City of Alexandria, Virginia
Waterfront Implementation

Technical Memorandum 1
DESIGN STORM SELECTION FOR HYDROLOGIC AND HYDRAULIC MODELING

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Abbreviations

Carollo	Carollo Engineers
CASSCA	City of Alexandria Storm Sewer Capacity Analysis
CSN	Chesapeake Stormwater Network
City	City of Alexandria
IDF	intensity-duration-frequency
in/hr	inches per hour
mgd	million gallons per day
MARISA	Mid-Atlantic Regional Integrated Sciences and Assessments
MSWMP	Master Storm Water Management Plan
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NVRC	Northern Virginia Regional Commission
NWS	National Weather Service
Tc	time of concentration
VDEQ	Virginia Department of Environmental Quality
VSMH	Virginia Stormwater Management Handbook

Technical Memorandum 1

DESIGN STORM SELECTION FOR HYDROLOGIC AND HYDRAULIC MODELING

1 Executive Summary

The design storm is a critical planning factor for evaluating stormwater system performance and determining infrastructure sizing. This memorandum documents the results of the design storm analysis for the Waterfront Implementation Project and recommends a design storm for use in both evaluating existing system performance and sizing future stormwater system upgrades in Old Town. The design storm's parameters (particularly total volume and peak rainfall intensity) are also assessed to balance existing rainfall patterns with projected climate change and the City of Alexandria (City)'s desire to reduce waterfront flooding to the maximum extent practicable. Based on the analysis presented in the subsequent sections, the following are recommended:

- Continue the use of the 10-year storm as outlined in the 2018 Master Storm Water Management Plan (MSWMP, Stantec) with a peak design rainfall intensity of 9.0 inches per hour based on the City intensity-duration-frequency (IDF) curves. The selected design storm adequately addresses future climate change impacts and will result in facility sizing that will reduce stormwater-related flooding to the maximum extent practicable.
- The 2-hour storm duration should be used to evaluate the sizing of required flood control facilities (storm conveyance, pump stations, and storage chambers). Model simulations with longer storm durations result in increased peak flows to the proposed pump stations. However, no increase in pump station size is necessary or recommended as a result.
- As is standard design practice, the use of real storm events and long-term simulations on the selected alternative are recommended to confirm the operation of any proposed storage against a range of storm durations and intensities.

These recommendations provide an analytical basis that is consistent with other City studies and a factor of safety against future storms that may be of higher intensity and/or frequency. It is also recommended to incorporate routine checks using more current information and climate model results to confirm that these design guidelines appropriately account for climate change effects.

2 Purpose

A critical planning factor for stormwater systems is the design storm for evaluating system performance and infrastructure sizing. Prior stormwater planning documents developed for the City of Alexandria were reviewed for guidance, including:

- 1989 City of Alexandria Design and Construction Standards (City of Alexandria).
- 2011 Rainfall Frequency and Global Change Model Options for the City of Alexandria, Virginia (CH2M Hill).
- 2016 City of Alexandria Storm Sewer Capacity Analysis (CASSCA, CH2M Hill) and associated technical memoranda.

- 2018 Master Storm Water Management Plan (MSWMP, Stantec).

This memorandum documents the results of this review and recommends a design storm for use in evaluating existing system performance as well as the current project alternative (see Figure 1). This memorandum also documents the results of sensitivity analyses conducted on the existing system and the current project alternative to confirm the recommended design storm.

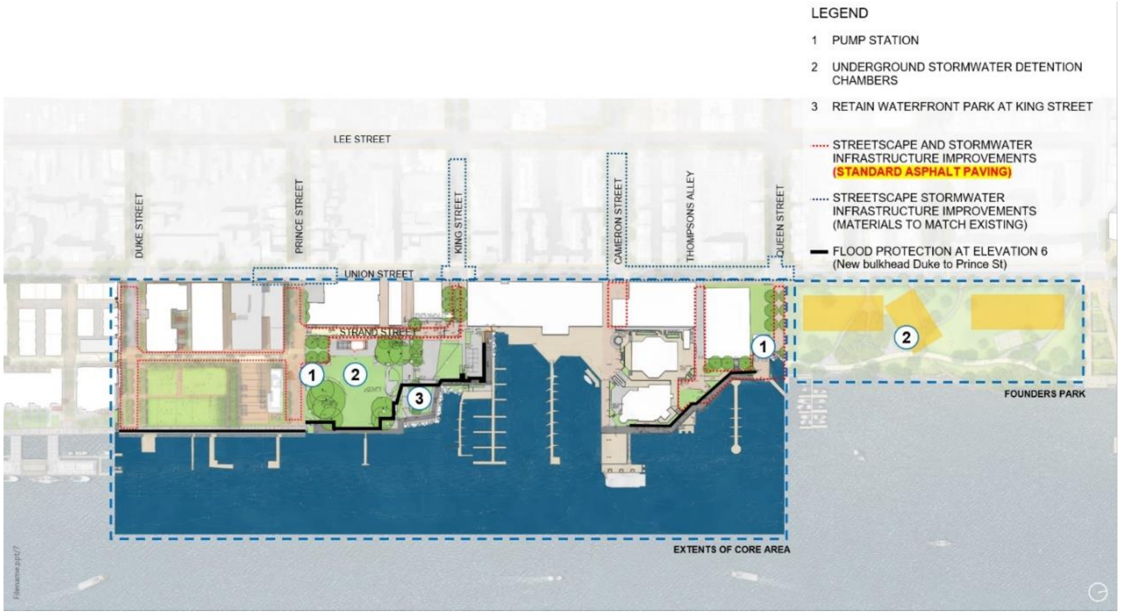

Figure 1 Current Project Alternative for Mitigating Flood in the Waterfront Core Area

3 Design Storm Selection

This section summarizes the selection of the peak intensity, storm event duration, and storm hyetograph. Together, these parameters define the design storm selected for evaluating performance of the existing system and the current project alternative. The design storm parameters (particularly total volume and peak rainfall intensity) were selected to balance existing rainfall patterns with projected climate change and the City's desire to reduce waterfront flooding to the maximum extent practicable. This evaluation uses the 10-year storm as the basis for storm event intensity and volume selection. The 10-year storm was selected as the basis of design in the MSWMP and is consistent with the Virginia Stormwater Management Handbook (VSMH, Draft, 2013) for protection against frequent flooding.

3.1 Peak Rainfall Intensity

Peak rainfall intensity is the critical factor that influences the required size of peak stormwater flow infrastructure such as pipes and pump stations. Peak rainfall intensity is driven by the time of concentration (Tc), which in heavily urbanized areas such as Alexandria can be as short as 5 to 15 minutes and therefore results in relatively high instantaneous rainfall intensities. Once the Tc is determined, available IDF curves provide the intensity in inches per hour (in/hr) for use in the design storm.

The CASSCA report and the MSWMP were reviewed to provide guidance on selection of Tc. The CASSCA study evaluated the performance of the large storm sewers (24 inches and greater) under various storm conditions. That study recommended a Tc of 15 minutes based on Tc computation for several inlets in the Hooffs Run pilot subwatershed and the Four Mile Run priority watershed. These watersheds include many large subwatersheds that are more residential and for which a longer Tc would be appropriate.

The MSWMP applied the Rational Method for facility sizing, which is consistent with standard industry practices and those recommended by the Virginia Stormwater Management Handbook (VDEQ, 2013) for individual land development projects and generally much smaller catchments to individual storm inlets. The selected time of concentration for the MSWMP was 5 minutes, which is a standard assumption for small urban watersheds.

The Waterfront Core Area is relatively small and more urban in comparison to the watersheds modeled in the CASSCA study. Therefore, we recommend proceeding with the 5-minute Tc consistent with the MSMWP.

Both the MSWMP and CASSCA then relied upon the City's IDF curves (1989, City of Alexandria) to select a peak rainfall intensity and develop a synthetic rainfall distribution (design hyetograph). As shown in Table 1, peak rainfall intensities according to the City IDF curves are generally more conservative than the more recent National Oceanic and Atmospheric Administration (NOAA) Atlas 14 IDF curves. Table 1 compares rainfall intensity using the City and NOAA Atlas 14 IDF curves for 5-minute storms (assumed for sizing in the MSWMP). As shown, rainfall intensities based on the City IDF curves range from almost 10 percent higher for the 1-year storm to over 50 percent higher for the 100-year storm compared to rainfall intensities using the NOAA Atlas 14 estimates. This is consistent with the CASSCA study, which in comparing the City's IDF curves with those from the region found that "For the 2-, 10-, and 100-year storms from 5 to 60 minutes Tc, Alexandria uses a significantly higher intensity for design (approximately 30 percent higher) than all the neighboring jurisdictions for these short durations," (CH2MHill, 2016; page 2-1).

Table 1 Comparison of Peak Rainfall Intensities using City of Alexandria and NOAA Atlas-14 IDF Curves

Recurrence Interval (year)	Rainfall Intensity (inches / hour)	
	City IDF Curve	NOAA Atlas 14 IDF Curve
1	4.60	4.28
2	6.20	5.12
5	8.10	6.10
10	9.00	6.80
25	10.80	7.72
50	12.50	8.39
100	13.80	9.05
500	-	10.50
1000	-	11.20

Notes:
(1) Adapted from 2018 Master Storm Water Management Plan (Stantec).

The effect of climate change was also reviewed to determine the appropriate peak intensity. A 2011 report entitled, "Rainfall Frequency and Global Change Model Options for the City of Alexandria, Virginia" (CH2M Hill) evaluated the potential effect of climate change on rainfall patterns within the City. The SimCLIM modeling application was used to create new IDF curves for Alexandria based on historical rainfall data collected at five local rainfall recording stations. The effects of climate change were then simulated by applying 12 daily general circulation models with low, medium, and high greenhouse gas emissions to predict future rainfall intensity and frequency.

Table 2 shows the 10-year and 100-year recurrence interval, 5-minute duration peak rainfall intensities using the City IDF curve, the NOAA Atlas 14 IDF curve, and the SimCLIM predicted IDF curve (1945-2010) with projections for Years 2050 and 2100. The predicted SimCLIM results reflect the average of the low, medium, and high emissions scenarios that were simulated.

Table 2 Projected Rainfall Intensities Due to Climate Change

IDF Curve	Intensity (inches / hour) for 10-year, 5-minute storm	Intensity (inches / hour) for 100-year, 5-minute storm
City of Alexandria (1989)	9.00	13.80
NOAA Atlas 14	6.80	9.05
SimCLIM (1945-2010)	7.08	9.07
SimCLIM 2050	7.38	9.58
SimCLIM 2100	7.67	10.09

Notes:

(1) Adapted from 2011 Rainfall Frequency and Global Change Model Options for the City of Alexandria, Virginia (CH2M Hill) and 2018 Master Storm Water Management Plan (Stantec), Table 4 (10-year Storm) and Table 5 (100-year Storm). Values presented represent the average of low, medium, and high emissions scenarios.

The 2011 report predicts that for both years 2050 and 2100, storms under 12 hours duration at the 10-year recurrence interval will have lower rainfall intensities than the design storm selected in the MSWMP. In fact, a 10-year storm using the City IDF curves (9.00 in/hr for a 5-minute duration) is nearly as intense as the SimCLIM modeled 100-year storm (1945-2010, 9.07 in/hour for a 5-minute duration).

Since 2011, global and regional climate models have been updated. The Chesapeake Stormwater Network (CSN) recently completed a comprehensive review of regional and national climate change reports and sea level rise projections (Wood, 2020). The CSN Report indicates that precipitation intensity is expected to increase by 5 to 35 percent by the middle of the century under a high-end emissions scenario. These projections also indicate that more frequent storms (lower recurrence interval) are expected to intensify more than less frequent storms (higher recurrence internal), and that longer-duration events (generally 12 hours or greater) will intensify more than shorter-duration events. The 9.0 in/hr peak rainfall intensity recommended by the MSWMP is at the high end of projected increases from the various studies summarized in the 2020 CSN Report.

Based on this review, it is recommended that the City use a 5-minute Tc and a design storm peak rainfall intensity of 9.0 in/hr. These design storm conditions correspond to a 10-year recurrence interval according to the City IDF curves; are more intense than the 10-year storm predicted for 2100 by the 2011 SimCLIM model; and are just as intense as the 100-year storm according to Atlas 14. Doing so will result in a more robust system design and provide more conservative facility sizing that will reduce stormwater-related flooding to the maximum extent practicable.

It should be noted that the effects of climate change continue to evolve as newer data is collected and global climate models are refined. Regional and local IDF curves currently being reviewed and updated through the Northern Virginia Regional Commission (NVRC). As these efforts are completed, the City should evaluate the City's IDF curves against the updated predictions to determine if any changes would be warranted based on more recent climate models.

3.2 Design Storm Hyetograph and Storm Event Duration

In order to apply the above criteria to the City of Alexandria's dynamic stormwater model, a synthetic, temporal rainfall distribution (design storm hyetograph) is required. The design storm hyetograph was based on the Natural Resources Conservation Service (NRCS) Type II distribution. This distribution yields maximum rainfall intensity at the approximate center of the 24-hour and 2-hour storms. The distribution was modified so that the simulated peak intensity for each duration storm equals 9.0 in/hr based on the City IDF curves. This approach for developing the hyetograph was similar to that used for the CASSCA study.

To evaluate the critical duration for facility sizing, 24-hour and 2-hour design storm hyetographs were developed. Use of the 24-hour storm duration is widely accepted as standard practice for system-wide storm capacity planning; it is also the duration used in the CASSCA studies. A 2-hour storm duration was also evaluated as it is more representative of the frequently occurring storms that have been characterized as causing "nuisance flooding" within the Core Area. Based on long-term statistics at the National Airport National Weather Service (NWS) gauge, storms of 2-hour duration or less represent approximately 40 percent of the storms that occur in any given year.

The City IDF curves report consistently higher storm intensities for all storm durations compared to other regional IDF curves[1] and exceed regional climate change models (as further discussed in Section 1.4.2). Because proposed infrastructure sizing is predominantly determined by the design storm peak intensity, this parameter warrants the most conservatism. Compounding a high peak rainfall intensity with comparatively higher storm depths could result in overdesign of stormwater management infrastructure. Overdesign of the stormwater infrastructure includes excess pump station capacity and/or pipe sizes that result in increased project and operational costs without substantial benefit. With this in mind, we initially selected a hybrid design storm with a more conservative peak intensity (from the City IDF curve) and lower total volume (from NOAA Atlas 14) as the basis of comparison for a sensitivity analysis.

Table 3 compares the modeled peak intensities for the 10-yr 24-hour and 2-hour design storms. Figure 2 presents the modeled 10-year 24-hour and 2-hour storm hyetographs.

Table 3 10-Year 24-Hour and 2-Hour Design Storm Comparison

Storm	24-hour Storm		2-hour Storm	
	Peak Intensity (in/hr)(1)	Total Depth (inches)(2)	Peak Intensity (in/hr)(1)	Total Depth (inches)(2)
10-year design storm	9.0	4.76	9.0	2.53

Notes:
(1) Based on City IDF Curves (1989, City of Alexandria).
(2) Based on Atlas 14 IDF Curves (2006, NOAA).

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[1] Comparison of Alexandria's Storm Design Criteria to Neighboring Jurisdictions (2009, CH2M Hill).

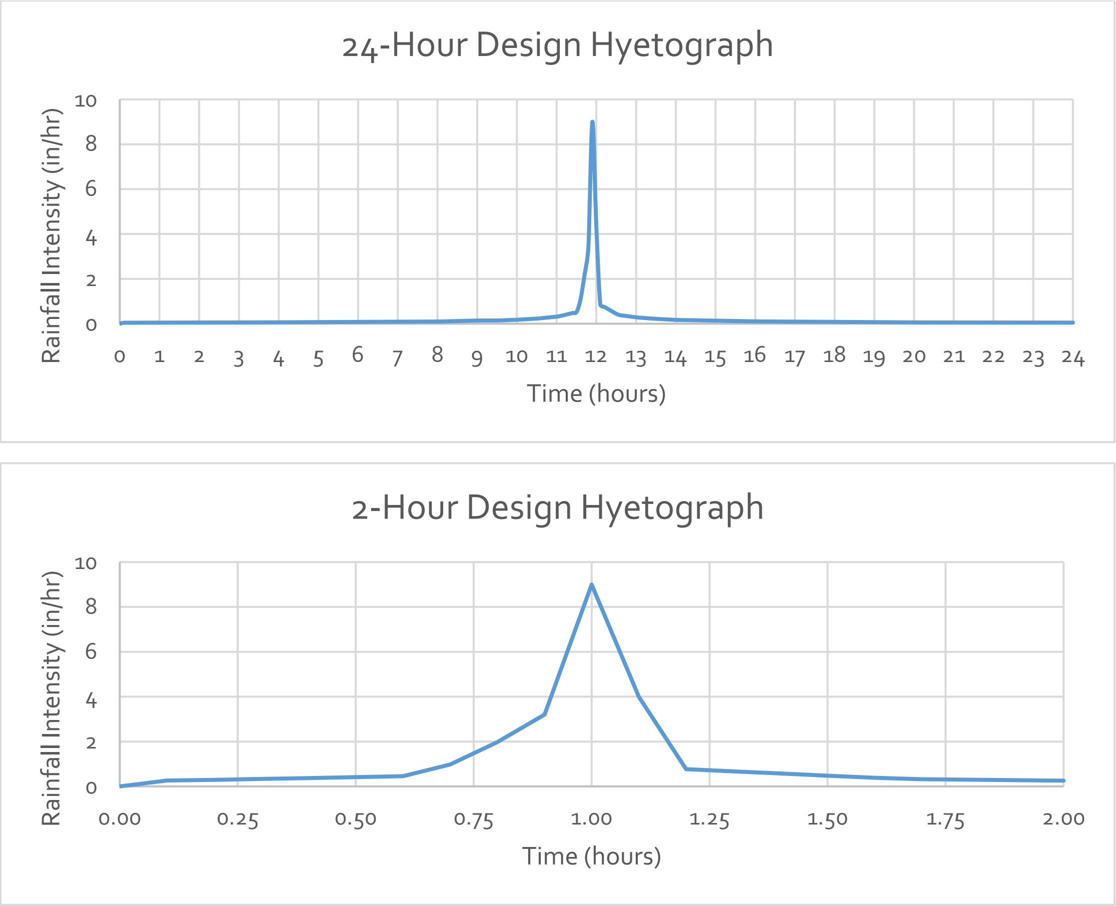

Figure 2 Design Storm Hyetographs for 10-year 24-hr and 2-hr Storms

4 Sensitivity Analyses

The XPSWMM model developed for the CASSCA study and modified for this project was applied to evaluate the sensitivity of the system to the design storm conditions, in particular storm duration and storm volume. Using the model, existing conditions (without stormwater improvements) and the current project alternative, as described in Figure 1, were evaluated under various design storms. The results of these evaluations were used to inform the selection of the design storm criteria.

4.1 Storm Duration

Using the two design storm hyetographs presented in Figure 2, the sensitivity of the existing City storm system was evaluated to determine an appropriate duration storm for sizing proposed facilities. Figure 3 presents model predicted flooding for the 24-hour and 2-hour design storms under various tide conditions (average low tide, average high tide, and high tide) as well as various outfall conditions (with and without proposed tide gates).

Using observed Potomac River level data from July 2004 through September 2020, the following average daily low-, average daily high-, and highwater elevations were estimated (elevations in North American Vertical Datum of 1988 [NAVD 88]) and applied as boundary conditions in the model:

- Average daily high water = 2.19 feet.
- Average daily low water = -0.83 feet.
- High water = 3.6 feet.

Further details on tide conditions are presented in Technical Memorandum #2 "Potomac River Flood Frequency Analysis" (2022, Carollo Engineers). In addition, the effect of the presence of tide gates on the stormwater outfalls was evaluated in this sensitivity analysis.

As expected, model predicted surface ponding increases with simulated tidal boundary (i.e., high tide conditions result in the largest predicted surface ponding volumes). More relevant to the selection of the design storm, however, the results indicate that the 24-hour storm results in slightly higher predicted ponding volumes (generally about 10 percent higher). However, model predicted peak flows (which drive the sizing of storm conveyance and pumping facilities) do not change significantly because the 2-hr and 24-hr storms both have the same peak 5-minute intensity (9.0 in/hr).

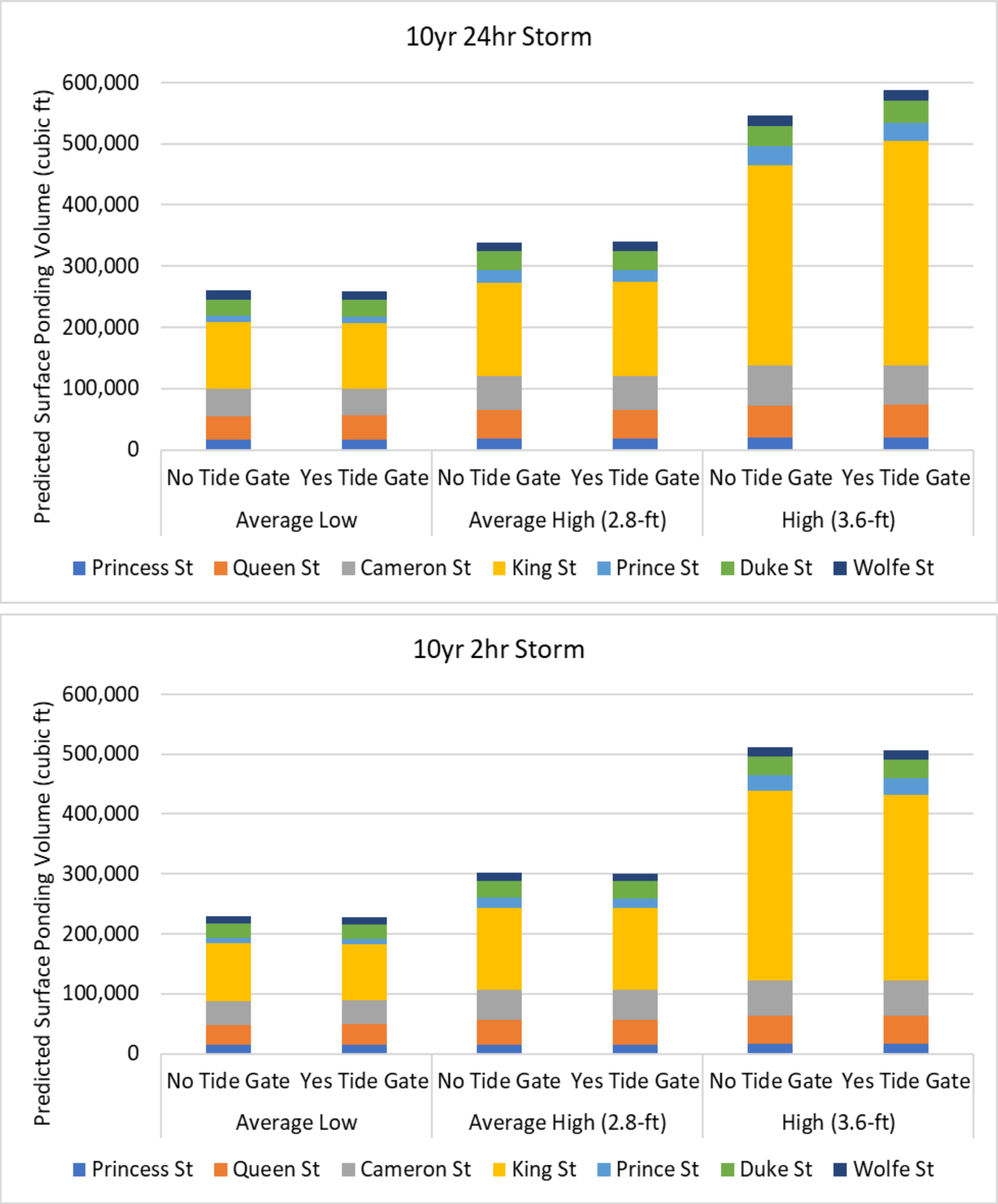

Figure 3 Predicted Surface Ponding During 24-hour and 2-hour Design Storm Conditions

4.2 Storm Event Volume

The original design storm hyetographs were developed to support the evaluation of stormwater conveyance and pump stations (i.e., the "No Storage" alternative). The critical design parameter for this infrastructure is peak flow, which is controlled primarily by the peak rainfall intensity rather than the stormwater volume.

As the project evolved, underground storage was identified as a potential enhancement to the flood mitigation solution, along with improved conveyance and stormwater pumping. The project alternative shown in Figure 1 maximizes the extent and capacity of the proposed underground stormwater detention chambers given existing site constraints. These chambers help manage stormwater by detaining a volume of water equal to the capacity of the chambers, thus reducing the peak flow to the two pump stations. Because the total capacity of the detention chambers was limited by site conditions, it was important to consider the storm event volume, not just the storm peak intensity, to size downstream stormwater infrastructure for this project alternative.

With underground storage under consideration and to address additional comments from the City, additional 10-year, 2-hour and 10-year, 24-hour design storm hyetographs were developed to reflect higher storm volumes associated with climate change. The current project alternative and the No Storage alternative were evaluated using these new storms to determine the potential effect on pump station sizing, predicted ponding at key intersections, operations of the two proposed pump stations.

4.2.1 Storm Event Volume Selection

To determine the appropriate volume, City IDF curves were reviewed as well recently published rainfall projections by the Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) Program that account for effects of climate change, as documented in "Projected Intensity-Duration-Frequency Curve Tool for the Chesapeake Bay Watershed and Virginia" (MARISA, 2021).

Figure 4 shows the MARISA report's rainfall depths projected out to the year 2070 (50-year projections) and 2100 (80-year projections) for 10-year, 5-minute and 10-year, 2-hour storms under low and high emissions scenarios. The solid red line on the chart on the left (5-minute duration storm) compares these depths to the City IDF curve 5-minute depth (0.75 inches, or 9.0 inches/hour). The solid red line on the chart on the right compares the MARISA projections for a 2-hour storm to the City IDF curve 2-hour depth (3.10 inches). The dashed red line on the chart on the right compares the MARISA projections for a 2-hour storm to the NOAA Atlas 14 2-hour storm currently used as the design storm depth for the alternative evaluations.

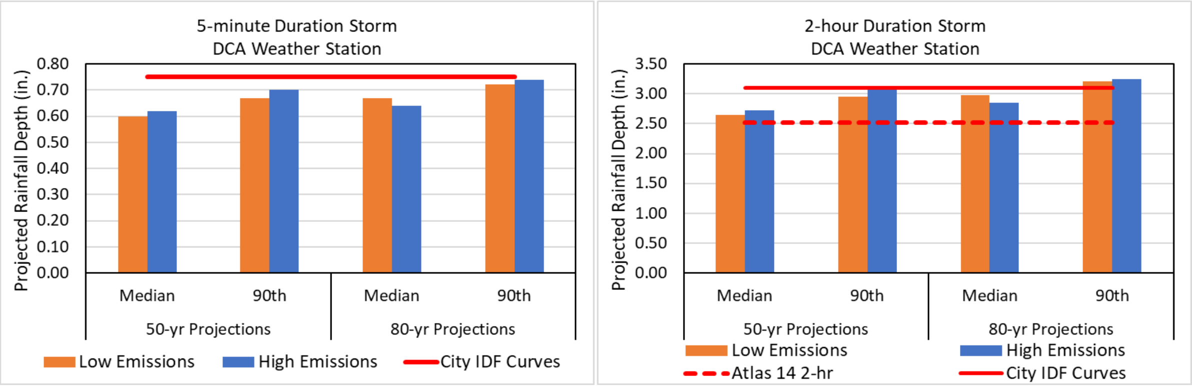

Figure 4 Comparison of MARISA Projected Rainfall Depths for Different Emissions Scenarios for the 10-year, 5-minute and 10-year, 2-hour Duration

As shown on the left, the 5-minute duration peak intensity based on the City's IDF curves (recommended for use earlier in this analysis) exceeds the MARISA projections under all emissions scenarios. As shown on the right, the volume for the 2-hour design storm using the City's IDF curves exceeds the predicted MARISA 2-hour storm volumes for the 80-year projections assuming median high emissions. The Atlas 14 volumes (recommended for use earlier in this analysis), however, are 8 percent to 26 percent less than the predicted MARISA 2-hour storm volumes under all scenarios for the 50-year and 80-year projections.

Table 4 compares the City IDF, Atlas 14, and MARISA projections for the 10-year, 2-hour and the 10-year, 24-hour storms. The 10-year 24-hour Atlas 14 storm volume is lower than the projected volumes for all future climate scenarios. The NOAA Atas 14 24-hour depth is 4.76 inches, while the MARISA projections estimate a median depth of 5.62 inches by for the 80-year projections under the low emissions scenario[2]. The MARISA predicted 10-year 24-hour storm depth is also greater than 10-year 24-hour storm depths estimated using the City's IDF curve, which showed a depth of 5.04 inches. Based on this evaluation, the team conducted sensitivity analysis on the highest total depth datasets for a 24-hour and 2-hour extreme storm event (5.62 inches and 3.10 inches respectively).

Table 4 Additional 10-Year 24-Hour and 2-Hour Design Storm Comparison

Storm	24-hour Storm		2-hour Storm	
	Peak Intensity (in/hr)	Total Depth (inches)	Peak Intensity (in/hr)	Total Depth (inches)
10 year (City)	9.0	5.04	9.0	3.10
10 year (Atlas 14)	6.8	4.76	6.8	2.53
10 year (MARISA)	7.7	5.62[1,3]	7.7	2.85[2]

Notes:
(1) Median 2050-2100 Low Emissions Scenario.
(2) Median 2050-2100 High Emissions Scenario.
(3) For the 10-year 24-hour storm, the MARISA model projects a greater storm volume under the low emissions scenario (5.62 inches) than under the high emissions scenario (5.38 inches).

The two additional storms were selected to reflect the most conservative 2-hour and 24-hour design storms given the information presented in Table 4. For consistency with the original model runs, the 5-minute peak intensity for the design storm hyetograph was set to 9.0 in/hr and to occur at the approximate center of the storm. The remainder of the hyetograph was developed using the most conservative (highest) volume and the NRCS Type II temporal distribution. The following additional storms were simulated:

- 2-hour storm: 10-year, 2-hour storm using a total depth of 3.10 inches and peak intensity of 9.0 inches/hour, both from the City IDF curves.
- 24-hour storm: 10-year, 24-hour storm using the MARISA 80-year median emissions scenario projected depth of 5.62 inches and peak intensity of 9.0 inches/hour from the City IDF curves.

In all three scenarios, the Olin Grading Plan was incorporated into the XPSWMM to reflect the higher grades along Strand Street. Additionally, the stormwater conveyance remained the same to analyze the impact of pump station sizing and system operations.

4.2.2 Storm Event Volume Evaluation

Using these two additional storms, the performance of both the current project alternative (as described in Figure 1) and the No Storage alternative (without underground storage chambers) was evaluated. The

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[2] For the 10-year 24-hour storm, the MARISA model projects a greater storm volume under the low emissions scenario (5.62 inches) than under the high emissions scenario (5.38 inches).

performance was compared against the specified level of service (LOS) established by the City of Alexandria in the MSWMP:

> "The City of Alexandria experiences frequent flooding from heavy rainfall... [with] the King Street intersections with Strand Street and North Union Street [as] low points in the waterfront area, which see flooding even during small storm events... [such that] the Flood Mitigation Implementation will reduce the common nuisance flooding that affects the area" (Stantec, 2016; page 1-1).

Building off of this, the following level of service was established based on discussions with City Staff during hydraulic modeling efforts:

- First, the storms being simulated are significantly more intense than the storms that frequently cause flooding currently. Infrastructure improvements that can manage these more intense simulated storms will effectively manage the smaller storms that currently cause frequent nuisance flooding in Old Town.
- Second, stormwater investments are targeted to reduce waterfront flooding to the maximum extent practicable, and therefore, flooding will not be eliminated under all scenarios including the design storm. Under design storm conditions it is understood that some residual flooding will be present for a short period of time. This residual flooding typically remains below the curbline with a total depth less than five inches and is removed in less than two hours once the stormwater conveyance system has capacity. XPSWMM results to date demonstrate that the residual ponding at the King Street intersections with Strand Street and North Union Street are generally the result of upstream areas of the stormwater network that are not improved under this project.
- Finally, the extent of disruption at the King Street intersections with Strand Street and North Union Street is an appropriate metric of success. While residual ponding is acceptable under design storm conditions; building flooding is unacceptable. Therefore, any residual ponding must remain concentrated in the right-of-way such that all properties are protected under design storm conditions.

Tables 5 and 6 summarize the results of these simulations for the proposed pump stations for the current project alternative with the detention chambers. The tables present the model predicted peak inflow to the pump station, predicted ponding at a critical upstream location, and operational impacts for the current 10-year 2-hour design storm and for the two additional storms.

Table 5 Proposed Pump Station at Waterfront Park Results

Design Storm Description / Relevant Results	Recommended 2-hour Storm[1]	Modified 2-hr Storm[2]	24-hr Storm[3]
Peak Inflow to PS (MGD)	60	62	77
Predicted Ponding Elevation @ King St and Union St	Below Curb	Below Curb	Below Curb
Operational impacts?	NA	Include in planned storage operation SOP for operating the control valve into the pump station for various storm events	Include in planned storage operation SOP for operating the control valve into the pump station for various storm events; higher energy costs because standby pump would be used.

Notes:
(1) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 2.53 in. Total Storm Duration = 2 hours.
(2) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 3.10 in. Total Storm Duration = 2 hours.
(3) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume =- 5.62 in. Total Storm Duration = 24 hours.

Table 6 Proposed Pump Station at Thompsons Alley Results

Design Storm Description / Relevant Results	Recommended 2-hour Storm[1]	Modified 2-hr Storm[2]	24-hr Storm[3]
Peak Inflow to PS (MGD)	2.5	2.6	18.5
Predicted Ponding Elevation @ Cameron St and Union St (Top of Curb 5.1 ft)	Below curb	Below curb	Below curb
Operational impacts?	NA	Include in planned storage operation SOP for operating the control valve into the pump station for various storm events	Include in planned storage operation SOP for operating the control valve into the pump station for various storm events; higher energy costs because standby pump would be used.

Notes:
(1) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 2.53 in. Total Storm Duration = 2 hours.
(2) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 3.10 in. Total Storm Duration = 2 hours.
(3) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume =- 5.62 in. Total Storm Duration = 24 hours.

The results on Table 5 and 6 indicate:

- Using a 10-yr 2-hr storm of 3.10 inches, which was based on the City IDF curves, results in ***no substantial increase in peak inflow*** to either pump station. While the peak inflow to the Waterfront Park pump station is slightly greater than the 60 MGD rated capacity, this will not result in any significant change to the predicted residual ponding when compared to the results using the Atlas 14 storm depth of 2.53 inches. The slightly higher peak flow can be managed by operating the storage with the connection between the underground storage and the pump station "open" to allow a continuous, controlled discharge during the event from the storage to the pump station. This effectively manages the peak flow and allows the basins to capture more of the storm volume. With this operational change in mind, therefore, are **no required changes to the recommended pump station capacity**.
- Using a 10-yr 24-hr storm does result in a significant increase in inflow to the pump stations. Again, the higher inflow can be managed with the same operational changes described for the 10-yr 2-hr storm of 3.10 inches above. Also, under this extreme scenario the standby pumps can run to provide additional pumping capacity and contain the excess runoff within the curbline. With this operational flexibility in mind, ***no increase in pump station size would be required***.

Tables 7 and 8 summarize the results of these simulations for the proposed pump stations for the No Storage project alternative. The table presents the model predicted peak inflow to the pump station, predicted ponding at a critical upstream location, potential modifications to the proposed design, and operational impacts for the current 10-year 2-hour design storm and for the two additional storms.

Table 7 Proposed Pump Station at Waterfront Park Results (No Storage)

Design Storm Description / Relevant Results	Carollo Recommendation[1]	2-hr Storm[2]	24-hr Storm[3]
Peak Inflow to PS (MGD)	117	119	121
Predicted Ponding Elevation @ King St and Union St	Below Curb	Below Curb	Below Curb
Operational impacts?	NA	None	None

Notes:
(1) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 2.53 in. Total Storm Duration = 2 hours.
(2) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 3.10 in. Total Storm Duration = 2 hours.
(3) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume =- 5.62 in. Total Storm Duration = 24 hours.

Table 8 Proposed Pump Station at Thompsons Alley Results (No Storage)

Design Storm Description / Relevant Results	Carollo Recommendation	2-hr Storm	24-hr Storm
Peak Inflow to PS (MGD)	84	88	89
Predicted Ponding Elevation @ Cameron St and Union St (Top of Curb 5.1 ft)	Below curb	Below curb	Below curb
Operational impacts?	NA	None	None

Notes:
(1) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 2.53 in. Total Storm Duration = 2 hours.
(2) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume = 3.10 in. Total Storm Duration = 2 hours.
(3) Peak Rainfall Intensity = 9.0 in/hr at a 5-minute duration. Total Storm Volume =- 5.62 in. Total Storm Duration = 24 hours.

The results on Tables 7 and 8 indicate:

- Using a 10-yr 2-hr storm of 3.10 inches, which was based on the City IDF curves, results in ***no substantial increase in peak inflow*** to the pump station, and therefore no required change to the recommended pump station capacity.
- Using a 10-yr 24-hr storm results in ***no substantial increase in peak inflow*** to the pump station, and therefore no increase in pump station size would be required.

Sensitivity analysis showed the importance of considering total depth of the selected design storm. It also illustrated that both pump stations as proposed are predicted to be capable of handling projected increased flows from larger storm events than the design criteria (10-year 2-hour storm and total storm depth of 2.53 inches). Carollo recommends continued use of this 10-yr 2-hr storm as the design standard for proposed infrastructure.

As is standard practice during detailed design, the proposed alternative and any future design should be evaluated using real storm events and long-term simulations to confirm the operation of the proposed infrastructure against a range of storm durations and intensities.

5 Conclusions & Recommendations

Based on the evaluation presented, the following are recommended:

- Continue the use of the 10-year storm and a peak design rainfall intensity of 9.0 inches/hour based on the City IDF curves. The selected design storm adequately addresses future climate change impacts and will result in facility sizing that will reduce stormwater-related flooding to the maximum extent practicable.
  - This does not imply that facilities sized using this design storm will prevent flooding from ever occurring again. Rather, it implies that the probability of flooding (even accounting for future climate change impacts) is very low - on the order of once in 10 years or more, versus several times a year under current conditions.
  - Using more extreme storm intensities would result in larger facilities, larger area of impact, and greater disruption to Old Town, driving up the cost, and potentially further delaying the project.
- The 2-hour storm duration should be used to evaluate the sizing of required flood control facilities (storm conveyance, pump stations, and storage chambers).
  - Carollo recommends the use of the 2.53-inch total storm depth from NOAA Atlas 14, regardless of whether the selected alternative includes underground storage or not.
  - Model simulations with higher storm depths result in increased peak flows to the proposed pump stations. However, no increase in pump station size is recommended. By operating any proposed storage to allow controlled flow continuously into the pump station, the pump stations can effectively manage the increased inflows without increasing surface ponding in the critical areas near the pump stations.
- As is standard design practice, the use of real storm events and long-term simulations on the selected alternative are recommended to confirm the operation of any proposed storage against a range of storm durations and intensities.

These recommendations provide an analytical basis that is consistent with other City studies (e.g., CASSCA) and a factor of safety against future storms that may be of higher intensity and/or frequency. They also incorporate routine checks using more current information and climate model results to confirm that these design guidelines appropriately account for climate change effects.

6 References

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