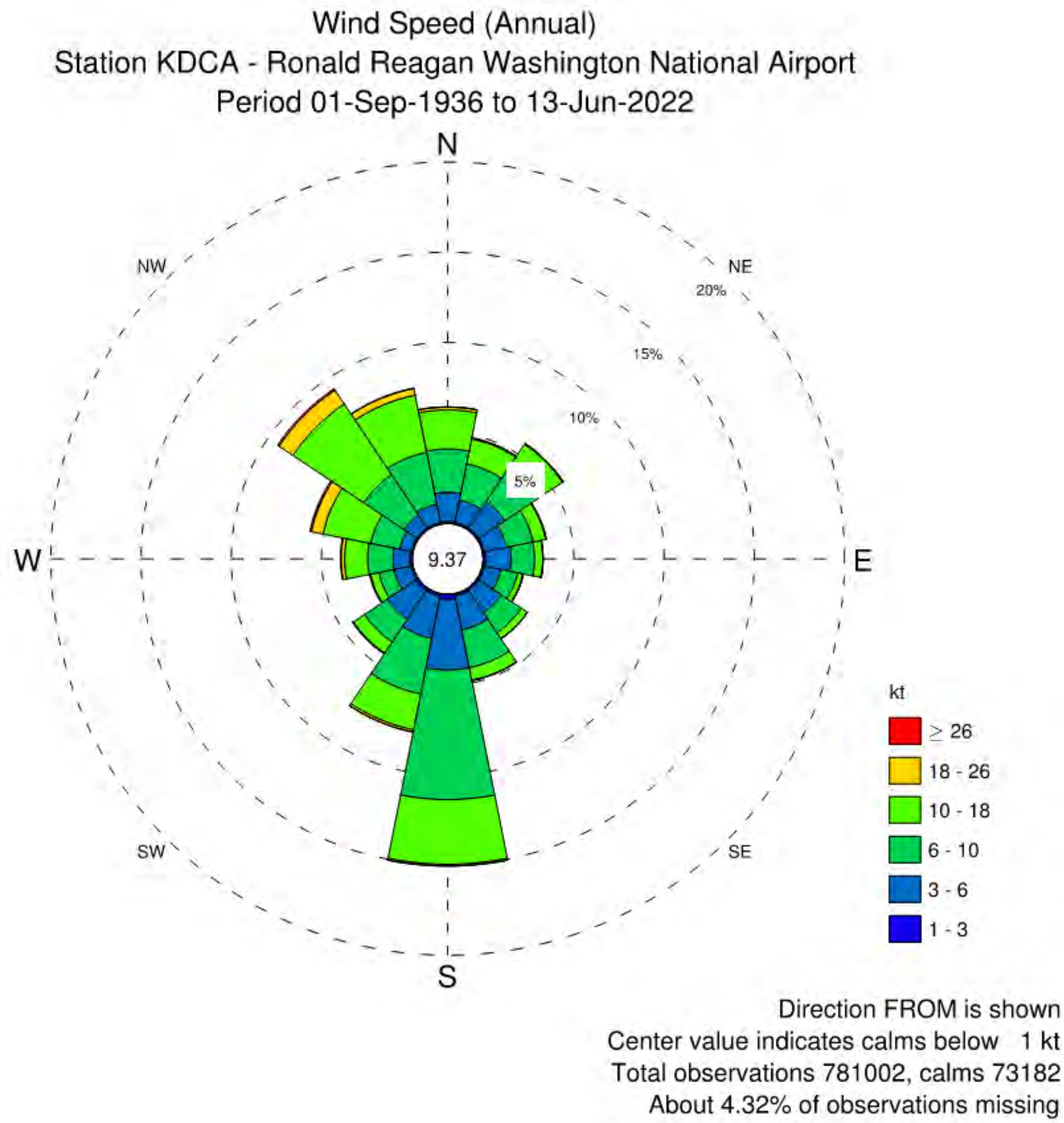


FIGURE 7. EXTREME WIND SPEEDS (2-MINUTE AVERAGE) AT THE PROJECT SITE.



Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	6.43	4.85	5.71	3.57	3.29	2.27	3.32	4.88	15.05	7.79	4.33	2.40	3.94	5.79	9.34	7.66	90.63
≥ 26																	0.28
18–26	0.16									0.13			0.20	0.66	0.92	0.38	2.83
10–18	2.17	1.40	1.27	0.71	0.46	0.30	0.40	0.70	3.59	2.02	0.74	0.47	1.28	2.68	4.72	3.23	26.13
6–10	2.40	2.06	2.57	1.53	1.29	0.94	1.33	2.14	7.21	3.14	1.51	0.85	1.40	1.64	2.68	2.93	35.63
3–6	1.60	1.25	1.72	1.25	1.41	0.95	1.47	1.91	3.91	2.37	1.89	0.98	0.95	0.67	0.86	1.05	24.25
1–3					0.11		0.11	0.10	0.24	0.12	0.14						1.53

FIGURE 8. WIND ROSE AT RONALD REAGAN NTIONAL AIRPORT.

3.2.3. Hurricanes

Hurricanes are storm systems that form over warm ocean water and move toward land. Hurricanes involve heavy rain, damaging wind speeds, flash flooding, and storm surge that can damage the seawall system. Hurricane season extends from June 1 to November 30, with its peak in September; Table 4 and Figure 9 show the historical hurricanes within 120 nm radius from the Project site.

It is assumed that the impacts from hurricanes at the Project site have been accounted in the wind (section 3.2.2), water level (section 3.2.4), Potomac River (section 3.2.5) analysis because the existing wind, water level, and stream gages near the Project site are assumed to have recorded data associated with hurricanes.

TABLE 4. LIST OF HURRICANES WITHIN 120 NM RADIUS OF THE PROJECT SITE. ALL HURRICANES MAKING LANDFALL ON THE ATLANTIC COAST UNLESS NOTED (NOAA, 2022).

Name	From	To	Category at landfall
Irene	8/21/2011	8/30/2011	H1
Isabel	9/6/2003	9/20/2003	H2
Floyd	9/7/1999	9/19/1999	H2
Connie	8/3/1955	8/15/1955	H2
Unnamed	8/13/1933	8/28/1933	H1
Unnamed	9/12/1903	9/17/1903	H1
Unnamed	9/22/1896	9/30/1896	H3 (Gulf of Mexico coast)
Unnamed	10/1/1894	10/12/1894	H3 (Gulf of Mexico coast)
Unnamed	9/25/1893	10/15/1893	H3
Unnamed	8/13/1879	8/20/1879	H3
Unnamed	10/18/1878	10/25/1878	H2
Unnamed	9/12/1876	9/19/1876	H1

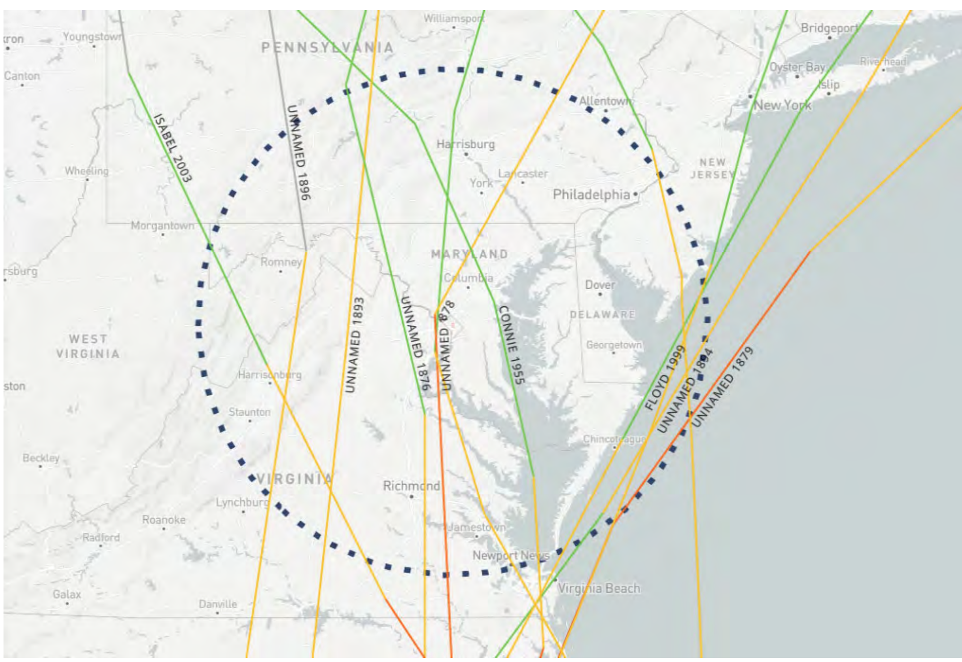


FIGURE 9. HURRICANES WITHIN 120 NM RADIUS OF THE PROJECT SITE (NOAA, 2022).

Hurricane Isabel tracked through the Chesapeake Bay region with high winds and high water levels making landfall in North Carolina and causing severe damages in Washington, DC. Isabel's path, which was west of the Chesapeake Bay, moving toward the north northwest, and roughly paralleling the Bay, meant that the counter-clockwise winds pushed lots of water from the Atlantic Ocean into the Bay. In Washington, DC, Hurricane Isabel is notoriously remembered for storm surges that created record high water levels with a storm tide crest observation of 8.88 ft NAVD88 on September 19, 2003 (NOAA Chesapeake Bay Interpretive Buoy System, 2013).

3.2.4. Water Levels

Coastal flooding can be a significant risk to NAMA assets and functions, and climate change potentially amplifies this risk. To design for a flooding risk, decision-makers need resources to quantify the hazard now (baseline) and for the future, including resilient and adaptable construction alternatives. The analysis below was completed to guide decision-makers through the range of alternatives that project teams could employ to maximize resiliency against coastal flood risk.

The active tide gauge nearest the Project site is located within Washington Channel in Washington, D.C. (NOAA CO-OPS Station 8594900; roughly 1 mile south-southeast of the tidal basin). Tidal datums at this site for the current tidal epoch (1983-2001) are shown in Table 5.

TABLE 5: TIDAL DATUMS FOR NOAA CO-OPS STATION 8594900 (WASHINGTON, D.C.; 1983-2001).

Tidal Datum		Elevation (*ft NAVD88*)
Highest Observed Water Level Oct 17, 1942 06:30	HOWL	9.65
Highest Astronomical Tide May 26, 2021 12:18	HAT	2.41
Mean Higher High Water	MHHW	1.77
Mean High Water	MHW	1.54
Mean Sea Level	MSL	0.15
Mean Low Water	MLW	-1.25
Mean Lower Low Water	MLLW	-1.40
Lowest Astronomical Tide Feb 1, 2014 21:00	LAT	-2.19
Lowest Observed Water Level Feb 26, 1967 04:24	LOWL	-6.45

Water levels have been measured on an hourly basis at NOAA Washington Channel Station (8594900) for nearly a century, from November 10, 1924, through May 31, 2022 (including two substantial data gaps from Jun. 1926 to Apr. 1931, and Nov. 2003 to Nov. 2004). The length of the water level record at the Washington Channel permits accurate calculations of extreme water levels at the site as well as an examination of the number of historical flooding events per year for much of the lifetime of the NAMA seawall.

Water within the Tidal Basin enters through the inlet gates on the Potomac River and exits through the outlet gates into Washington Channel. Water levels within the Tidal Basin are not separately measured though it is theorized a tidal lag exists between the two bodies of water. As part of this Project, water level gages have been installed within the Inlet Bridge gates. Early analysis suggests a tidal lag of 15-40 minutes but little to no elevation differences with the Washington Channel Station.

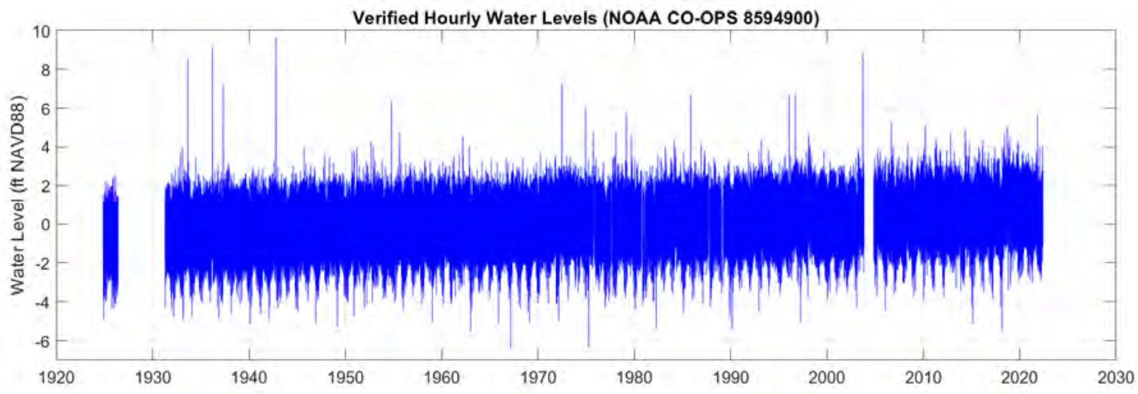


FIGURE 10. VERIFIED HOURLY WATER LEVELS AT NOAA CO-OPS 8594900.

In addition to recording several high-water-level events that have occurred since the NAMA seawall was first installed, the data also reveals a trend that water levels have steadily increased over time. The current best-fit linear trend for the average monthly water level (Figure 11) is 0.14 in/yr (3.44 mm/yr) (NOAA COOPS, 2022). This corresponds to an increase in sea level of approximately 1.1 ft at the site since 1924 and an estimated 1.6 ft since the seawalls were first constructed in 1884.

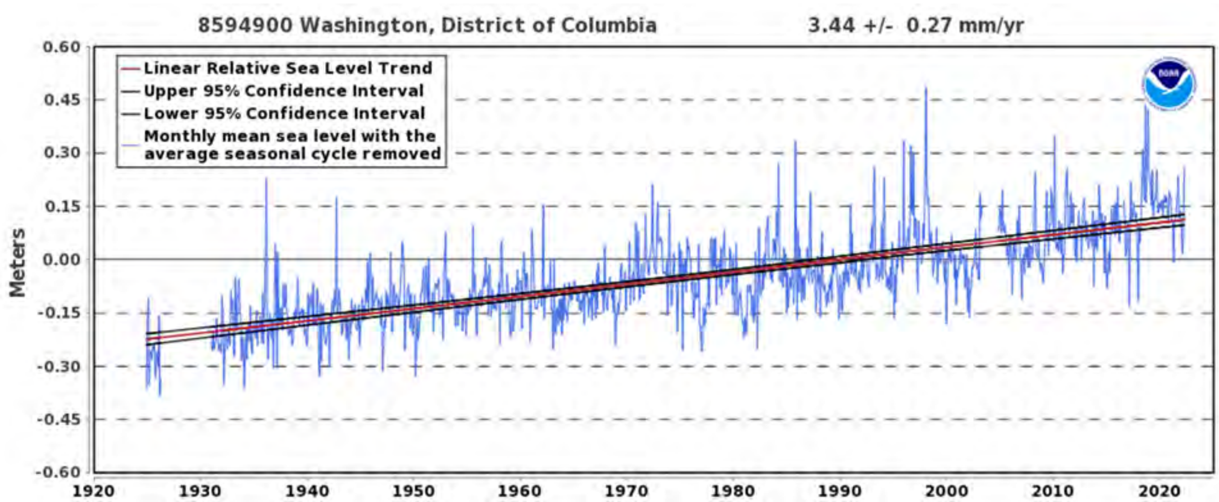


FIGURE 11. OBSERVED SEA LEVEL TREND AT NOAA CO-OPS STATION 8594900.

3.2.4.1. Extreme Water Levels

To calculate recurrence intervals for extreme water levels, we removed the observed long-term sea level trend at the site from hourly water level observations, creating a timeseries of water levels relative to current conditions. M&N calculated extreme water levels based on the largest events observed within the detrended water level record using the peak over threshold method. Numerous probability distributions were tested against the data and the probability distribution providing the best fit was selected. The distribution was then corrected to reflect elevations relative to NAVD88 by adding (1) the elevation of mean sea level for the current tidal epoch (0.15 ft NAVD88) and (2) sea level rise since the mid-point of the current tidal epoch, assuming a continuation of the linear historic trend calculated by NOAA (0.34 ft). The best-fit extreme value curve is shown in Figure 12 along with observed water levels which have been corrected to reflect current sea levels. Water levels associated with discrete return periods are shown in Table 6.

TABLE 6. EXTREME WATER LEVELS AT THE PROJECT SITE (REF 2022).

Return Period	Water Surface Elevations (ft NAVD88 in 2022)
5 years	5.09
10 years	6.32
25 years	8.27
50 years	9.94
100 years	11.75

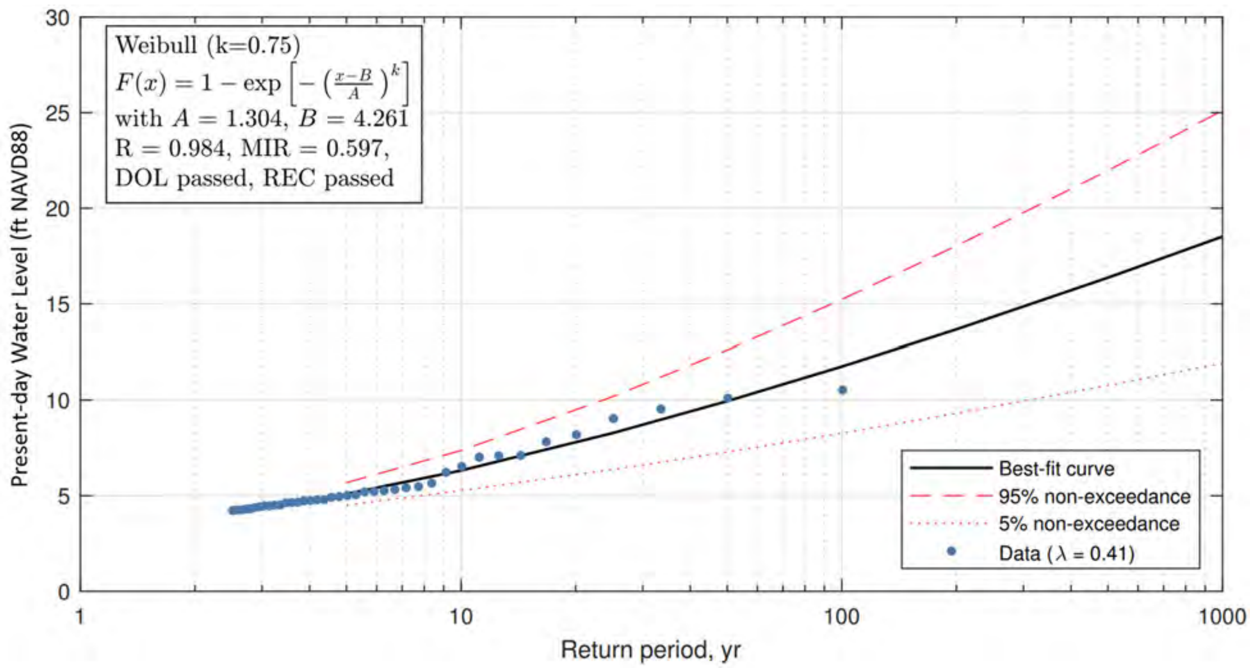


FIGURE 12. EXTREME VALUE ANALYSIS FOR PRESENT-DAY-EQUIVALENT WATER LEVELS AT NOAA STATION 8594900.

3.2.4.2. Flood Frequency and Duration

Water levels are currently able to reach higher elevations at the Project site than when the NAMA seawall was first constructed. Changes in flood frequency and duration over time were evaluated for water surface elevation thresholds ranging from 1 to 6 ft NAVD88. These thresholds were selected to identify changes over time in flood events with return periods of less than 10-year. Changes in the number of flood events per year and the average flood event duration over time associated with events defined by elevations of 1.75, 2.50, and 4.75 ft NAVD88 are shown in Figure 13, Figure 14, and Figure 15, respectively. These thresholds were selected as they represent (1) NOAA published MHHW, (2) the current NAMA seawall crest elevation, and (3) the proposed functional top of wall elevation; figures for the full set of elevation thresholds are attached in Appendix A. Each figure depicts the average number of events per year for (1) the full record, (2) the past 50 years, and (3) the past 20 years, as well as the best-fit curve for the number of events per year over time.

The published MHHW is based on the tidal epoch currently listed by NOAA from 1983 to 2001 (NOAA, 2022), which has not yet been updated to reflect the 2001 to 2022 higher water levels. Thus, the actual MHHW is likely higher than the 1983-2001 MHHW reported by NOAA.

Flooding events with water levels exceeding low thresholds below 3 ft NAVD88 have increased both in frequency (number of events per year) and average duration since 1925. For example, water levels have exceeded 1.75 ft NAVD88 roughly 400 times per year during the past 20 years, whereas water levels exceeded the same elevation roughly 235 events per year during the past 90 years. In addition, flood events exceeding 1.75 ft NAVD88 have lasted 3 to 4 hours on average over the past 20 years, whereas the same events lasted 1.5 to 2 hours roughly a century ago. These differences in flood frequency and duration are in part due to the slow increase in sea level, causing “clear sky” flooding above the NAMA seawall crest.

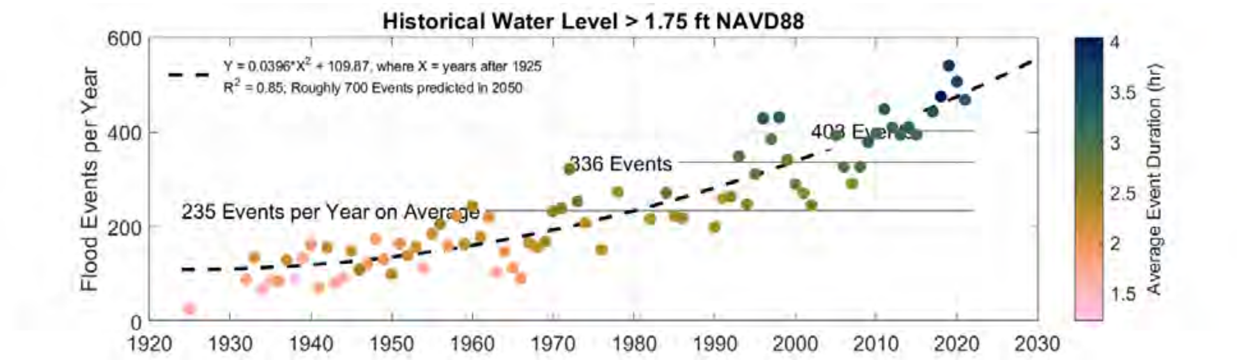


FIGURE 13. NUMBER OF EVENTS PER YEAR AND AVERAGE DURATION FOR FLOOD EVENTS EXCEEDING 1.75 FT NAVD88.

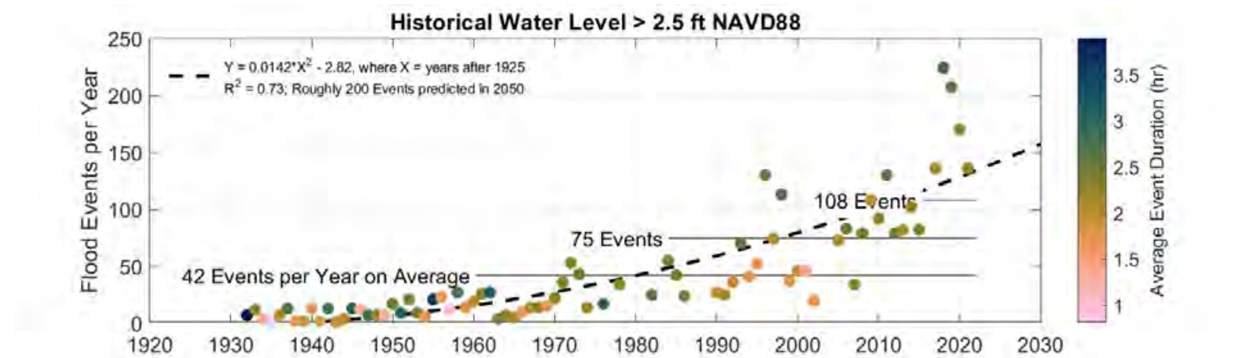


FIGURE 14. NUMBER OF EVENTS PER YEAR AND AVERAGE DURATION FOR FLOOD EVENTS EXCEEDING 2.5 FT NAVD88.

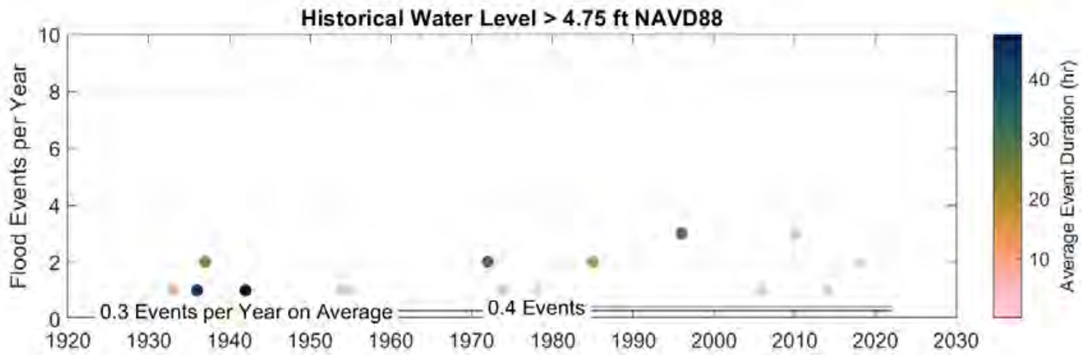


FIGURE 15. NUMBER OF EVENTS PER YEAR AND AVERAGE DURATION FOR FLOOD EVENTS EXCEEDING 4.75 FT NAVD88.

The gradual increase in the frequency of flood events for a given elevation threshold is evident in Figure 16, which depicts the reduction in the average interval between flood events over time. For example, flooding events that exceed an elevation of 3 ft NAVD88 have occurred on average once every month based on the full record (1924-2022). However, looking only at the last 20 years, flood events that exceed 3 ft NAVD88 have occurred roughly once every two weeks. The average interval between flood events that exceeds 4 ft NAVD88 has similarly reduced from roughly 1 year to 6 months. This reduction in the average interval between flood events is consistent among all flooding thresholds between 2 ft and 4.75 ft NAVD88. Estimates for the last 20 years converge with estimates for the last 50 years for elevations greater than 4.75 ft due to the few high water events in the recent record. However, the average interval between floods for these higher elevations is still shorter over the past 50 years than over the full record.

Overall, the water level analysis shows over time (1) an increase in the number of events that can cause flooding at the Project site with water elevations higher than 2.5 ft NAVD88 and (2) an increase in the duration of flooding. To illustrate the severity of flooding at the Project site, Figure 17 illustrates the Tidal Basin West under a 2.67 ft NAVD88 recorded water level (Washington Channel NOAA gage), which has a return period less than 5 years, and is estimated to occur approximately 75 times per year (based on the latest 20 years of water level records).

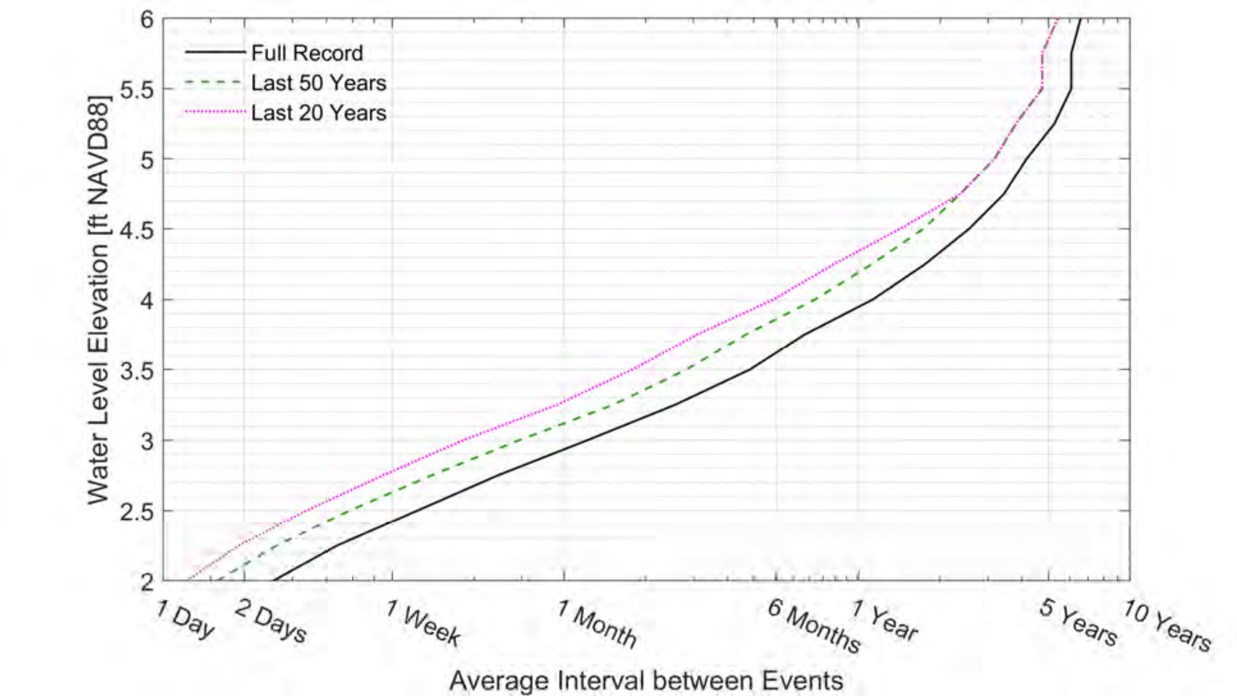


FIGURE 16. AVERAGE INTERVAL BETWEEN FLOODING EVENTS AS A FUNCTION OF WATER LEVEL RECORD LENGTH AND FLOOD ELEVATION THRESHOLD.

FIGURE 17. EXAMPLE OF FLOODING ON TIDAL BASIN WEST ON JUNE 7TH, 2022 WITH RECORDED WATER LEVEL AT 2.64 FT NAVD88.

3.2.5. Potomac River Watershed

The Potomac River located west of Washington, DC has a tributary area at the Project site of 11,680 sq mi extending from Washington, DC to the Appalachian Mountains, covering parts of Pennsylvania, West Virginia, Virginia, and Maryland. The Hydrologic Unit Code (HUC) watershed, taken from (USDA, 2022), is shown in Figure 18. Potomac River discharges were analysed to assess their influence on water levels at the NAMA Seawall.

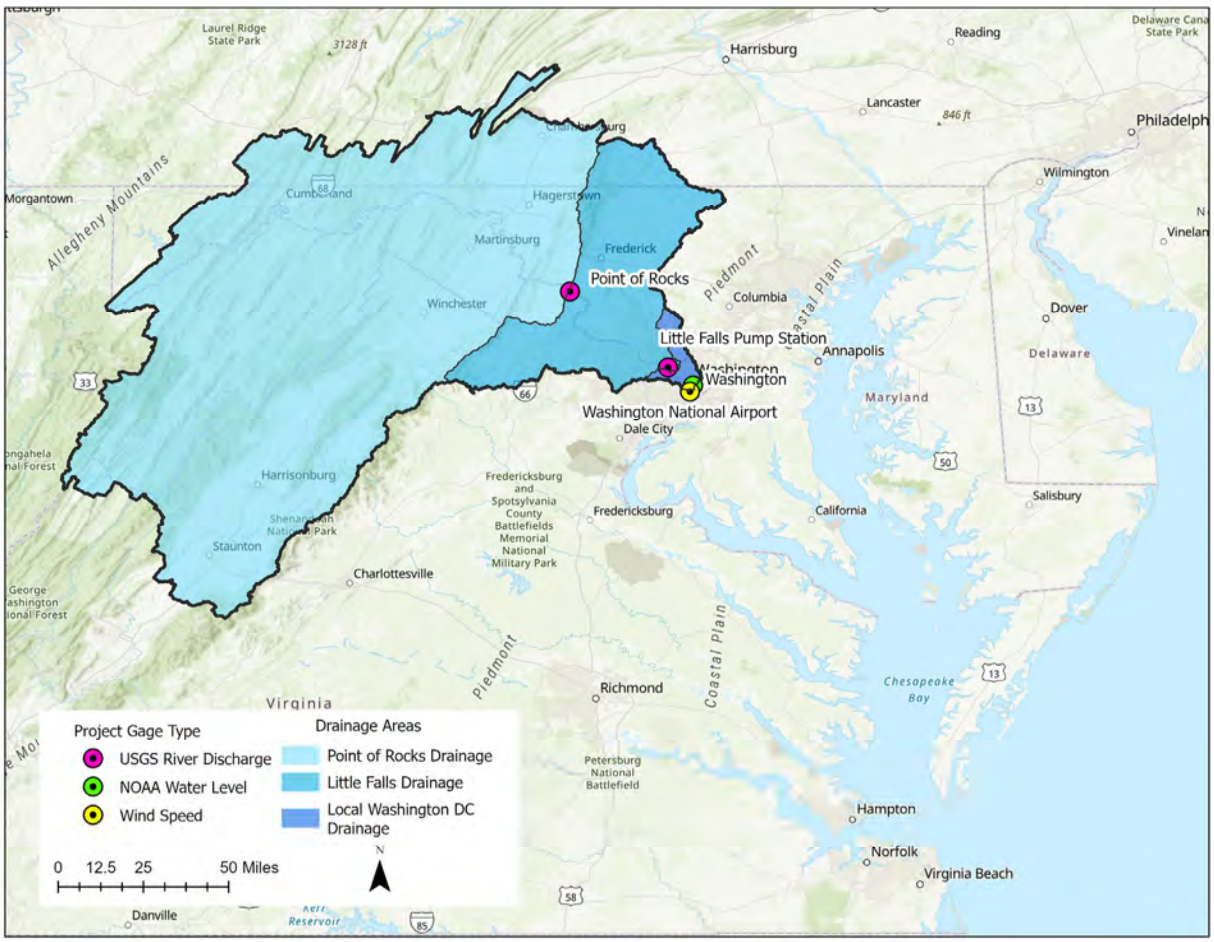


FIGURE 18. POTOMAC RIVER WATERSHED TIBUTARY TO THE PROJECT SITE WITH USGS STREAM GAGE LOCATION AND ASSOCIATED TRIBUTARY AREAS.

3.2.5.1. Discharge Statistics

The USGS has monitored Potomac River flows (or discharge) since the late 1800s. Two stations located along the Potomac River course; Point of Rocks (01638500) and Little Falls Pump Station (01646500) were selected for data analysis, see Figure 18. The watershed tributary areas and associated percentages are shown in Table 7.

TABLE 7. POTOMAC RIVER WATERSHED AREAS.

Sub-watershed	Discrete Area (sq mi)	Cumulative Area (sq mi)	Discrete %	Cumulative %
Point of Rocks	9,651	9,651	83%	83%
Little Falls Pump Station	1,909	11,560	16%	99%
Washington, DC	120	11,680	1%	100%

Figure 19 depicts the river discharge long-term monthly average for Little Falls Pump Station and Point of Rocks. Both stations show similar patterns throughout the water year (water year defined from October 1st to September 30th): river flows peaking in early spring (March and April) and low flows dominating during the summer months (July through September). As expected, the Little Falls Pump Station gage has higher flows because of its larger tributary drainage area.

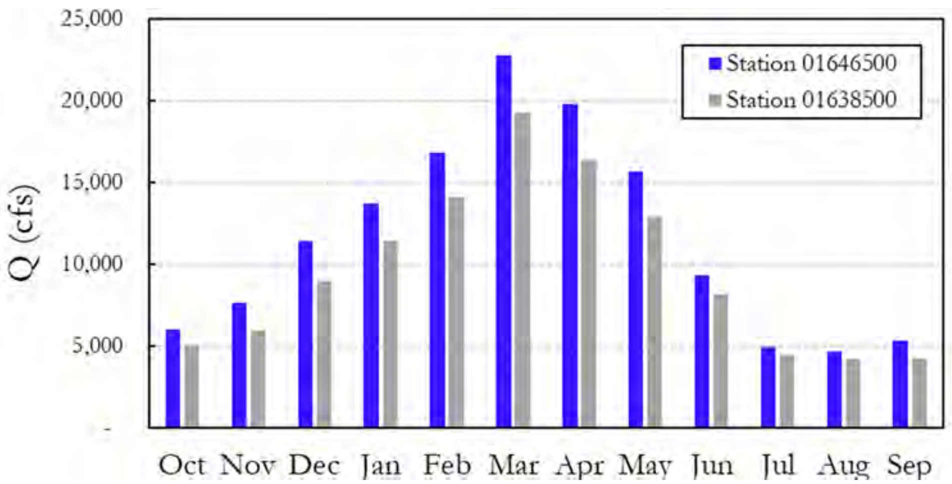


FIGURE 19. POTOMAC RIVER LONG-TERM MONTHLY AVERAGE DISCHARGE AT USGS LITTLE FALLS PUMP STATION (01646500) AND POINT OF ROCKS (01638500) IN WATER YEAR.

Little Falls Pump Station is the closest station located 7 mi upstream of the Project site. The Potomac River is affected by daily tides from the Chesapeake Bay up to Chain Bridge, which is located 1.5 mi downstream of Little Falls USGS Station, above chain Bridge, tidal effects diminish rapidly, and riverine characteristics are dominant (FEMA, 2010). Thus, the Potomac River influence at the Project site was analysed using the USGS Little Falls Pump Station stream gage station (01646500). The effects of other environmental forcings will be analysed in subsequent coastal modelling phase of this project.

Figure 20 provides a histogram of the mean daily discharge showing a highly low flow-skewed distribution. In other words, discharge for the Potomac River is predominantly low with high discharge events occurring on a low frequency. Table 8 presents the minimum, maximum and the non-exceedance values for the observed mean daily discharge. Approximately 50% of the time, the mean daily discharge remains below 6,700 cfs, and throughout the length of the record mean daily flows have exceeded 77,200 cfs only around 1% of the time.

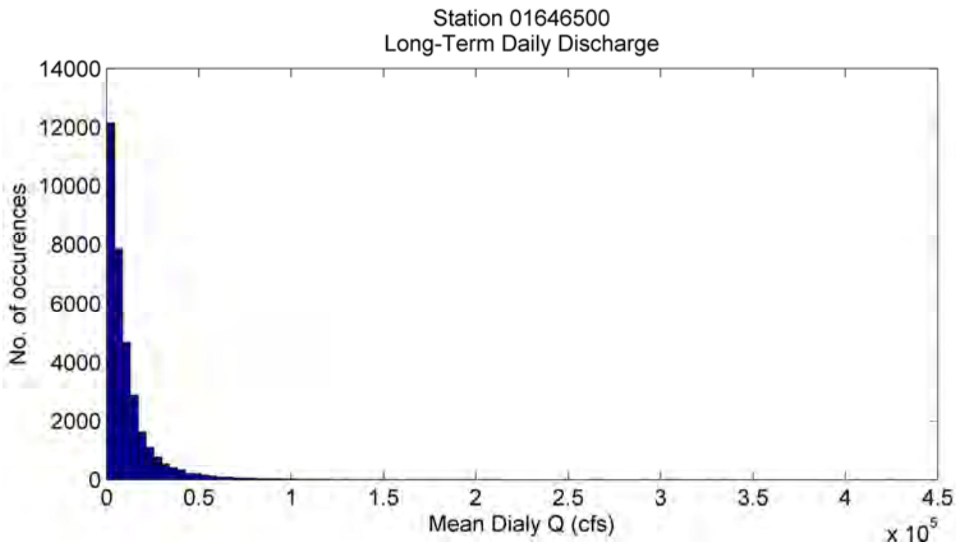


FIGURE 20. MEAN DAILY DISCHARGE HISTOGRAM AT LITTLE FALLS USGS STATION (01646500).

TABLE 8. STATISTICAL ANALYSIS FOR MEAN DAILY DISCHARGE AT LITTLE FALLS USGS STATION (01646500).

Non-exceedance	Q (cfs)		Statistics	Q (cfs)
25%	3,100		Min	200
50%	6,700		Max	426,000
75%	13,600		Mean	11,600
90%	25,700		Std	16,100
95%	38,000		Mode	10,600
99%	77,200		-	-

3.2.5.2. Extreme Discharge at Potomac River

An Extreme Value Analysis (EVA) was performed following the Peak Over Threshold (POT) method, based on the largest 40 discharge events in the 125-year record. Results are presented in Figure 21 and Table 9.

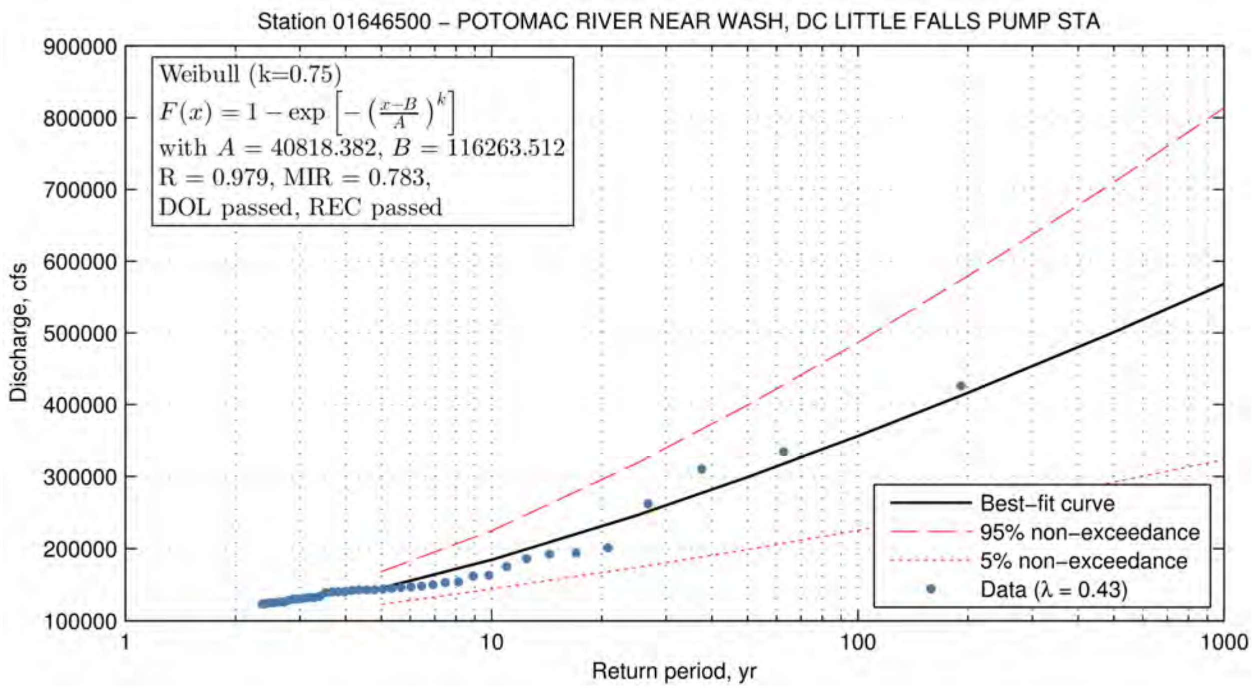


FIGURE 21. EXTREME VALUE ANALYSIS OF MEAN DAILY DISCHARGE AT LITTLE FALLS PUMP STATION USGS STATION (01646500).

TABLE 9. EXTREME VALUE ANALYSIS OF MEAN DAILY DISCHARGE AT LITTLE FALLS PUMP STATION USGS STATION (01646500).

Return Period (yr)	Mean Daily Discharge (cfs)
5	145,300
10	184,300
25	246,200
50	298,900
100	355,700

3.2.5.3. Precipitation

Local precipitation associated with the Washington, DC subarea (120 sq mi, see Table 7) is not expected to influence the Potomac River discharge at the Project site because it only constitutes 1% of the total Potomac River tributary area. Potomac River watershed rainfall-runoff processes are captured in the USGS gages. However, local flooding associated with sheet flow and the and urban drainage system could influence the flooding depths at the Project site.

In Washington, DC overall, the rainiest months are May, June, July, and September. On average, July is the wettest month with 4.33 in of precipitation, while February is the driest month with 2.62 in of precipitation (see Figure 22). The long-term average annual precipitation is 41.82 in (NOAA, 2022).

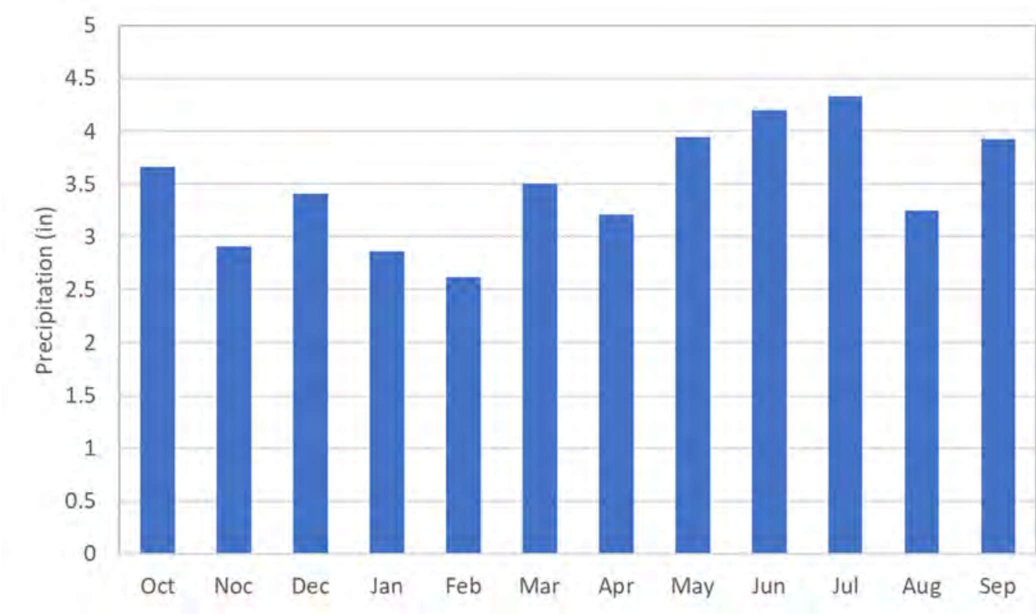


FIGURE 22. WASHINGTON, DC LONG-TERM MONTHLY PRECIPITATION AVERAGES IN WATER YEAR (NOAA, 2022).

3.2.6. Relationship Between Water Level and Potomac River

To get a better understanding of the relationship between the Potomac River discharge and water levels at the Project site, the maximum daily water level residuals (measured minus predicted water level) from NOAA Washington, DC tide gage station were compared against the mean daily discharge from the USGS Little Falls stream gage. Figure 23 provides the graphic comparison of these variables.

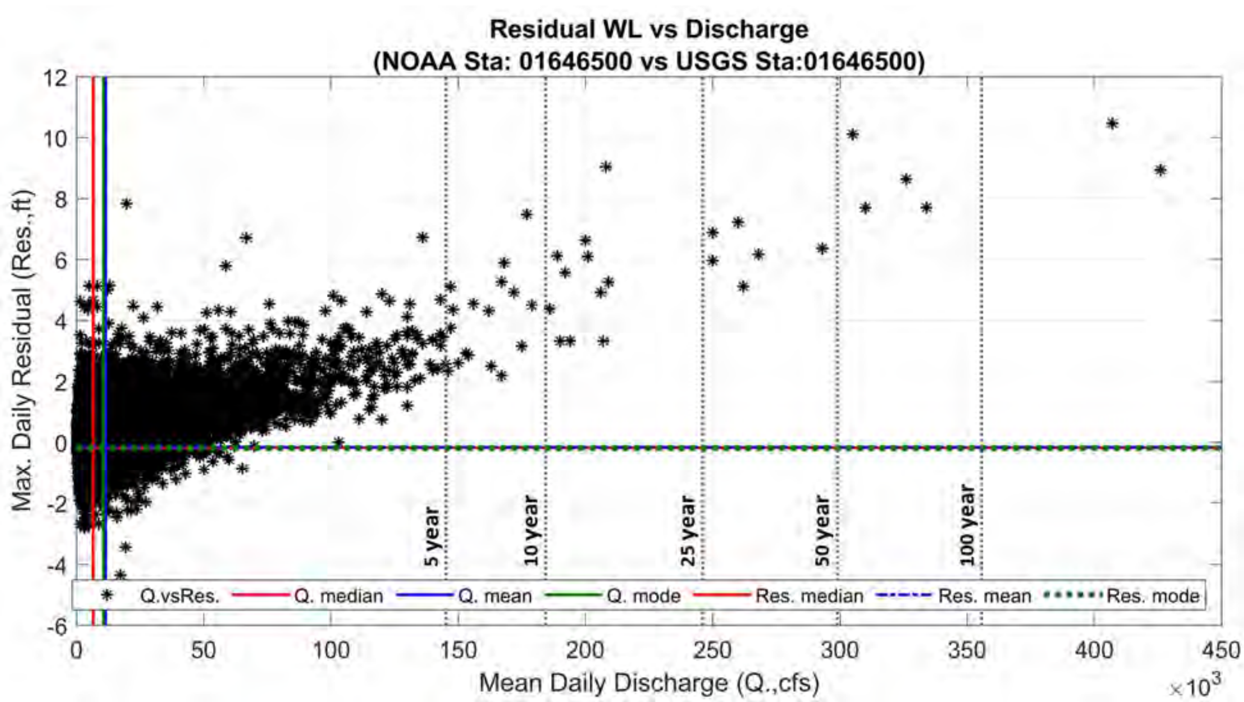


FIGURE 23. MAXIMUM DAILY WATER LEVEL RESIDUAL (NOAA WASHINGTON CHANNEL STA. 8594900) VS MEAN DAILY DISCHARGE (USGS LITTLE FALLS PUMP STATION 01646500).

The majority of the data points are concentrated towards the low discharge-low residual values (far-left end of the plot). A data trend follows that for a larger discharge in the Potomac River, higher water level residuals are observed; this is the typical and anticipated response for water levels during extreme large discharge and/or storm events.

However, the analysis also indicates that high water levels are not exclusive of large discharge events; high water level can be associated with low river discharge. For instance, water level residuals of up to 5 ft can occur with a river discharge lower than 6,700 cfs median discharge. Residuals higher than 2.5 ft, under which the East Tidal Basin would be flooded, have occurred with a river flow lower than a 5-year event. This type of event occurs regularly at the Project site and drive the "daily flooding" conditions observed during the filed visit as illustrated in Figure 17. This suggests that there are other environmental forcings, such as storm surge, driving the observed high-water levels at the site.

This analysis leads to the conclusion that while high river discharges associated with watershed/riverine processes lead to high water levels at the Project site, high water levels can also be associated with other factors acting independently of Potomac River riverine processes, such as: storm surge, local pluvial processes, and wind events.

3.2.7. Waves and Overtopping

The NAMA seawall currently experiences wave overtopping due to waves generated by local winds and/or boat wakes. A desktop analysis was conducted to determine the magnitude of overtopping rates that have been historically observed at the site. Site-specific numerical modelling of locally-generated waves will be conducted in the next Project phase to refine the estimates presented here.

3.2.7.1. Wind Waves

Locally-generated wind waves were estimated at four representative locations along the NAMA seawall: one location each at the northern and southern limits of the Potomac-facing seawall, as well as along the southeast and southwest portions of the Tidal Basin (Figure 24). Hourly directional wind wave heights and periods were estimated from directional fetches (open-water distances) and 2-minute-average 10-meter wind speeds and directions measured at the Washington National Airport (Figure 6; Table 2) through methods developed for the Coastal Engineering Design and Analysis System (CEDAS) (Leenknecht, Szuwalski, & Sherlock, 1992; Smith, 1991). Maximum fetch lengths for each location are provided in Table 10. Waves heights and wave periods were calculated for the combined period of record between wind and water level data from 1938 to 2022. Note that any wind shielding by trees along the Potomac or surrounding the Tidal Basin is not accounted for in these wave height estimates; as a result, the wave heights presented here are potential maximum values.

TABLE 10: MAXIMUM FETCH AND ASSOCIATED DIRECTION FOR REPRESENTATIVE LOCATIONS ALONG NAMA SEAWALL.

	West Potomac Park North	West Potomac Park South	Tidal Basin West	Tidal Basin East
Maximum Fetch (ft)	3.2 mi	3.3 mi	0.5 mi	0.4 mi
Direction of Maximum Fetch (deg N)	150 deg	165 deg	320 deg, 350 deg	10 deg

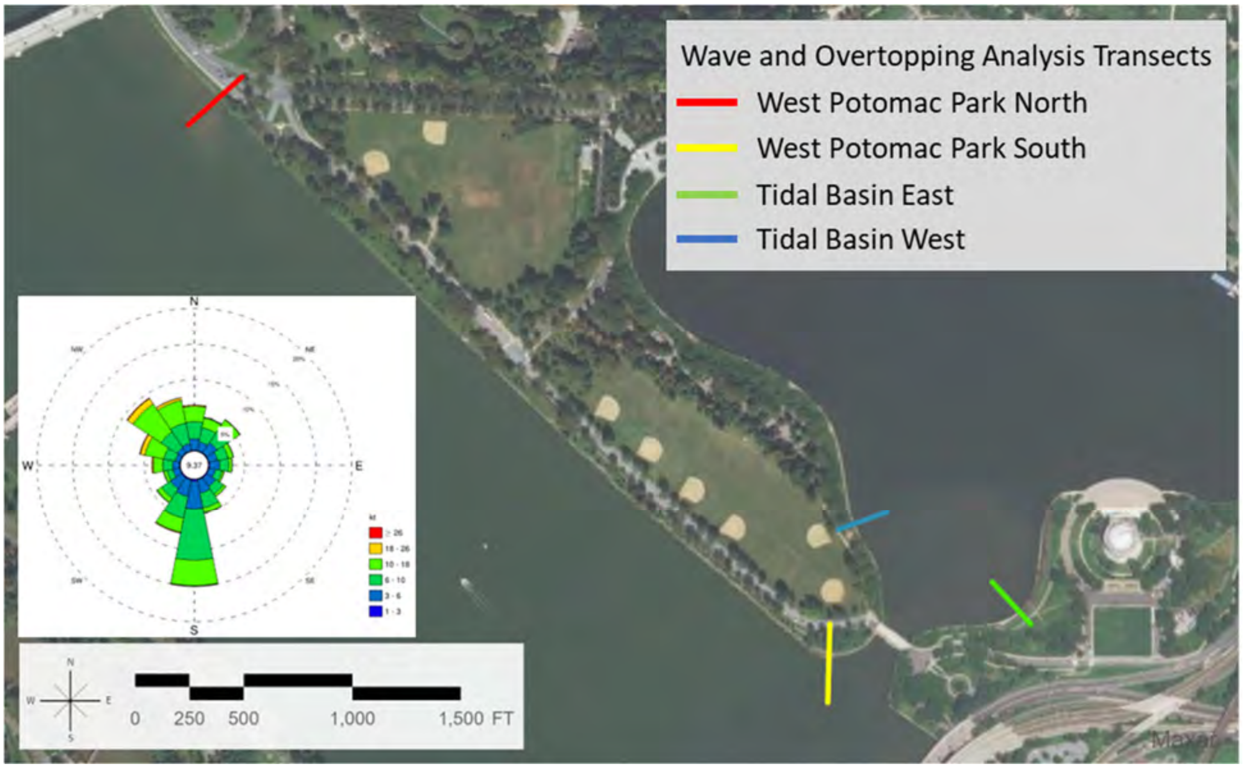


FIGURE 24. LOCATIONS OF WAVE AND OVERTOPPING ANALYSIS TRANSECTS.

Maximum and average locally-generated wave characteristics, significant wave height (Hs) and peak wave period (Tp), estimated at each of the analysis transects are provided in Table 11 from 1938 to 2022. Local surface winds may generate wave heights that exceed 3 ft on the Potomac River; the largest waves are anticipated along the Potomac River shoreline near the southern extent of the Project footprint. Along the southern perimeter of the Tidal Basin, locally-generated wind waves are predicted to reach up to 2 ft in height; the largest waves are anticipated along the southeast quadrant of the Tidal Basin due to the larger open-water distances. Extreme wave height distributions for Potomac River (South) and Tidal Basin (East) analysis transects, representing the largest waves expected along the Potomac River and Tidal Basin shorelines, are shown in Figure 25 and Figure 26. Extreme locally-generated wind wave heights are provided in Table 12.

TABLE 11. MAXIMUM AND AVERAGE LOCALLY-GENERATED WIND WAVE CHARACTERISTICS (HS AND TP) ESTIMATED AT EACH ANALYSIS TRANSECT.

		West Potomac Park North	West Potomac Park South	Tidal Basin West	Tidal Basin East
Hs	Maximum	3.0 ft	3.6 ft	1.9 ft	2.2 ft
	Average	0.3 ft	0.2 ft	0.1 ft	0.2 ft
Tp	Maximum	3.3 sec	3.6 sec	2.3 sec	2.5 sec
	Average	0.9 sec	0.8 sec	0.6 sec	0.7 sec

TABLE 12. EXTREME SIGNIFICANT WAVE HEIGHTS FOR LOCALLY-GENERATED WIND WAVES AT EACH ANALYSIS TRANSECT.

		Hs West Potomac Park North	Hs West Potomac Park South	Hs Tidal Basin West	Hs Tidal Basin East
Return Period	5-year	2.3 ft	2.4 ft	1.3 ft	1.5 ft
	10-year	2.5 ft	2.7 ft	1.4 ft	1.6 ft
	25-year	2.8 ft	3.1 ft	1.5 ft	1.8 ft
	50-year	2.9 ft	3.4 ft	1.5 ft	1.9 ft
	100-year	3.1 ft	3.8 ft	1.6 ft	2.1 ft

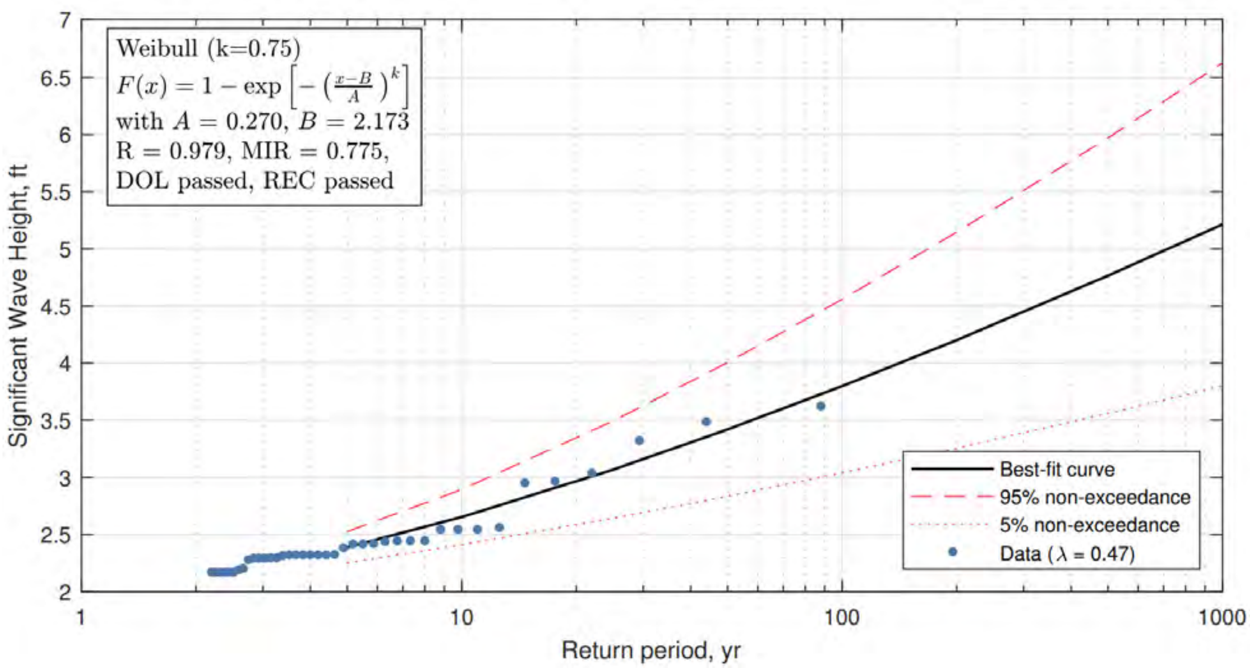


FIGURE 25. EXTREME WAVE HEIGHTS ESTIMATED FOR THE WEST POTOMAC PARK SOUTH ANALYSIS TRANSECT.

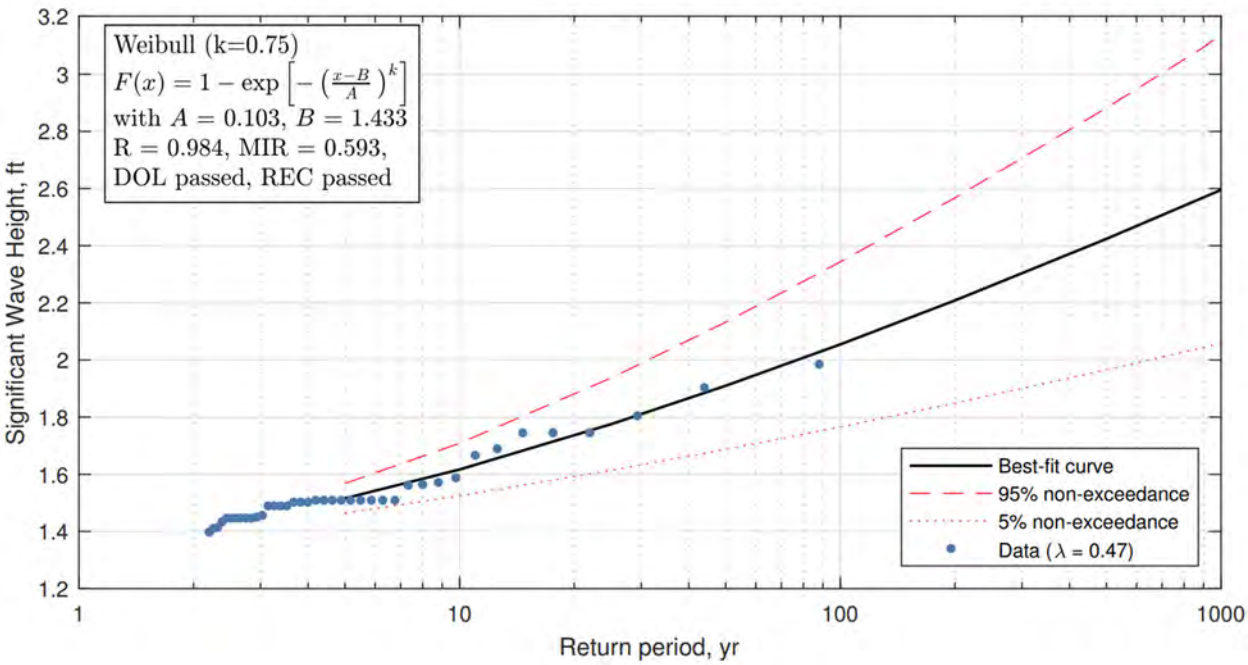


FIGURE 26. EXTREME WAVE HEIGHTS ESTIMATED FOR THE TIDAL BASIN EAST ANALYSIS TRANSECT.

3.2.7.2. Boat Wakes

From observations, boat wakes at the site were estimated to have a maximum wave height of 2 ft and a maximum wave period of 3 sec along the Potomac River (Sloop, 2022) These values are at the upper end of likely boat wake conditions at the Project site. Typical wake conditions along the Project shoreline facing the Potomac River were estimated for a Coast Guard cutter-type design vessel passing close to shore following Kriebel and Seelig (2005) These conditions likely produce wave heights of 0.91 ft at the shore, with a wave period of 1.8 sec; supporting calculations are shown in Appendix B. Boat wake within the Tidal Basin are assumed to be negligible and are not considered in this analysis.

3.2.7.3. Overtopping

Site-specific wave overtopping rates were calculated for the hourly timeseries of water levels and wind-waves for wall toe elevations (Table 13) and multiple potential wall crest elevations using equations for vertical seawalls contained in the EurOtop Manual (2018). The results presented in this section assume water level and winds speeds associated with hurricanes were recorded by the wind and water level gages. Extreme overtopping rates for specific return periods were estimated from the hourly overtopping rate timeseries. Overtopping rates are consistently highest at the Potomac River (South) analysis transect along the Potomac River due to the larger locally-generated wave heights caused by the co-incidence of strong wind speeds from the south (Figure 8) with a more southerly fetch (Table 10). Overtopping rates in the Tidal Basin are consistently highest at the Tidal Basin (Southeast) analysis transect due to the more northwesterly fetch (Table 10) coinciding with stronger winds from the northwest (Figure 8).

TABLE 13. OVERTOPPING ANALYSIS TRANSECT GEOMETRIES.

Analysis Location	Seawall Toe Elevation (ft NAVD88)	Future Potential Seawall Crest Elevations (ft NAVD88)
Potomac River (North End)	-6 ft	+2 to +6 ft
Potomac River (South End)	-5 ft	+2 to +6 ft
Tidal Basin (Southwest)	-6 ft	+2 to +6 ft
Tidal Basin (Southeast)	-10 ft	+2 to +6 ft

Overtopping rates for a range of return periods and future potential wall crest elevations are presented for each of the Potomac River (South) and Tidal Basin (Southeast) analysis transects in Figure 27 and Figure 28. Note that overtopping by boat wakes along the Potomac River is negligible relative to potential wind-wave overtopping. The wind-driven wave overtopping results were compared against hazard thresholds for erosion of grass-covered crests, safety of pedestrian and vehicle traffic, and structural safety for seawalls provided in Tables 3.1 (Figure 29) and 3.3 (Figure 30) of the EurOtop Manual (2018).

Overtopping due to locally-generated waves at the Project site for the existing NAMA seawall crest (approximately 2.5 ft NAVD88) is expected to produce conditions that are safe for pedestrian traffic (<8 L/s/m) both along the Potomac River and the south-eastern perimeter of the Tidal Basin during events with return periods of up to 100 years. Overtopping during events with return periods of 100 years or less is expected to erode patchy grass cover at the seawall crest, but may not erode crests with uniform vegetation coverage.

Wave overtopping rates are reduced for higher seawall crest elevations. At both the Potomac River (South) and Tidal Basin (Southeast), the 100-year overtopping rate estimated for a seawall crest at +4.0 ft NAVD88 is nearly half of the same rate for a seawall crest at +2.5 ft NAVD88. However, the 100-year overtopping rates for the +4.0 ft NAVD88 crest elevation remains above EurOtop (2018) thresholds for the start of damage for seawall crests with patchy grass cover. The lower overtopping rate (associated with the higher seawall crest elevation) will produce less damage for the same structure geometry, though the extent of potential damage reduction is unknown.

Overtopping rates are largely driven by site water levels due to the limited fetch, both on the Potomac River and within the Tidal Basin. The overtopping rates shown in Figure 27 and Figure 28 are based on recorded water levels from 1938 to 2022 which include the increase in sea level at the site over the period of record; in other words, the overtopping results are not detrended from SLR. As a result, wave events in the past may produce lower overtopping rates than if the same event occurred today.

In addition, the overtopping rate thresholds provided by EurOtop (2018) are general empirical guidelines and do not reflect site-specific seawall geometries. Thus, the rates calculated in this study provide a general indication of the range of conditions that have occurred at the site but are unable to define the extent of site-specific damage induced by any particular event.

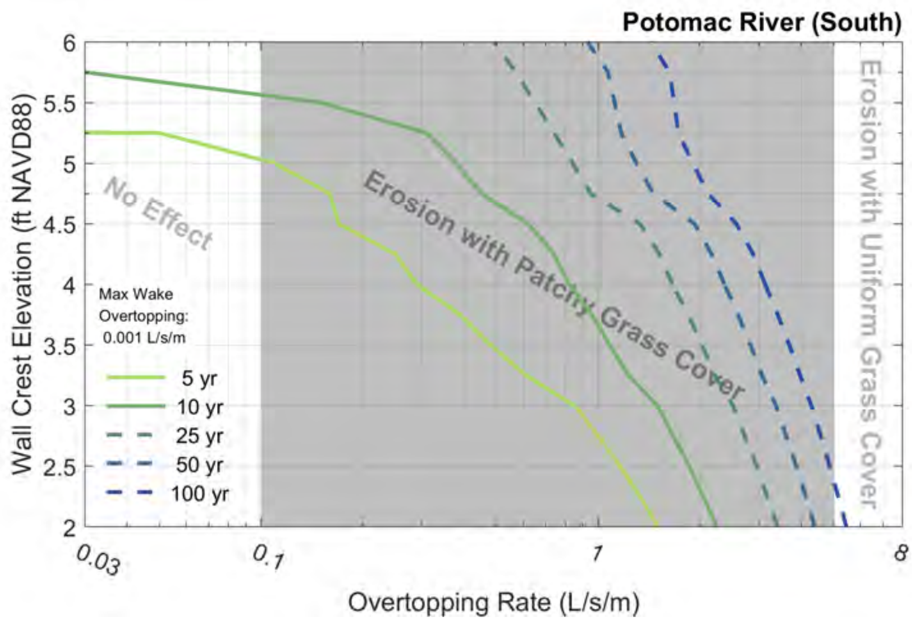


FIGURE 27. OVERTOPPING RATES FOR A RANGE OF WALL CREST ELEVATIONS AND RETURN PERIODS AT THE POTOMAC RIVER (SOUTH). RETURN PERIODS OF 25 YEARS OR MORE ARE DASHED TO INDICATE UNCERTAINTY. GREY SHADING INDICATES OVERTOPPING IS EXPECTED TO ERODE PATCHY GRASS COVER ON SEAWALL CRESTS BUT NOT CAUSE DAMAGE TO UNIFORM GRASS COVER.

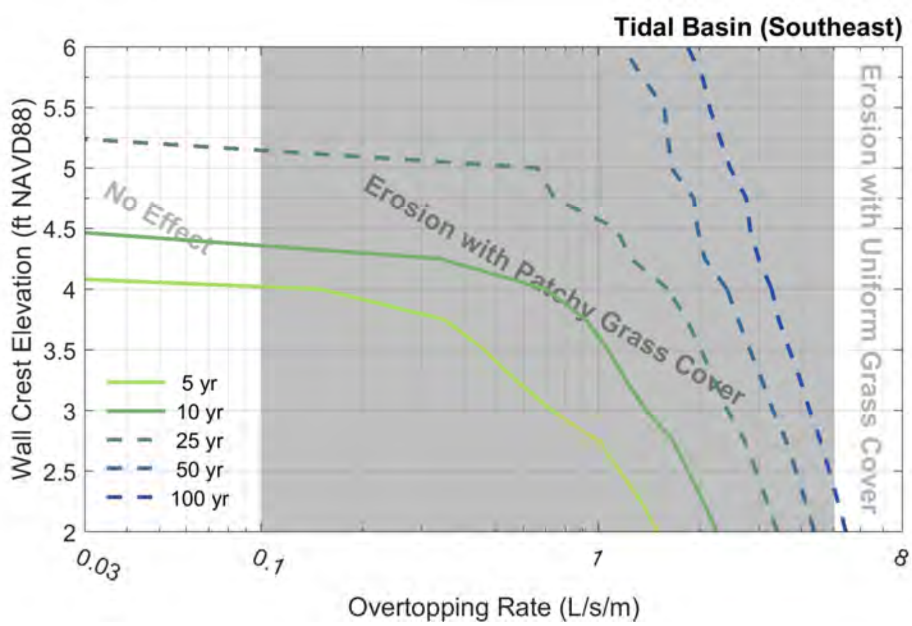


FIGURE 28. OVERTOPPING RATES FOR A RANGE OF WALL CREST ELEVATIONS AND RETURN PERIODS AT THE TIDAL BASIN (SOUTHEAST) ANALYSIS TRANSECT. RETURN PERIODS OF 25 YEARS OR MORE ARE DASHED TO INDICATE UNCERTAINTY. GREY SHADING INDICATES OVERTOPPING IS EXPECTED TO ERODE PATCHY GRASS COVER ON SEAWALL CRESTS BUT NOT CAUSE DAMAGE TO UNIFORM GRASS COVER.

Hazard type and reason	Mean discharge q (l/s per m)	Max volume V_{max} (l per m)
Rubble mound breakwaters; H_{m0} > 5 m; no damage	1	2,000-3,000
Rubble mound breakwaters; H_{m0} > 5 m; rear side designed for wave overtopping	5-10	10,000-20,000
Grass covered crest and landward slope; maintained and closed grass cover; H_{m0} = 1 – 3 m	5	2,000-3,000
Grass covered crest and landward slope; not maintained grass cover, open spots, moss, bare patches; H_{m0} = 0.5 – 3 m	0.1	500
Grass covered crest and landward slope; H_{m0} < 1 m	5-10	500
Grass covered crest and landward slope; H_{m0} < 0.3 m	No limit	No limit

FIGURE 29. EUROTOP (2018) TABLE 3.1 DEPICTING LIMITS FOR WAVE OVERTOPPING FOR STRUCTURAL DESIGN OF BREAKWATERS, SEAWALLS, DIKES AND DAMS. AT MOST, HM0 IS APPROXIMATELY ONE METER AT THE PROJECT SITE.

Hazard type and reason	Mean discharge q (l/s per m)	Max volume V_{max} (l per m)
People at structures with possible violent overtopping, mostly vertical structures	No access for any predicted overtopping	No access for any predicted overtopping
People at seawall / dike crest. Clear view of the sea. H_{m0} = 3 m H_{m0} = 2 m H_{m0} = 1 m H_{m0} < 0.5 m	 0.3 1 10-20 No limit	 600 600 600 No limit
Cars on seawall / dike crest, or railway close behind crest H_{m0} = 3 m H_{m0} = 2 m H_{m0} = 1 m	 <5 10-20 <75	 2000 2000 2000
Highways and roads, fast traffic	Close before debris in spray becomes dangerous	Close before debris in spray becomes dangerous

FIGURE 30. EUROTOP (2018) TABLE 3.3 DEPICTING LIMITS FOR OVERTOPPING FOR PEOPLE AND VEHICLES. AT MOST, HM0 IS APPROXIMATELY ONE METER AT THE PROJECT SITE.

3.2.8. Temperature and Ice

3.2.8.1. Temperature

Temperature in the Washington, DC area is not considered a driving factor in the NAMA Seawall design; however, the high and low temperatures could affect the vegetation at the Project site particularly the Cherry Blossom trees which are part of the NAMA National Park.

In Washington, DC overall, the average temperatures for winter and summer months are 39.7°F and 74.6°F, respectively; see Figure 31 for monthly averages. The long-term annual temperature is 55.5°F. However, statewide climate trends show the average temperature to be increasing at a rate of +0.2°F/decade, as shown in Figure 32. This temperature change can impact sensitive flora resulting in reduction in health. This will be considered when looking at landscaping within the project site.

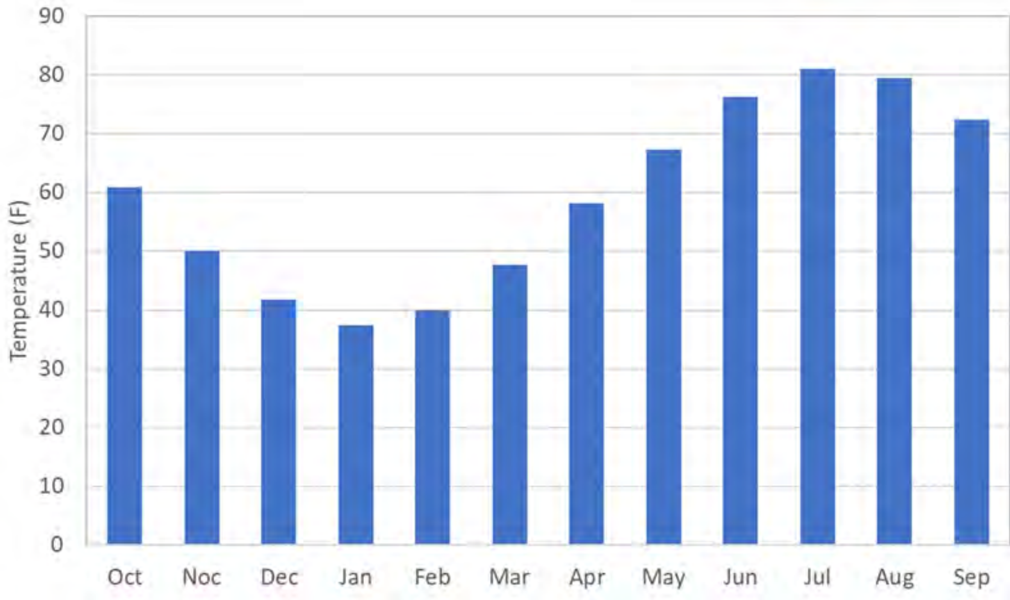


FIGURE 31. WASHINGTON, DC LONG-TERM MONTHLY TEMPERATURE AVERAGES IN WATER YEAR (NOAA, 2022).

FIGURE 32. 5 YEAR TREND OF AVERAGE TEMPERATURE, STATE OF MARYLAND (NOAA, 2022)

3.2.8.2. Ice

Once an ice cover is formed, it may thicken and can cause rapid increases in stage that can cause flooding and damage. Therefore, the impacts of ice at the Project Site would need to be incorporated in scour and seawall design. The extreme growth of ice thickness at the Project site was calculated by using the Ronald Reagan airport temperature records (from 1936 to 2022), calculating the associated accumulated freezing degree days (AFDD), and fitting an extremal distribution curve to the AFDD. The extreme growth of ice thickness was then estimated using the Stefan equation (USACE, 2002). Results are shown in Figure 33 and Table 14.

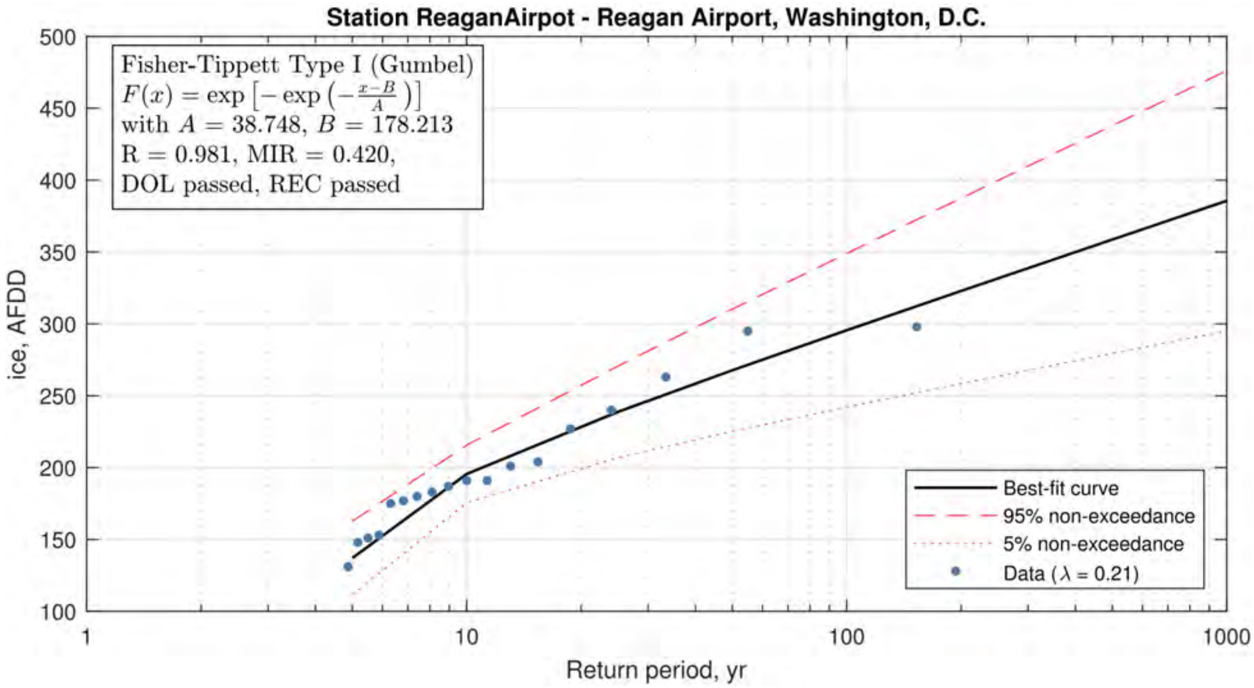


FIGURE 33. EXTREME VALUE ANALYSIS OF AFDD.

TABLE 14. EXTREME VALUE OF AFDD AND ASSOCIATED ICE THINKESS FOR POTOMAC RIVER AND TIDAL BASIN BASED ON STEFAN EQUATION.

Return Period (yr)	AFDD	Ice Thickness (in) Potomac River (alpha = 0.40)	Ice Thickness (in) Tidal Basin (alpha = 0.60)
5	137	5	7
10	196	6	8
25	239	6	9
50	268	7	10
100	296	7	10

3.2.9. Geotechnical Considerations

3.2.9.1. Earthquakes and Liquefaction

Based on existing data from a previous geotechnical analysis conducted for a project in the Washington Channel, the soils in the vicinity of the NAMA Seawall Project have the potential to liquify; where a liquefaction analysis based on the 2015 International Building Code (IBC 2015) design earthquake indicates sands encountered below the water table have the potential to liquefy during the design seismic event. Since piles are anticipated to be used in the Seawall design, ultimately the consequence of liquefaction in this scenario is the loss of geotechnical pile capacity (ECS, 2016). However, for further discussion on earthquake potential specific to the Project site please refer to the geotechnical analysis report.

3.2.9.2. Soil Settlement

Many areas along the seawall are already failing due to the combination of past settlement and washout of fill, and loss of wall integrity. Dewberry and Davis (2011) indicates the obeserved settlement at the Project site was caused by primary and secondary consolidation of the alluvial soils below the dredge material and of the dredge material itself.

The preliminary geotechnical report of July 2011 indicates there is a very thick zone of “weak soils,” typically to a depth of 82 to 92 feet. The geotechnical data generally found very little organic material other than a peat layer. Such pockets of organic material could contribute to significant differential settlement over an extended period of time. This is true in that all areas will undergo similar primary consolidation in reaction to the load. The non-organic soils will see little secondary consolidation while the “pocket” of organic material undergoes potentially significant secondary consolidation leading to a differential settlement between the two areas.

Reports indicate that the seawalls may have stopped settling (Dewberry and Davis, 2011) under present conditions, but that any additional load would result in additional settlement.

The risk associated with the on-going settlement will be mitigated through the foundation design. However, for further discussion on soil settlement at the Project site please refer to the geotechnical analysis report.

3.2.10. Toxic Gas Release

As part of this project, a geotechnical analysis including collecting boring samples was undertaken. During the boring collection, methane gas was frequently encountered. Concentrations were such work had to be halted until the methane could naturally, or in some cases mechanically, escape down to acceptable working levels. As designs to mitigate future settlement require pile foundations, methane gas is likely to be encountered by the contractor. Additionally, the release of the methane gas will need to be considered within the geotechnical design and how it will affect the settlement of the surrounding area. More information on methane gas can be found in the geotechnical analysis report.

3.3. Future Hazard Risks (Future Conditions)

3.3.1. Sea Level Rise Projections

One of the main impacts of climate change at the Project site is sea level rise (SLR); hazards at the Project site will evolve over time in response to rising sea levels. Sea level rise is influenced by processes at global, regional, and local scales. At the global scale, sea level rise is influenced by an increase in the volume of ocean water due to thermal expansion and by an increase in ocean water mass caused by loss of land ice or a net loss in terrestrial water reservoirs. These volume changes vary across the globe due to spatial changes in climate processes (IPCC, 2019). Other processes related to ocean-atmosphere dynamics also contribute to distinct spatial patterns in regional sea level change. These spatial variations in the climate processes that affect sea level rise are reflected in historic sea level observations within the contiguous United States compared to global mean sea level rise (Figure 34).

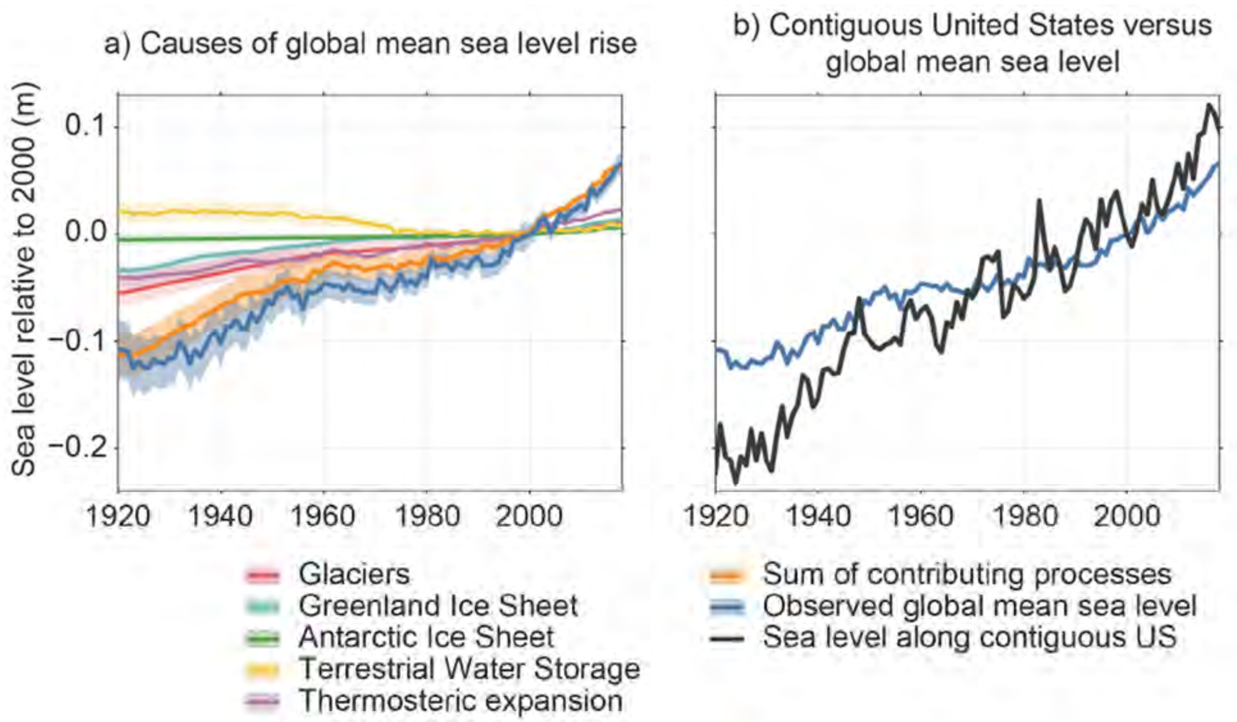


FIGURE 34. TRENDS IN THE CAUSES OF GLOBAL MEAN SEA LEVEL RISE, GLOBAL MEAN SEA LEVEL, AND SEA LEVEL ALONG THE CONTIGUOUS U.S. (NOAA, 2022).

Local rates of land movement must also be accounted for to fully capture the potential change in coastal hazard conditions at the Project site. Sea level measured relative to land is called "relative" sea level (RSL). Sinking land, known as subsidence, leads to higher RSL rise and increased flood risk. In contrast, uplifting land reduces sea level and promotes the seaward migration of coastlines. Together, subsidence and uplift are referred to as vertical land motion, or VLM. RSL trends have been tracked at the local level over the past century. The current linear trend for average monthly water levels at the NOAA Washington Channel station shows an average rise in RSL of 3.44 mm per year, equivalent to a change of 1.13 ft in 100 years.

Sea level rise projections are available from multiple sources at the global, regional, and local level. Relevant projections for the Project site are currently available from:

- Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC, 2021), the
- National Oceanic and Atmospheric Administration, (NOAA, 2022), and the
- Department of Defense Regional Sea Level (DRSL) Database (U.S. Department of Defense, 2016).

Future scenarios in the 6th Assessment Report (IPCC AR6) are divided into five Shared Socio-Economic Pathways (SSPs) based on possible future greenhouse gas emissions and other anthropogenic drivers of climate change. NOAA and Department of Defense projections are based on a defined set of five end-of-century global mean sea level rise scenarios designed to capture the plausible range of global sea level changes. IPCC AR6 projections are utilized within this study as they provide the greatest level of site-specific probabilistic information on RSL rise. RSL projections for SSP2-4.5 and SSP5-8.5 were selected as the moderate and upper-end scenarios, respectively for hazards analysis; the medium-confidence projections for these scenarios at Washington, D.C. are shown in Figure 35 .

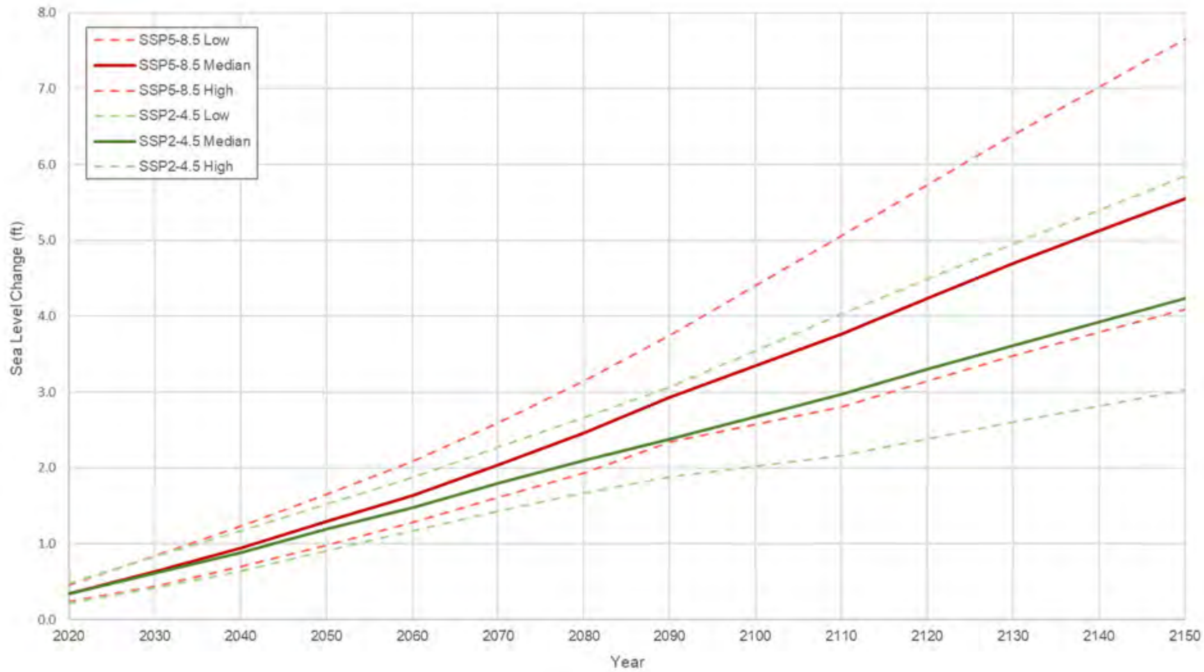


FIGURE 35. MODERATE (IPCC AR6 SSP2-4.5) AND UPPER END (SSP5-8.5) SLR PROJECTIONS FOR WASHINGTON, D.C.; DASHED LINES INDICATE THE 16.7 TO 83.3 PERCENTILE RANGE.

3.3.2. Sea Level Rise Implications

3.3.2.1. Water Levels

SLR is expected to exacerbate the flood hazards at the Project site. Probabilistic relative SLR projections for the Washington, DC, NOAA gauge (Garner, et al., 2021), based on Intergovernmental Panel on Climate Change (IPCC, 2021) 6th Assessment Report (AR6) guidance, were used with water level frequency curves developed in Section 3.2.4 to project future water levels at the Project site by combining probabilities. Three elevation thresholds 2.5, 3.5, and 4.5 ft NAVD88 (based on the current +2.5 ft NAVD88 NAMA seawall crest elevation with potential 1-ft and 2-ft increases in crest elevation) were selected to evaluate increases in flood frequency due to SLR. Results are shown on Figure 36 and Figure 37 for the moderate (SSP2-4.5) and upper end (SSP5-8.5) climate scenarios, respectively.

Results indicate that sea levels have exceeded the current NAMA seawall crest elevation roughly 50 days per year for the past 20 years. This is consistent with the average of 108 flooding events per year for the past 20 years shown in Figure 14, as this nuisance flooding is often caused by an elevated twice-daily high tide.

The upper-end SLR projection does not substantially differ from the moderate SLR projection until 2090 where the difference is approximately 0.5 ft. As a result, water levels are expected to exceed the current seawall crest elevation roughly 200 days per year by 2030 (and roughly 330 days per year by 2050). Thus, increasing the existing NAMA seawall crest elevation by 1 ft is anticipated to delay this frequency of flooding by roughly 35 years. The largest difference in nuisance flooding between moderate and upper end projections occurs for flooding that exceeds the existing crest elevation by 2 ft. In addition, water levels are anticipated to exceed +4.5 ft NAVD88 roughly 200 days per year by 2100 and 2080 for the moderate and upper-end projections, respectively. This indicates that raising the existing NAMA seawall crest elevation by 2 ft may delay frequent flooding at the site by 50-70 years, depending on future rates of sea level rise.

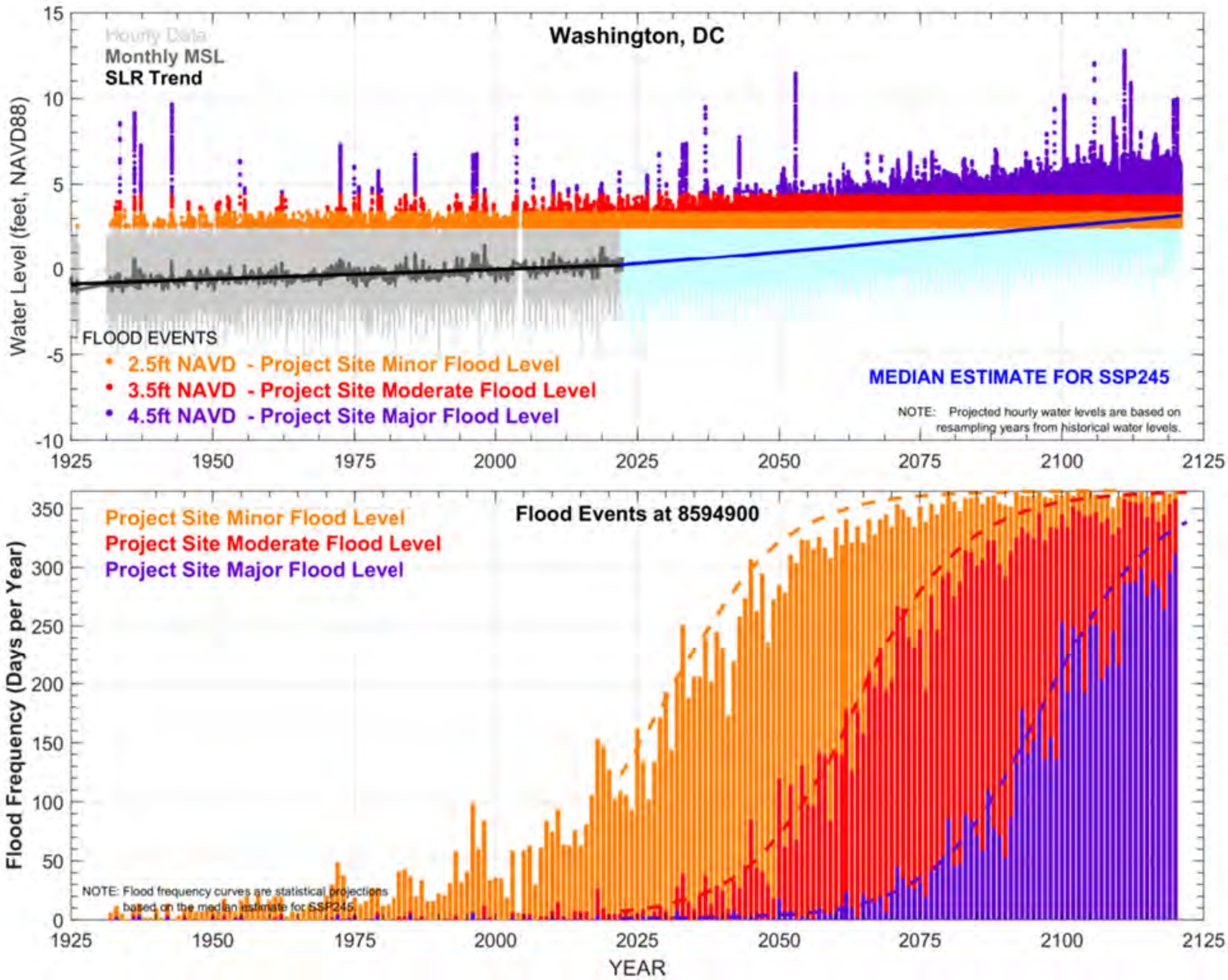


FIGURE 36. PROJECTED WATER LEVELS BASED ON MODERATE SLR PROJECTION (MEDIAN SSP2-4.5) AT WASHINGTON CHANNEL NOAA STATION. TOP: HISTORICAL WATER LEVEL OBSERVED WITH A POTENTIAL TIME SERIES OF FUTURE WATER LEVELS; GREY SHADING INDICATES MEASURED WATER LEVELS; COLORED SHADING INDICATES TIMES WHEN WATER LEVELS EXCEED A SPECIFIC FLOOD ELEVATION. BOTTOM: BARS DEPICT THE NUMBER OF DAYS ASSOCIATED WITH FLOODING FOR EACH YEAR BASED ON RESAMPLING; DASHED CURVES DEPICT PROBABILITY-BASED PROJECTIONS FOR THE NUMBER OF FLOODING DAYS FOR SPECIFIC FLOOD ELEVATION.

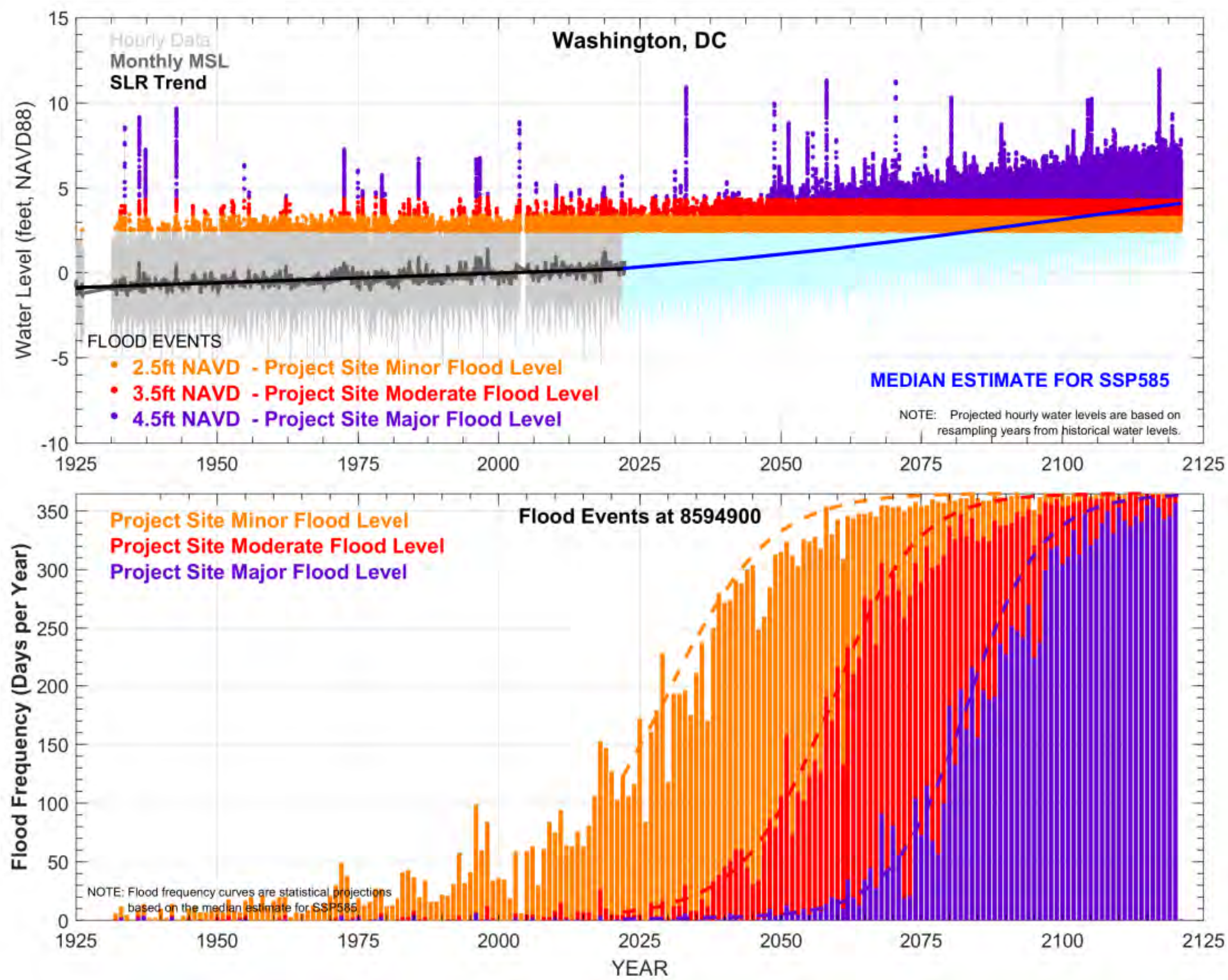


FIGURE 37. PROJECTED WATER LEVELS BASED ON UPPER END SLR SCENARIO (MEDIAN SSP5-8.5) AT WASHINGTON CHANNEL NOAA STATION. TOP: HISTORICAL WATER LEVEL OBSERVED WITH A POTENTIAL TIME SERIES OF FUTURE WATER LEVELS; GREY SHADING INDICATES MEASURED WATER LEVELS; COLORED SHADING INDICATES TIMES WHEN WATER LEVELS EXCEED A SPECIFIC FLOOD ELEVATION. BOTTOM: BARS DEPICT THE NUMBER OF DAYS ASSOCIATED WITH FLOODING FOR EACH YEAR BASED ON RESAMPLING; DASHED CURVES DEPICT PROBABILITY-BASED PROJECTIONS FOR THE NUMBER OF FLOODING DAYS FOR SPECIFIC FLOOD ELEVATION.

Figure 38 and Figure 39 depict how the average interval *between* flood events is projected to change over time with SLR for moderate and upper end projections, respectively. The projected flood intervals for the three elevations with SLR for the next 50 years are summarized in Table 15.

By 2052, water levels are projected to exceed the existing NAMA wall crest elevation at least once per day; in addition, water levels are projected to exceed the existing seawall crest by 1 ft nearly as often as water levels currently exceed the NAMA seawall crest. By 2072, water levels are projected to exceed the existing seawall crest by 1 ft roughly once per day; water levels are also projected to exceed the existing seawall crest by 2 ft roughly once every 1 to 2 weeks. These projections of frequent on-site flooding indicate that SLR will (1) cause the Project site to be more frequently flooded by “clear sky” nuisance flooding and (2) cause flood depths to increase over time.

TABLE 15. AVERAGE INTERVAL BETWEEN FLOOD EVENTS WITH SLR.

	SLR Projection	Water Surface Elevation		
		+2.5 ft NAVD88	+3.5 ft NAVD88	+4.5 ft NAVD88
2022	N/A	2.7 days	50 days	330 days
2052	Moderate SSP2-4.5	0.7 days	4.1 days	74 days
	Upper end SSP5-8.5	0.7 days	3.0 days	56 days
2072	Moderate SSP2-4.5	0.6 days	1.1 days	13 days
	Upper end SSP5-8.5	0.6 days	0.8 days	5.8 days

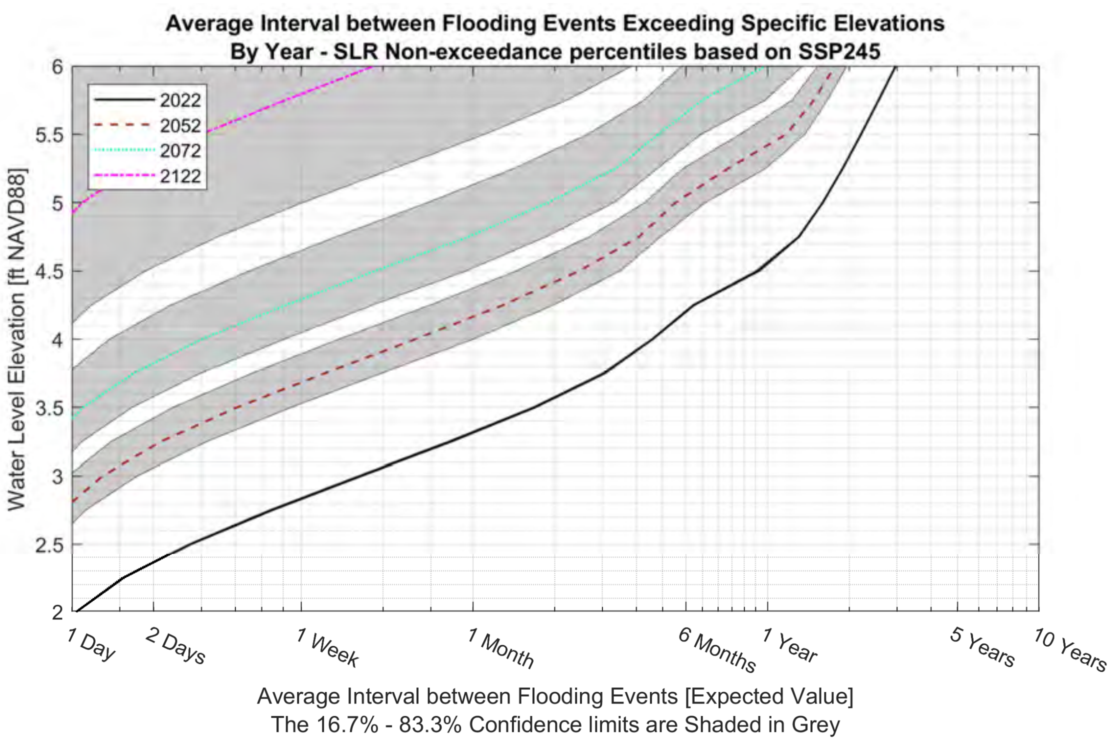


FIGURE 38. PROJECTED AVERAGE INTERVAL BETWEEN FLOOD EVENTS FOR SPECIFIC YEARS AND FLOOD ELEVATION THRESHOLDS, BASED ON MODERATE SLR PROJECTION (IPCC SSP2-4.5).

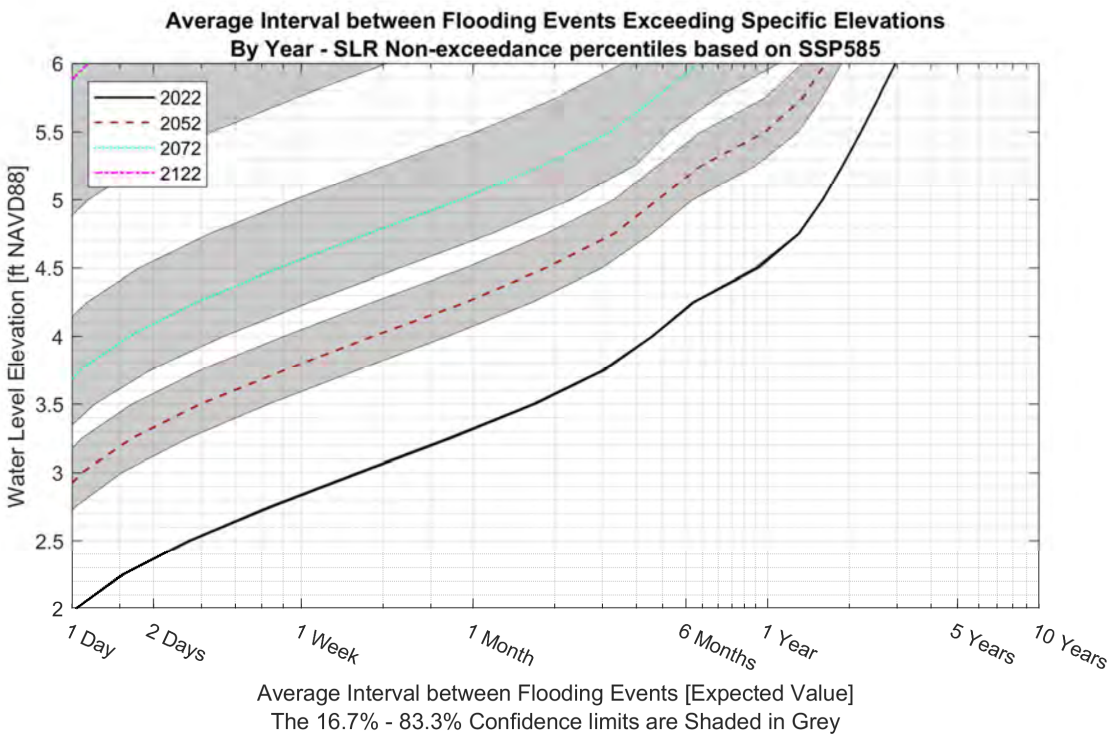


FIGURE 39. PROJECTED AVERAGE INTERVAL BETWEEN FLOOD EVENTS FOR SPECIFIC YEARS AND FLOOD ELEVATION THRESHOLDS, BASED ON UPPER END SLR PROJECTION (IPCC SSP4-8.5).

3.3.2.2. Wave Overtopping

SLR is anticipated to increase overtopping hazards at the Project site caused by locally-generated wind waves and increasing water levels. Figure 40 and Figure 41 depict the projected wave overtopping rates at the Potomac River (South) and Tidal Basin (Southeast) (see Figure 24 for transect location), respectively for the upper-end (SSP4-8.5) SLR projection in 2050 (+1.3 ft of SLR since 2005), assuming no future changes in wind climate or open-water distances for generating waves.

At both the Potomac River (South) and Tidal Basin (Southeast), the increase in water level due to SLR is anticipated to cause overtopping rates to increase for all crest elevations. The 2050 overtopping rates are typically 50% higher than historical overtopping rates at the site. With sea level rise, wave events with return periods of more than 25 years are projected to cause erosion of uniform grass coverage on seawall crests with elevations below 4.0 ft NAVD88. The hazards associated with wave events with return periods of 25-years or less are not expected to substantially change. In addition, none of the tested wave/seawall crest elevation combinations are associated with substantial danger to pedestrian traffic (Figure 30). Note that high seawall crest elevations may have been able to minimize overtopping hazards for short return period wave events in the past (Figure 27 and Figure 28), but will be less able to do so in the future with SLR.

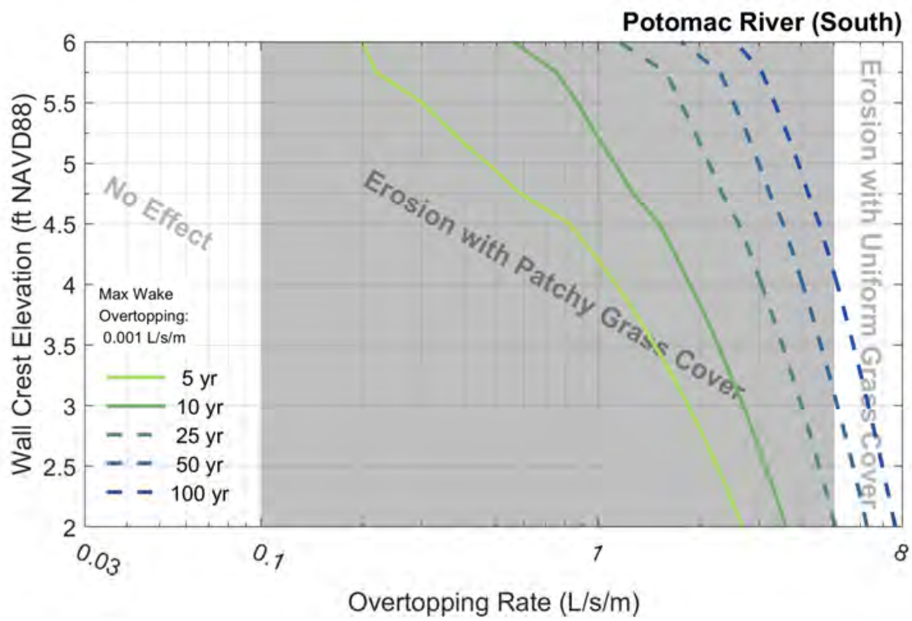


FIGURE 40. 2050 PROJECTED OVERTOPPING RATES BASED UPPER-END (SSP4-8.5) SLR PROJECTION FOR A RANGE OF WALL CREST ELEVATIONS AND RETURN PERIODS AT THE POTOMAC RIVER (SOUTH). RETURN PERIODS OF 25 YEARS OR MORE ARE DASHED TO INDICATE UNCERTAINTY. GREY SHADING INDICATES OVERTOPPING IS EXPECTED TO ERODE PATCHY GRASS COVER ON SEAWALL CRESTS BUT NOT CAUSE DAMAGE TO UNIFORM GRASS COVER.

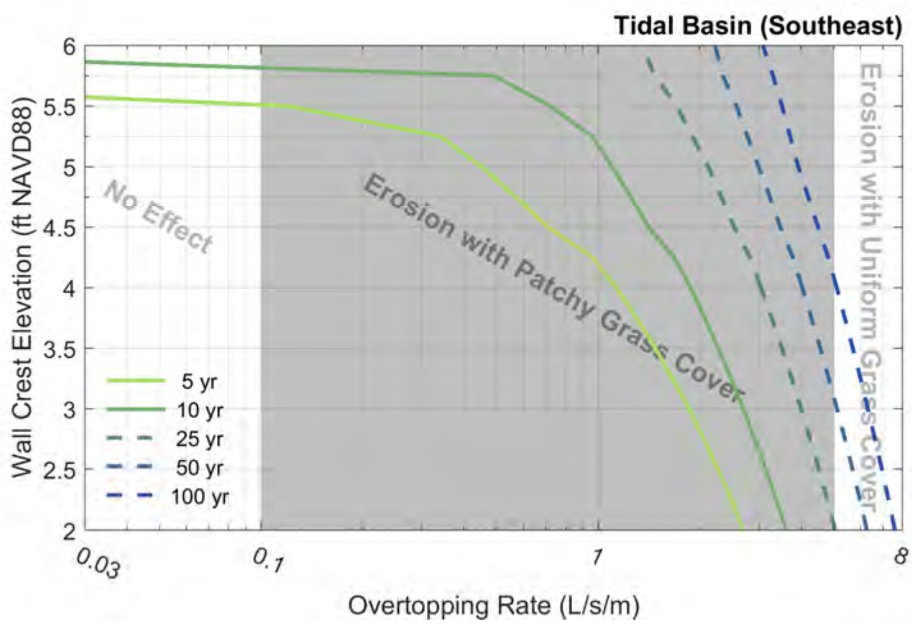


FIGURE 41. 2050 PROJECTED OVERTOPPING RATES RATES BASED ON UPPER-END (SSP4-8.5) SLR PROJECTION FOR A RANGE OF WALL CREST ELEVATIONS AND RETURN PERIODS AT THE TIDAL BASIN (SOUTHEAST). RETURN PERIODS OF 25 YEARS OR MORE ARE DASHED TO INDICATE UNCERTAINTY. GREY SHADING INDICATES OVERTOPPING IS EXPECTED TO ERODE PATCHY GRASS COVER ON SEAWALL CRESTS BUT NOT CAUSE DAMAGE TO UNIFORM GRASS COVER.

3.3.3. Climate Change Implications

Global climate change has been observed in the environment and has had measured effects on water levels as described in section 3.2.2, but climate change refers to more than an increase in water level. It also includes changes in other weather phenomena. In this section and based on existing studies, we are describing the potential effects climate change could have on storm surge, frequency of flooding, and precipitation in the Project vicinity.

- Storm Surge
  Coastal lines over the world are facing increasing extreme sea levels. Vousdoukas, et al. (2018) presetned probabilistic projections of extreme sea levels for the present century taking into consideration changes in mean sea level, tides, wind-waves, and stormsurges. By the end of this century this applies to most coastlines around the world, implying unprecedented flood risk levels unless timely adaptation measures are taken. From Vousdoukas, et al. global results, it was estimated that at the Chesapeake Bay, the extreme sea level is expected to rise by approximately 15% and 20% by 2100 under a moderate-emission-mitigation-policy (RCP4.5) and a high-end scenario (RCP8.5), respectively (Vousdoukas, et al., 2018).

  In the coastal modelling task of this project, which is currently undergoing, we will study through numerical modelling the effect SLR will have at the Project site and the potential non-linear response of storm surge to SLR.

- Frequency of Flooding

  Taherkhani, et al. (2020) quantified rate of increase in the occurrence of extreme water level events due to sea level rise and suggests that every 10 years (or less) sea-level rise would double the odds of exceeding the present-day 50-year water-level event at Chesapeake Bay. Overall, present-day extreme water-level events will become commonplace within the next few decades.

- Precipitation

  From a hydrological perspective, Mallakpour and Villarini (2017) show that there is a statistically significant of at least 5% increasing trend in both magnitude and frequency of heavy precipitation in the Potomac River Basin. Similarly, IPCC 2007 projected a robust tendency of increased precipitation in the vicinity of Project site due to an increase in water vapor in the atmosphere, with a multi-model average increase amount of around 0.2 mm/day (Trenberth, 2011). Increasing precipitation would lead to larger river discharge, leading to potential riverine flooding at the Park, and scour of the Potomac River bank.

Even though frequency of flooding and increase precipitation are considered effects of climate change, water levels (including storm surge) and sea level rise are the largest driving forces that impose risks on the NAMA Seawall. Thus, their implications and effects on the future will be assessed with numerical modelling in the next Project phase.

4. Considerations and Strategy

Based on the existing conditions at the Project site and the analyses presented in this report, the highest risks associated with the NAMA Seawall and Shoreline Project are coastal flooding and geotechnical factors, such as soil settlement and liquefaction. Geotechnical considerations will be addressed on the geotechnical report. The coastal flooding risks at the site are high water levels associated with storm surge and/or Potomac River fluvial processes, waves, and wave overtopping; such risks will continue to pose a hazard to the NAMA seawall in the future and will be amplified due to sea level rise. The effects sea level rise may have on storm surge at the project are currently being investigated by the M&N team under the coastal modelling task. The results from such analysis will be used to provide recommendations for the design of the seawall. Table 16 presents a summary of the coastal risks evaluated under existing conditions (excluding SLR) at the project site.

TABLE 16. SUMMARY OF THE COASTAL RISKS EVALUATED UNDER EXISTING CONDITIONS (EXCLUDING SLR) AT THE PROJECT SITE.

Return Period (year)	Water Surface Elevations (ft NAVD88)	Significant Wave Height West Potomac Park South (ft)	Significant Wave Height Tidal Basin East (ft)	Overtopping Rate with Top of Wall at 4.5 ft West Potomac Park South (L/s/m)	Overtopping Rate with Top of Wall At 4.5 ft Tidal Basin East (L/s/m)
5	5.09	2.4 ft	1.5 ft	x	x
10	6.32	2.7 ft	1.6 ft	x	x
25	8.27	3.1 ft	1.8 ft	x	x
50	9.94	3.4 ft	1.9 ft	x	x
100	11.75	3.8 ft	2.1 ft	x	x

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