City of Alexandria, Virginia
Waterfront Implementation

Technical Memorandum 2
POTOMAC RIVER FLOOD FREQUENCY ANALYSIS

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COMMONWEALTH OF VIRGINIA
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Abbreviations

Carollo	Carollo Engineers
CSN	Chesapeake Stormwater Network
FT	feet
IPCC	Intergovernmental Panel on Climate Change
MHHW	Mean Higher High Water
MSL	Mean Sea Level
MSWMP	Master Storm Water Management Plan
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
SLR	sea level rise
USACE	United States Army Corps of Engineers
WAIS	West Antarctic Ice Sheet

Technical Memorandum 2

POTOMAC RIVER FLOOD FREQUENCY ANALYSIS

1. Purpose

The Potomac River is a regular source of flooding in Old Town Alexandria. The City of Alexandria's Waterfront Implementation Project aims to mitigate riverine flooding as part of a larger, comprehensive flood mitigation investment. Previous planning efforts considered raising the shoreline protection to various elevations between 4.0 and 10.2 feet (NAVD88)[1]. After considering community-preference to maintain waterfront access while eliminating more regular flooding occurrences, the 2018 Stantec *Master Storm Water Management Plan* recommended a 6.0 feet level of protection.

Collectively, this technical memorandum evaluates and confirms if the 6.0 feet level of protection should continue to be the established design criteria. To do so, the following tasks were completed and summarized herein:

- Analyze historical Potomac River elevations to quantify the following parameters:
  - Current average low-tide, high-tide, and high-water values.
  - Frequency of bulkhead overtopping along the waterfront.
  - Frequency of flooding caused by tidal backflow.
- Evaluate the level of riverine flooding protection proposed in the *Master Storm Water Management Plan* (Stantec, November 2018) to consider the most up-to-date future projections of sea level rise (SLR) for the Potomac River.
- Recommend the appropriate design criteria for riverine protection against project goals, funding constraints, and latest climate science; justify tidal back-up control as both interim and long-term solutions for the project.

2. Historical Potomac River Level Analysis

The 2007 Initial Flooding Assessment (URS) characterized the following types of flooding events:

- "Tidal backflow" flooding typically occurs during high tide events that are common during new and full moons. This type of flooding can occur without local rainfall and originates from river water backup into the storm sewer system.
- "Storm surge" flooding typically occurs because of offshore low pressure, which raises river surface elevation and is exacerbated by high tide. Storm surge flooding is a common effect of tropical storm systems and results from water levels overtopping the existing shoreline elevation.
- "Heavy rainfall" flooding occurs when the City's storm drain system is overwhelmed by rainfall, typically during short-duration, intense rainfall events. The majority of runoff entering the storm drain system in the core area comes from the uphill area west of Union Street.

[1] The URS 2010 Report *Potomac River Waterfront Flood Mitigation Study: Evaluation and Recommendation of Mitigation Measures* considered three discrete flood events: nuisance flooding (at elevation 4.0 feet), intermediate flooding (at elevation 8.0 feet), and extreme flooding (at elevation 10.2 feet).

This project memorandum is focused on analyzing tidal backflow and storm surge flooding (i.e., all flooding originating from the Potomac). Heavy rainfall flooding is analyzed in *Technical Memorandum 1: Design Storm Selection for Hydrologic and Hydraulic Modeling* (TM1, 2022, Carollo Engineers).

To approximate the frequency of tidal backflow and storm surge flooding, historic Potomac River levels were reviewed. Figure 1 illustrates the daily maximum and daily minimum river levels reported at the USGS gauge at Cameron St Dock (0165258890) from July 2004 through December 2021. The highest-recorded water levels (historic crests) in this period are marked on the figure in red. Also shown are action levels used by the National Weather Service (NWS) and local forecasters for determining critical Potomac River levels in Alexandria. These include:

- Action Stage (2.5 feet): Stage that represents the level where the NWS or a partner/user needs to take some type of mitigation action in preparation for possible significant hydrologic activity.
- Flood Stage (3.3 feet): Established stage above which a rise in water surface level begins to create a hazard to lives, property, or commerce. The issuance of flood advisories or warnings is linked to flood stage.
- Moderate Flood Stage (4.2 feet): Stage above which some inundation of structures/roads near the river occurs. Some evacuations of people and/or transfer of property to higher elevations may be necessary.
- Major Flood Stage (6.6 feet): Stage defined as having extensive inundation of structures and roads. Significant evacuations of people and/or transfer of property to higher elevations are necessary.

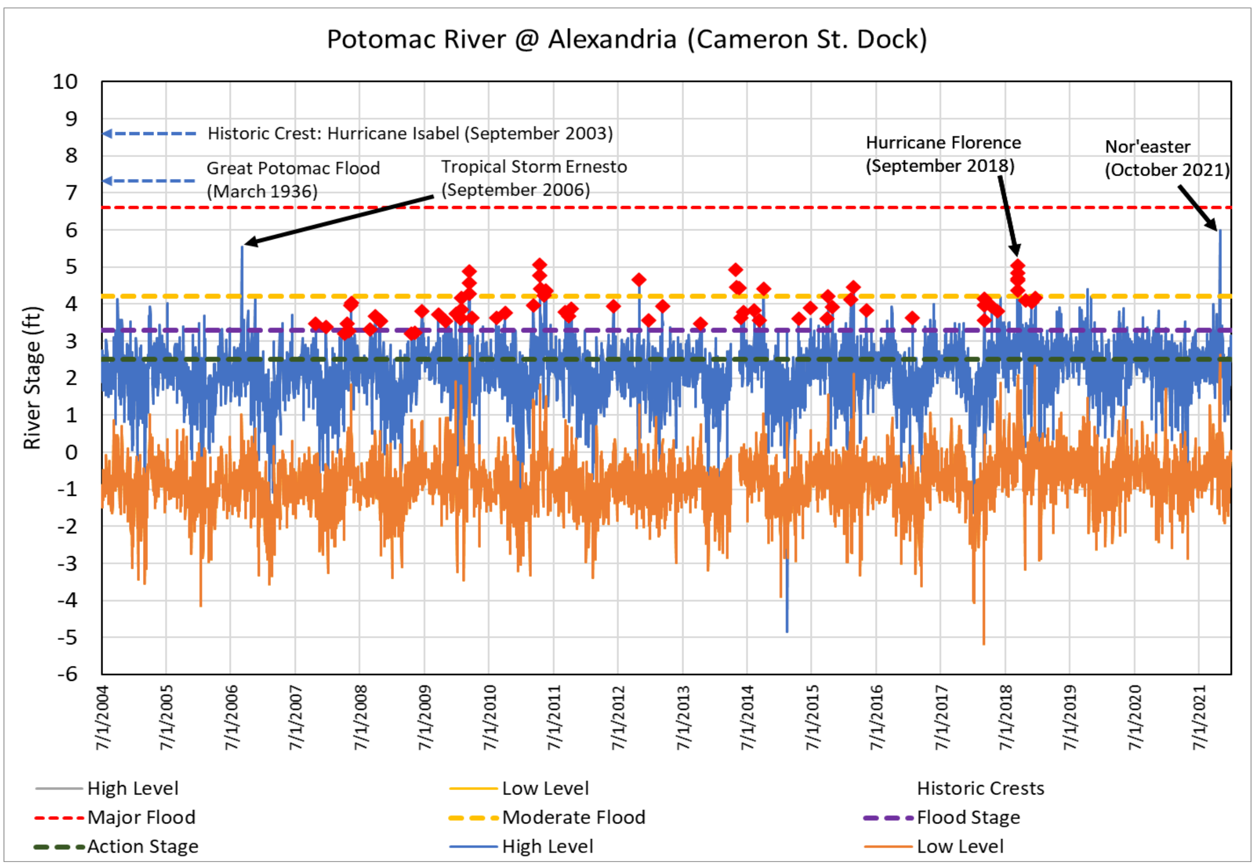

Figure 1 Potomac River Daily High and Low Levels (July 2004 – December 2021; all Levels in NAVD 1988)

As shown on Figure 1, the Potomac River near Old Town Alexandria exceeds Action Stage of 2.5 feet nearly one-third of the year on average (112 days per year). The Flood Stage of 3.3 feet is exceeded approximately 16 days per year, while the Moderate Flood Stage of 4.2 feet is exceeded about 2 days per year. The two highest water levels observed in the 2004 to 2021 period were 5.54 feet in September 2006 (due to Tropical Storm Ernesto) and 5.99 feet due to the October 2021 Nor'easter (which had almost identical pressure and wind conditions to Tropical Storm Ernesto). River levels exceeded 6.0 feet twice in recorded history; the highest was 8.66 feet in September 2003 as a result of Hurricane Isabel, while the second highest was 7.40 feet observed during the Great Potomac Flood of March 1936.

To evaluate potential solutions, it is standard practice to correlate shoreline elevations with local Mean Higher High Water (MHHW) levels. MHHW is the 19-year average of the highest high tide of each tidal day, reported in feet. The National Atmospheric and Oceanic Administration (NOAA) defines MHHW levels for select tide gauges around the country, with the gauge nearest to Alexandria being in Washington, D.C. The MHHW NOAA reports for Washington DC is 1.77 feet (NAVD88), however this value does not accurately reflect current sea levels in Alexandria because 1) Washington is upstream of Alexandria and consistently has lower high tides as a result and 2) because NOAA last updated this value in 2001, meaning it has not been adjusted for sea level rise seen over the last 20 years. Table 1 shows the differences in sea levels caused by these two effects, as well as a calculated effective MHHW for the available data at the Cameron St Dock tide gauge in Alexandria.

Table 1 Sea Level Statistics for Washington, D.C., and Alexandria

NOAA-Reported Mean Sea Level - Washington, D.C. (1983 – 2001)	0.15 feet
NOAA-Reported Mean Higher High Water - Washington, D.C. (1983 – 2001)	1.77 feet
Observed Mean Sea Level - Washington, D.C. (2004 – 2021)	0.45 feet
Observed Mean Sea Level - Cameron St Dock (2004 – 2021)	0.68 feet
Effective Mean Higher High Water - Cameron St Dock (2004 – 2021)[2]	**2.19 feet**

Tidal differences between D.C. and Alexandria result in an average 0.23-foot difference in mean sea level, while sea level rise over the last 20 years has contributed an additional 0.30 feet to MSL in Washington, D.C. This analysis provided confidence in using the calculated effective MHHW of 2.19 feet to evaluate coastal flooding issues and solution.

2.1. Tidal Backflow Flooding

Tidal backflow flooding occurs when the water level in the river exceeds the street elevation of stormwater sewer inlets or manholes. River water backs up through the stormwater outfalls and rises onto streets through storm sewer inlets and manholes. Figure 2 presents stormwater outfalls in the Core Area and identifies the number of low-lying structures (storm sewer inlets or manholes) that may be responsible for tidal backflow flooding caused by high Potomac River levels.

[2] To determine an effective MHHW for Alexandria, Carollo followed the procedure laid out in NOAA's *Computational Techniques for Tidal Datums Handbook* (NOAA, 2003) and applied it to data from 2004 - 2021 at the Cameron St Dock tide gauge in Alexandria (USGS 0165258890).

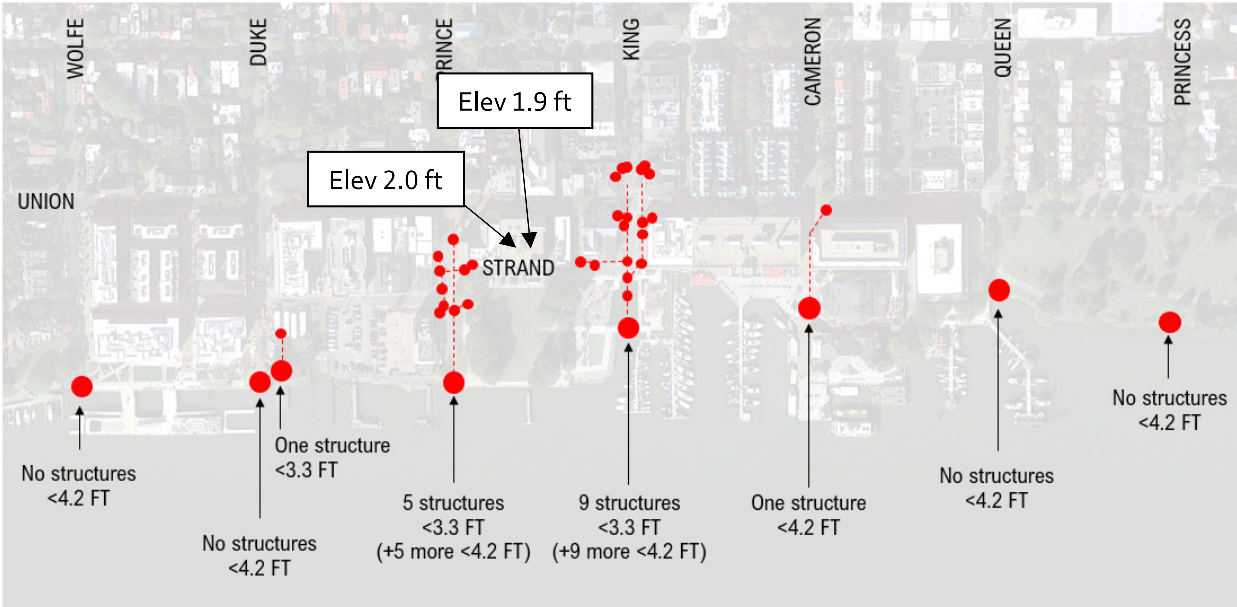

Figure 2 Location of Low-Lying Manholes/Inlets in Core Area

In December 2021, the Carollo team completed a detailed site survey to determine precise elevations of these low-lying components and quantify their backflow risk. The areas most susceptible to tidal backflow flooding in the Core Area are connected to the Prince and King Street outfalls. The two inlets called out in Figure 2 are the lowest-lying within the Core Area, with elevations less than the effective MHHW and the flood Action Stage. As a result, these inlets may flood more than 100 times per year.

2.2. Storm Surge Flooding

Storm surge flooding occurs when the Potomac River elevation exceeds the existing shoreline infrastructure, which is comprised of a structural bulkhead (of various materials), riprap and a concrete slope. Like the tidal backflow analysis above, an approximate frequency of surge flooding can be determined by comparing shoreline elevations to the historical tides presented in Figure 1. The 2021 survey showed multiple areas with elevations below the Moderate Flood Stage of 4.2 feet, with certain areas below the Flood Stage height of 3.3 feet. This suggests that storm surge elevations exceed most of the existing shoreline elevations in the Core Area approximately 2 days per year on average. Certain lower areas, such as the Point Lumley boat slip and King Street Square, are below the flood Action Stage and may flood up to 16 times per year.

Most storm surge events are minor in nature - resulting in river elevations only a few inches to a foot above shoreline elevations and persisting for a short period of time (on the order of minutes to an hour). These minor events result in ponding in the immediate vicinity of the shoreline and typically occur without any notable impacts to local infrastructure, property, or daily activities.

More serious storm surge events occur when the river level is elevated well above the shoreline for multiple hours, allowing for a large volume of water to be pushed inland. In the October 2021 Nor'easter, the river level was higher than the Moderate Flood Stage (4.2 feet) for approximately 12 hours and peaked at 5.99 feet. This caused multiple feet of storm surge flooding on Strand and King Street, which extended down Union Street from Prince to Thompsons Alley. Parking garages on Union Street were flooded and there were significant impacts to businesses and private property in Old Town (The Washington Post, 2021).

In order to further understand how different river elevations correlate to predicted flooding, Carollo utilized the XPSWMM model to visualize the extent of inundation under three selected tidal levels - El. 4.2 feet, 6.6 feet, and 8.66 feet. These elevations were selected because all exceeded the existing shoreline elevations and would be expected to cause some disruption to the Core Area. These modeling exercises confirmed direct correlation between the severity of a storm surge event and resultant flooding within the Core Area. As shown in Figure 3, a higher river stage results in more flooding, and greater risk to buildings and properties. While a 4.2-foot storm surge event results in the most significant damage along the King Street intersections with Strand and Union Street, an 8.66-foot event results in substantial damage to almost all properties just east of Lee Street.

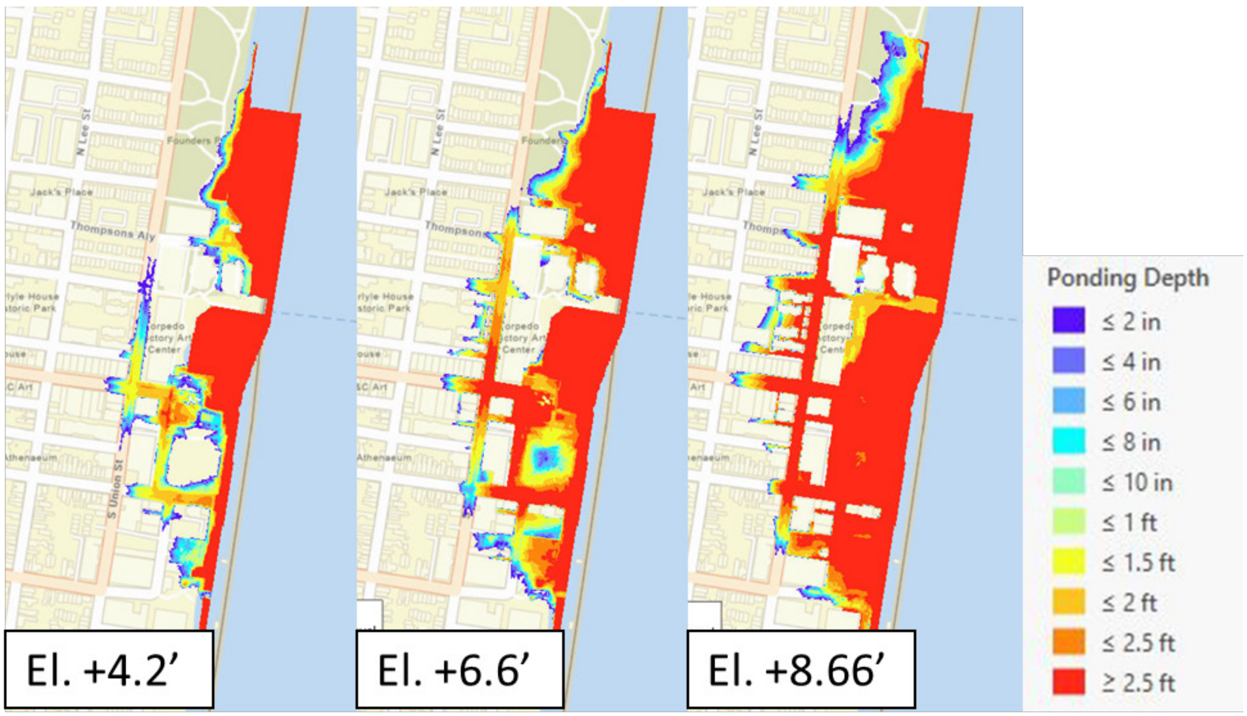

Figure 3 Predicted Flooding Under Various Flood Stages with Existing Shoreline Elevations

During a significant storm surge event, the rainfall and associated flooding due to insufficient conveyance capacity is insignificant compared to riverine flooding. This was confirmed by simulating 8.66-foot river elevations both with and without compounding design storm rainfall conditions (as defined in TM1). Figure 4 shows a similar extent and impact of flooding with over 3 feet of floodwaters under both conditions. The rainfall produces some additional flooding further upstream, in and around the Lee Street intersections, but all excess runoff is contained within the curbline.

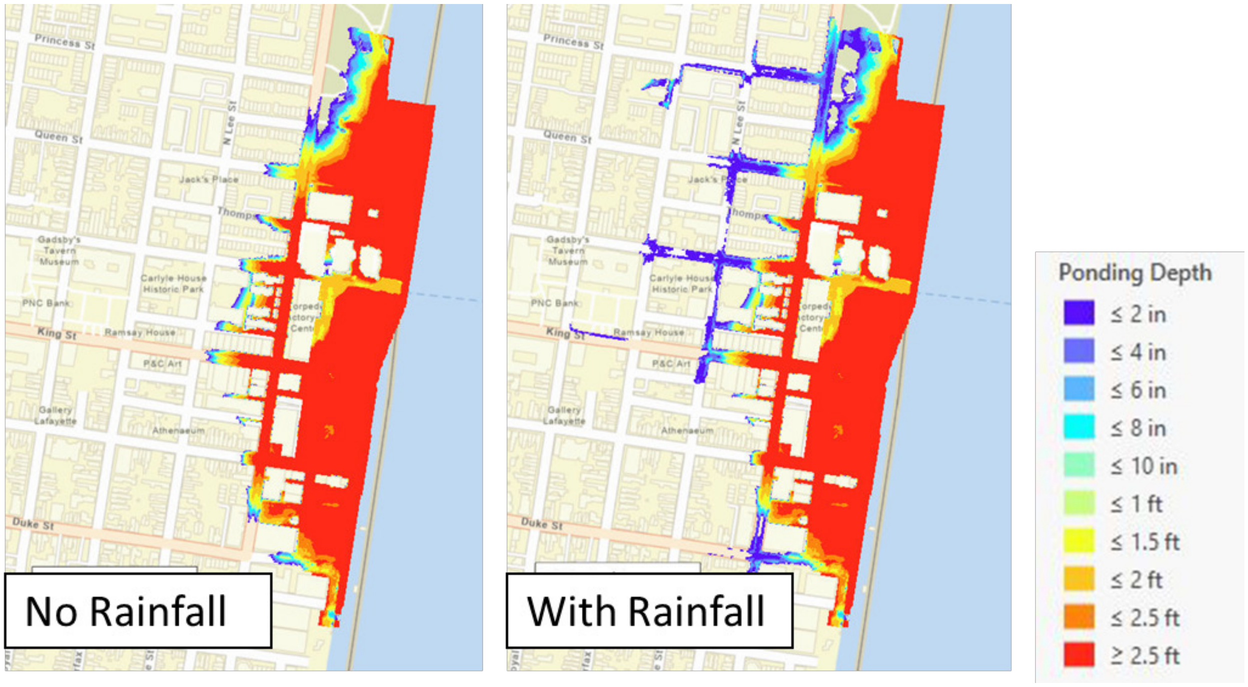

Figure 4 Predicted Flooding Under the El. +8.66ft Flood Stage with and without Design Storm Rainfall Conditions

3. Proposed Solutions

Using the historic river level analysis presented above, Carollo evaluated several proposed flood mitigation alternatives presented in the MSWMP.

To control tidal backflow flooding, the MSWMP recommends installing CheckMate in-line valves at all outfall locations as part of the Waterfront Implementation project. As the City continues to vet alternative flood mitigation solutions, available project funding, and community priorities, it was recommended that backflow prevention should be explored independent and in advance of the full project (TM5, 2022, Carollo Engineers).

To control storm surge flooding, the MSWMP recommends a new bulkhead be constructed at a 6.0-foot elevation, which represents protection to a current 10-year recurrence interval. The level of protection was developed with considerable community input and reflects the desire to balance storm surge protection with continued community access to the waterfront.

Figure 5 compares the proposed bulkhead elevation (6.0 feet, shown in green) to historic river elevations from 2004-2021. A 6.0-foot elevation bulkhead would have prevented all instances of surge flooding in the past 18 years, including the October 2021 Nor'easter, and would have been overtopped only twice in the full historical record.

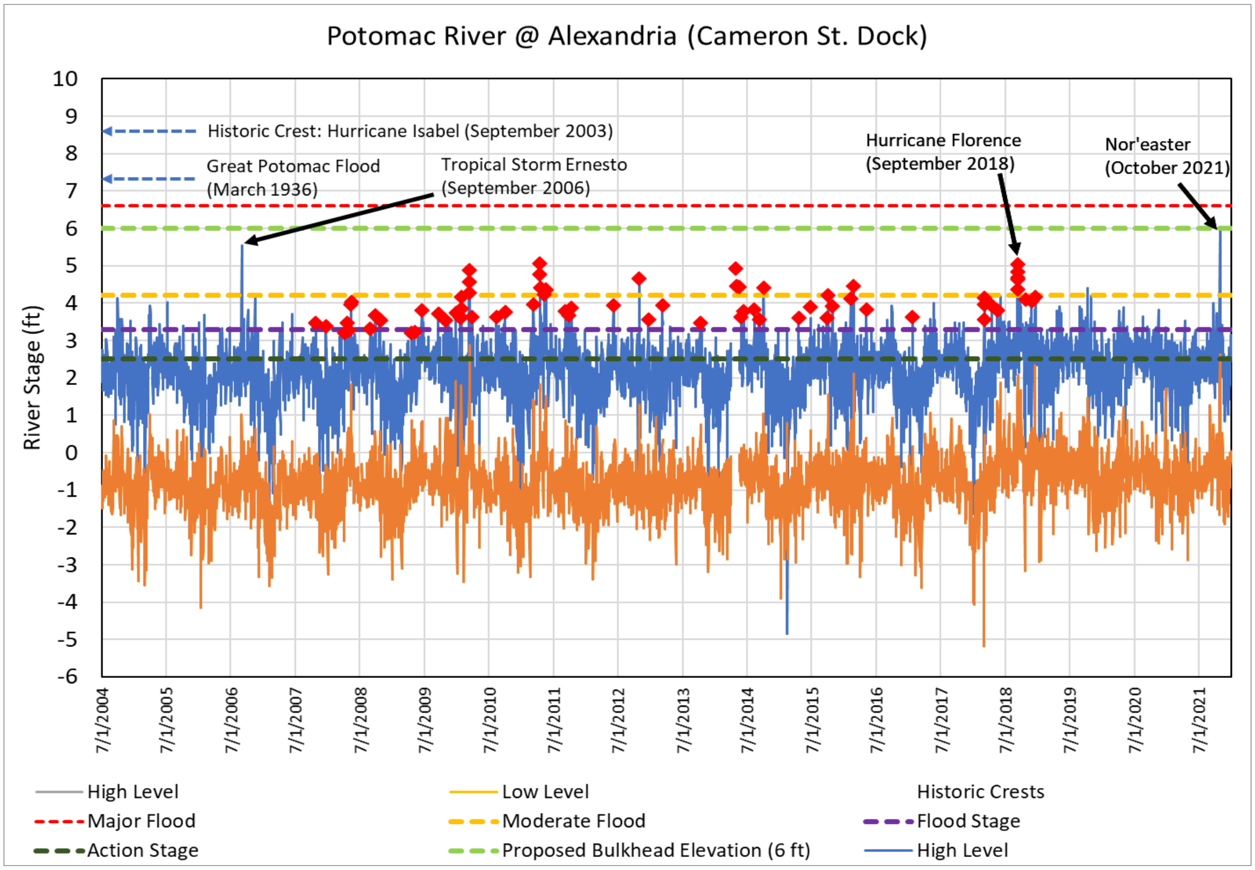

Figure 5 Potomac River Daily High and Low Levels with Proposed 6-Foot Bulkhead

Carollo performed a floodwall breach analysis to understand how the inclusion of a El. +6.0-foot bulkhead along with other flood mitigation measures would improve resiliency within the Core Area. In general, model results demonstrated that as the level of infrastructure investment increases, the resultant recovery time reduces, thus, improving overall system resilience. Figure 6 compares the recovery time at critical low-lying locations in the Core Area based on implementation of stormwater management and/or shoreline infrastructure improvements. Stormwater infrastructure includes upgraded pipe capacity and conveyance as well as two new stormwater pumping stations that are sized according to the design storm defined in TM1. Shoreline infrastructure assumes a new 6.0-foot bulkhead. Results indicate that layering stormwater infrastructure improvements with additional shoreline protection reduces recovery time by up to 50 percent.

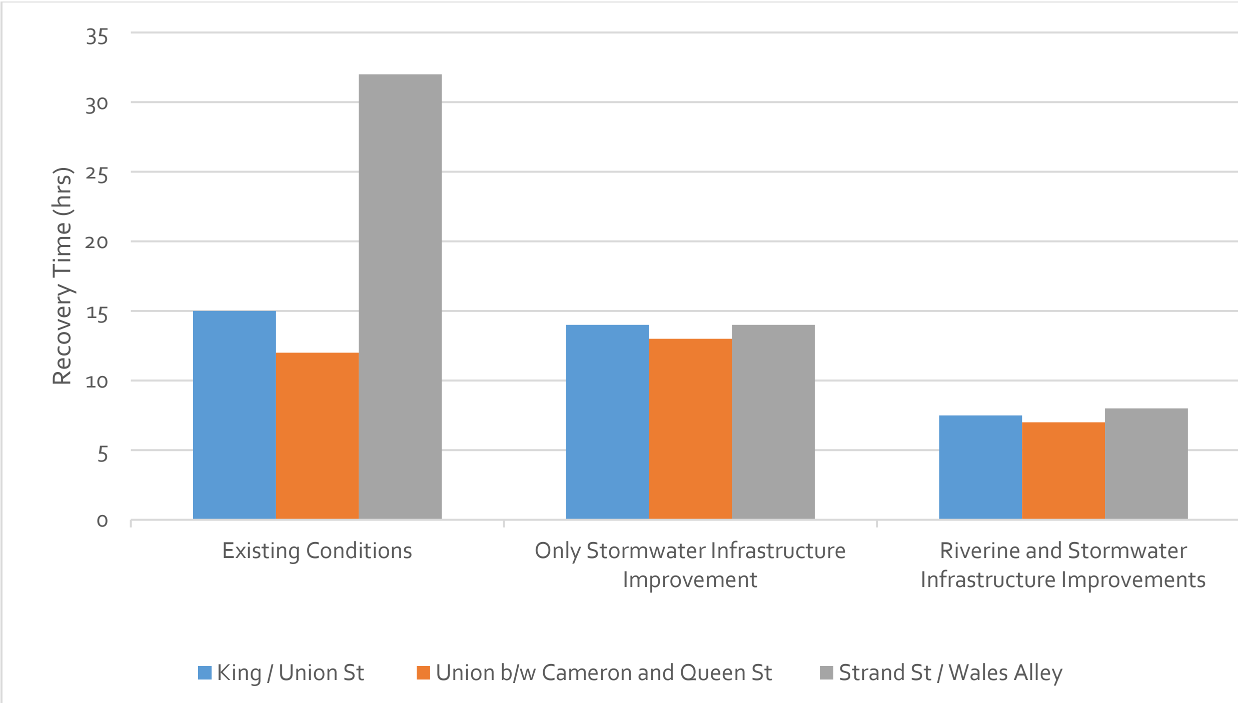

Figure 6 XPSWMM Predicted Recovery Times with El. +8.66ft Storm Surge and Design Storm Rainfall Conditions

In this proposed solution, stormwater pumps are designed to engage once river levels recede to a specific elevation below that of the shoreline infrastructure. Thus, the inclusion of a new structural bulkhead allows stormwater pumps to begin evacuating water earlier – once river elevations recede below 6.0 feet. Without the new bulkhead, the pumps will not begin evacuating water until river elevations receded below approximately 4 feet depending on the specific location and condition of existing shoreline infrastructure.

The continued use of the proposed 6.0-foot level of shoreline protection is discussed in the following section in the context of predicted sea level rise.

4. Sea Level Rise

Tidal backflow and storm surge flooding are both directly impacted by sea level rise (SLR) resulting from global climate change. Melting continental ice sheets and thermal expansion of warmer oceans have contributed to approximately a foot of SLR since 1900, and the rate of SLR is projected to further increase in the next century (NOAA, 2022).

Carollo reviewed recent reports and surveys to assess how best to plan for the effect of SLR on Potomac River levels. The Chesapeake Stormwater Network (CSN) recently completed a comprehensive literature review of regional and national climate change reports and sea level rise projections (Wood, 2020). From their review, "Sea level rise is projected to average approximately 2 feet across the Mid-Atlantic by 2100 under a mid-level emissions scenario…". This review of intermediate SLR scenarios was inclusive of the U.S. Army Corps of Engineers (USACE) 2100 Intermediate projection shown in Figure 7. All intermediate scenarios reviewed by the CSN were all in general agreement of anticipating approximately 2 additional feet of SLR by 2100.

However, other studies/scenarios project significantly higher rates of SLR for the Potomac River by the end of the century. For example, the USACE study Wood referenced also modeled almost 6 feet of SLR by 2100 in their high emissions scenario projection. As shown in Figure 7, the difference between the intermediate and high scenarios is drastic toward the end of the century.

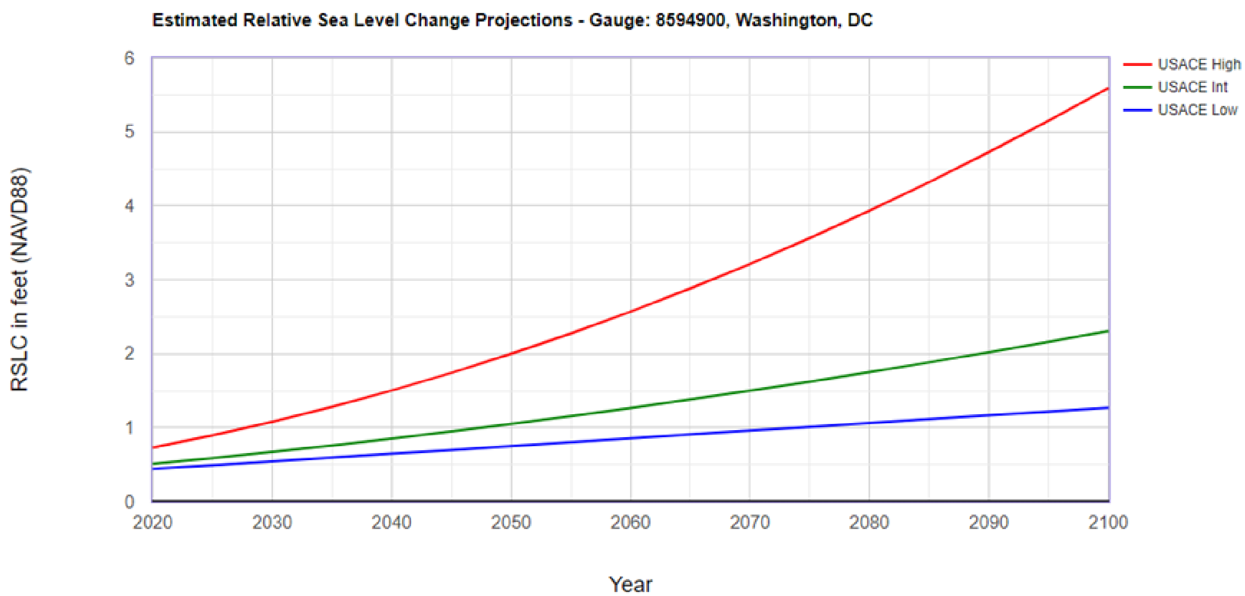

Figure 7 USACE SLR Projections at Washington DC Tide Gauge, 2020-2100

Likewise, in 2017 the National Oceanic and Atmospheric Administration (NOAA) released a study that categorized an additional 2 feet of SLR as between an "intermediate" and "intermediate-low" scenario for the greater D.C. area. That same NOAA study modeled an "Extreme" scenario that would result in 11-foot SLR by 2100, and High and Intermediate-High scenarios that would result in 9 and 7 feet SLR, respectively.

In November 2019, then-Governor Northam signed Executive Order 45, asserting "the Commonwealth shall use the National Oceanographic and Atmospheric Administration (NOAA) **Intermediate-High** scenario curve…as the state standard for predicting sea level rise" (Executive Order 45, *Floodplain Management Requirements and Planning Standards for State Agencies, Institutions, and Property).* According to the National Oceanic and Atmospheric Administration (NOAA) 2017 study, an Intermediate-High scenario correlates to about 7 feet of sea level rise in the Metro DC area by 2100. This recommendation was carried forward in various state-level master planning efforts and as recently as December 2021 was utilized as the standard for the *Virginia Coastal Resilience Master Plan*. While the executive order requires consideration of the Intermediate-High scenario for all state-owned property and projects, it does not hold municipalities to this standard. As such, the City can decide whether to consider this curve for the Waterfront Implementation Project or not. To determine the scenario most appropriate for this project specifically, it is important to first consider the causes of this uncertainty and the relative likelihood of these future SLR scenarios.

4.1. Sea Level Rise Uncertainty

The 2017 NOAA study categorized an additional 2 feet of SLR as between an "intermediate" and "intermediate-low" scenario for the greater D.C. area. That same NOAA study modeled an "Extreme" scenario that would result in 11-foot SLR by 2100, and High and Intermediate-High scenarios that would result in 9 and 7 feet SLR, respectively. The difference between a 2-, 7-, and 11-foot SLR may appear stark without proper context; however, these variations can be explained by uncertainties in SLR projections. Well-understood and accounted for, these uncertainties lead to large variabilities in any modeling effort of SLR projected out further than the mid-century. In fact, the Intergovernmental Panel on Climate Change (IPCC) recently released their sixth assessment report, which qualified their discussion on SLR projections with the following disclaimer:

> "Beyond 2050, uncertainty in climate change induced SLR [sea level rise] increases substantially due to uncertainties in emission scenarios and the associated climate changes, and the response of the Antarctic ice sheet in a warmer world," (IPCC AR6, 2021).

The main cause of SLR uncertainty stems from assumptions of glacial stability in the West Antarctic Ice Sheet (WAIS), where approximately 10 to 12 feet of SLR is currently locked up in high-risk marine glaciers. These glaciers are subjected to significant subsurface water intrusion, destabilizing them from below while they simultaneously melt from above.

The surface melt is relatively easily predicted under various emissions and warming scenarios, but the subsurface destabilization is harder to model long-term and can significantly speed up the collapse of these glaciers into the ocean. If a given study projects these WAIS glaciers will essentially completely collapse by 2100, the resulting SLR is about 10 to 12 feet, as seen in the NOAA 2017's extreme projection. Models that project a slower collapse will show the same amount of SLR by 2300 or 2400 for example, instead of 2100.

NOAA modeled the most extreme scenario possible (i.e., complete WAIS glacier collapse by 2100) while establishing their baseline (i.e., low) scenario with no significant WAIS glacier contribution to SLR. These were the only two scenarios they modeled; the High, Intermediate-High, Intermediate, and Intermediate-Low scenarios in this study are linear steps in between the Low scenario and Extreme scenario and are not modeled results.

In the 2022 update to this study, NOAA clarified that the more extreme scenarios represent "low probability, high impact" scenarios that merit inclusion because they cannot be ruled out. The various NOAA scenarios are intended to consider the full range of potential future sea level rise scenarios, and mainly reflect the uncertainty in WAIS glacier response, rather than different emissions or warming scenarios. **Thus, the sea level rise projected by 2100 in the Extreme, High, and Intermediate-High scenarios is significantly less likely to occur than the SLR projected in the Low, Intermediate-Low or Intermediate scenarios.**

Given the array of flooding issues requiring mitigation in Old Town, and the limited budget available for this project, Carollo does not recommend building extreme shoreline fortifications to protect to these future low probability scenarios. **As such, Carollo does not recommend using the state-endorsed NOAA Intermediate-High scenario or the other NOAA 2017/2022 long-term scenarios** in design considerations for the Waterfront Implementation project's immediate planning efforts. The primary reasons for this are summarized as follows:

- The higher NOAA scenarios represent complete or near-complete West Antarctic glacial collapse in the next 80 years – a possible scenario but certainly not the expected scenario.
- The scenarios are relatively arbitrary when the modeled extreme or baseline scenarios are not employed.
- Adapting these extreme scenarios to today's decision-making for the Waterfront Implementation Project would not lead to smart investment decisions considering the limited budget available.

Considering the wide variability of modeled scenarios and the understood uncertainties in long-term SLR projections, Carollo recommends considering an additional 2 feet of sea level rise in development of this project. This is in line with NOAA, USACE and other projections for the most likely sea level rise scenario given current emissions trends and no significant changes to the expected stability of the WAIS.

Considering an additional 2-feet SLR will ensure the Waterfront Implementation Project protects against the most regular tidal conditions through 2050, by which time it should be clear from the observed sea level rise trend whether this 2-foot projection will be exceeded by the end of the century.

This guidance should only be applied to the Waterfront Implementation Project at this current time and should not be taken as City-wide guidance or be used in the future without a re-evaluation of the most up-to-date data and projections at that time. SLR projections will continuously be updated and refined; as such, the City can and should re-evaluate the need for more drastic sea-level control whenever new investments are being made in waterfront areas.

5. Implications of Sea Level Rise

Adding 2 feet SLR to the Potomac River suggests the future MHHW would be 4.19 feet (when starting with the effective MHHW shown in Section 2). Figure 8 shows this projected future MHHW compared to the 6.0 elevation level of protection and low-lying stormwater infrastructure in Old Town.

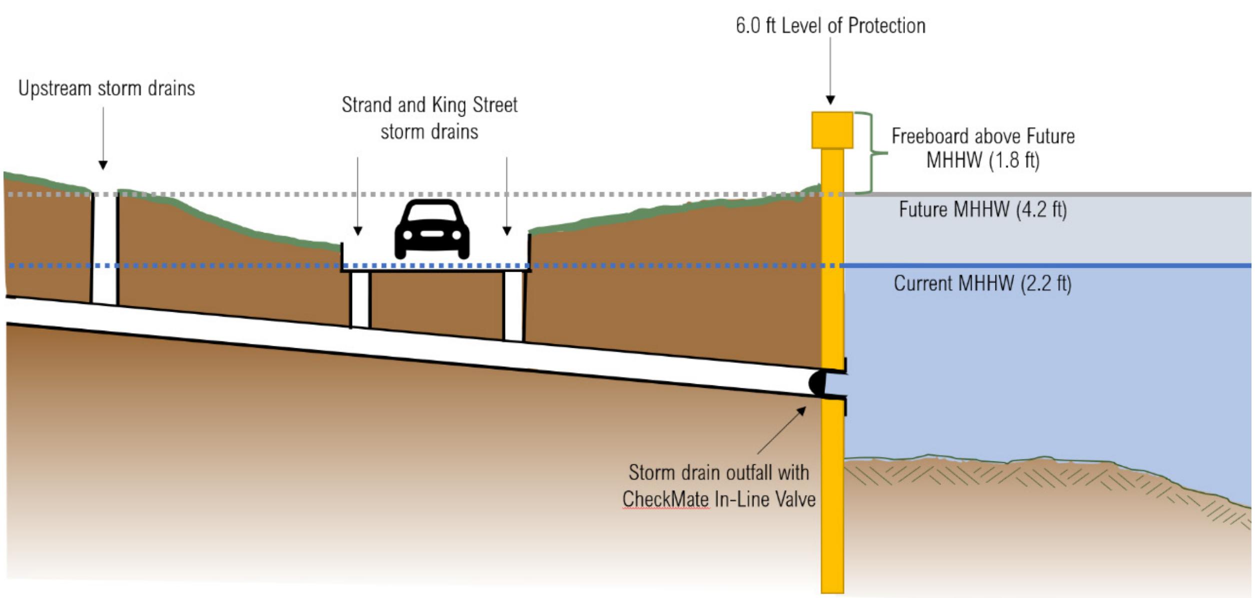

Figure 8 Impacts of Sea Level Rise on MHHW

The MSWMP's recommendation of shoreline protection at 6.0-foot elevation represents protection to a current 10-year recurrence interval surge event. With the addition of 2 feet SLR, this level of shoreline protection will not protect to a future 10-year surge event. Adding 2 feet of sea level rise results in 1.8 feet of freeboard to protect from storm surge over MHHW. Analysis of the last 17 years of data at the Cameron St Dock tide gauge suggests that surge may exceed 1.8 feet above MHHW approximately 2 times per year. However, as previously discussed in this memo, most of the surge events in the historical record are short-duration, low-elevation incidents that do not have significant community impacts. Investment in both stormwater and shoreline protection will enable the City to recover more quickly in comparison to existing conditions.

Budget limitations will necessitate changes from the MSWMP. There is not enough funding available to construct an entirely new bulkhead, meaning the project will rely on shorter-term shoreline protection to supplement the existing bulkhead while deferring bulkhead maintenance to a later time. Considering this, Carollo maintains the recommended 6.0-foot elevation is appropriate, providing robust protection in the short term and delaying the need for more expensive bulkhead replacements. Should more funding become available, the design-builder should consider bulkhead replacements and building to a higher elevation to protect to future 10-year recurrence interval storms.

6. Conclusions & Recommendations

Based on the evaluation presented, the following are recommended:

- Gates or valves such as the ones under consideration for this project will provide protection against the more frequent tidal backflow flooding that occurs when the Potomac River backs up through the storm sewers and spill out of storm inlets.
- Given the current funding reality, a complete bulkhead replacement is not feasible; therefore, riverine protection will likely focus on landscape-based solutions with little to no bulkhead repair or reconstruction. Recognizing this infrastructure will likely serve as an intermediate step to a full bulkhead reconstruction, the recommended shoreline protection level of 6.0 feet is sufficient.
  - The existing data on Potomac River levels indicate that the proposed protection elevation of 6 feet would have been exceeded twice since 1936 (84 years).
  - Mid-Atlantic SLR is projected to average approximately two feet by 2100 (most likely sea level rise scenario given current emissions trends). There are well-understood uncertainties that result in significantly higher rates of SLR, however these are low-probability scenarios and would not become apparent until at least 2050. The 6-foot level of protection should sufficiently protect against the most regular tidal conditions through 2050, inclusive of sea level rise.
  - SLR projections beyond 2050 contain large uncertainties and will be refined in the coming decades; when funding becomes available, the City can consider comprehensive bulkhead replacements, at which point they should assess the need for higher elevation protection, such as protection to a future 10-yr storm event inclusive of sea level rise.
- In event that the shoreline is overtopped, or breached, the rainfall and associated flooding due to insufficient conveyance capacity is insignificant compared to shoreline flooding. During a breach event, the benefits of flood protection investment can be quantified by recovery time. It is recommended to invest in both stormwater and shoreline infrastructure improvements to reduce the overall recovery time to the maximum extent practicable, and thus, improve overall resilience.

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