City of Alexandria Storm Sewer Capacity Analysis

Summary Report

Prepared for

City of Alexandria

February 2016

CH2MHILL®

Executive Summary

Introduction

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze the storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system for each watershed within the City of Alexandria were modeled for a 10-year, 24-hour storm event (the City's recommended design event) using an industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure (GI), storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed-wide alternatives for managing stormwater were developed and presented as possible solutions for each watershed.

City Characteristics

The City of Alexandria covers approximately 10,000 acres (15.3 square miles) and the drainage is subdivided into eight separate stormwater watersheds that eventually drain to the Potomac River and the Chesapeake Bay as well as three combined sewersheds that are served by Alexandria Renew Enterprises (Figure ES-1). The separate stormwater watersheds are:

- Backlick Run
- Cameron Run
- Four Mile Run
- Holmes Run
- Hooffs Run
- Potomac River
- Strawberry Run
- Taylor Run

Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The City's storm sewersheds are approximately 43 percent impervious[1], the majority of which is buildings, roads, and parking (Figure ES-2). Stormwater runoff in the separate stormwater system is conveyed to the receiving streams through a network of over 1,077,000 linear feet (LF) of pipe (200 miles) and 130,960 LF of streams (25 miles).

[1] Based on 2011 basemap data provided by the City of Alexandria. More recent (2013) basemap data is available, however the hydrologic models described in this report were developed prior to the release of the 2013 data, therefore information contained within this report is based on 2011 basemap data unless otherwise stated.

FIGURE ES-1
City of Alexandria Stormwater Watersheds
City of Alexandria Storm Sewer Capacity Analysis

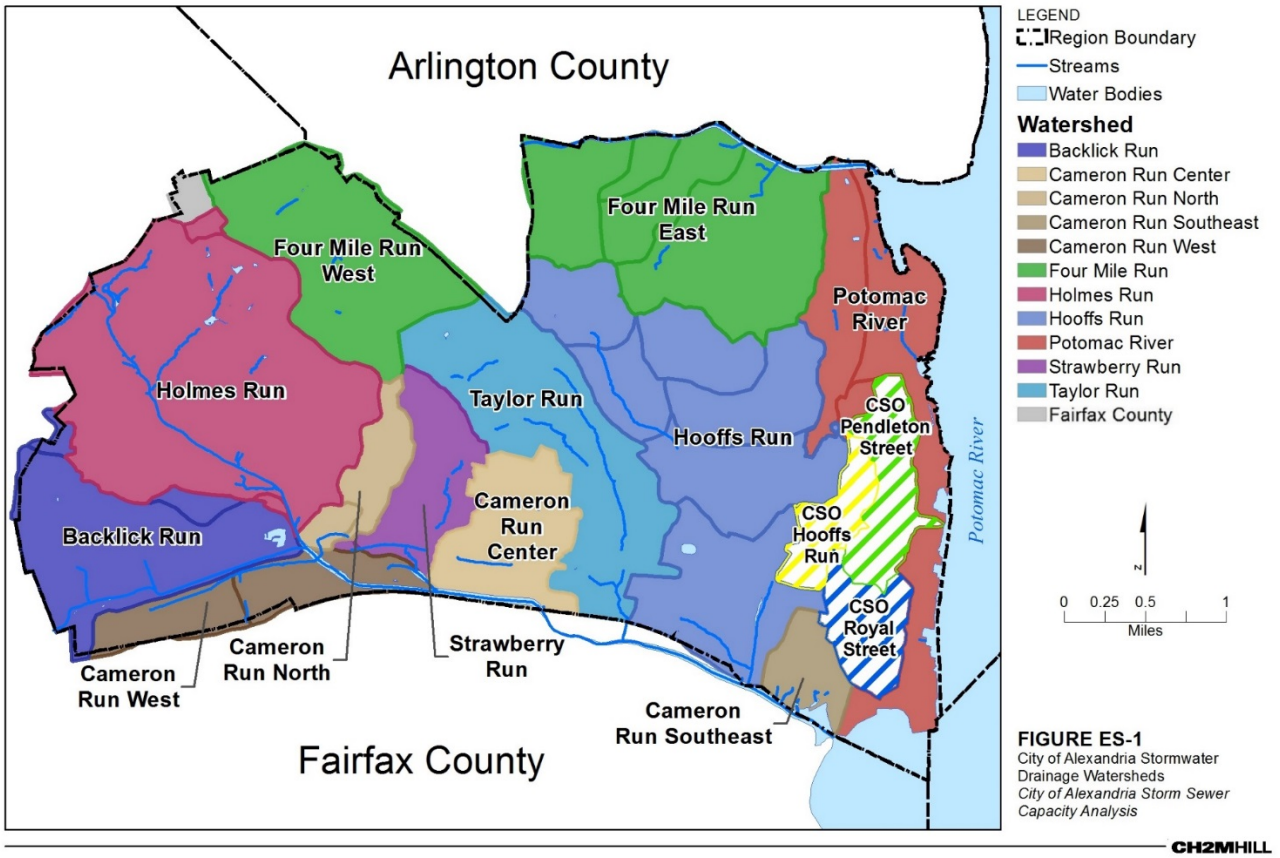
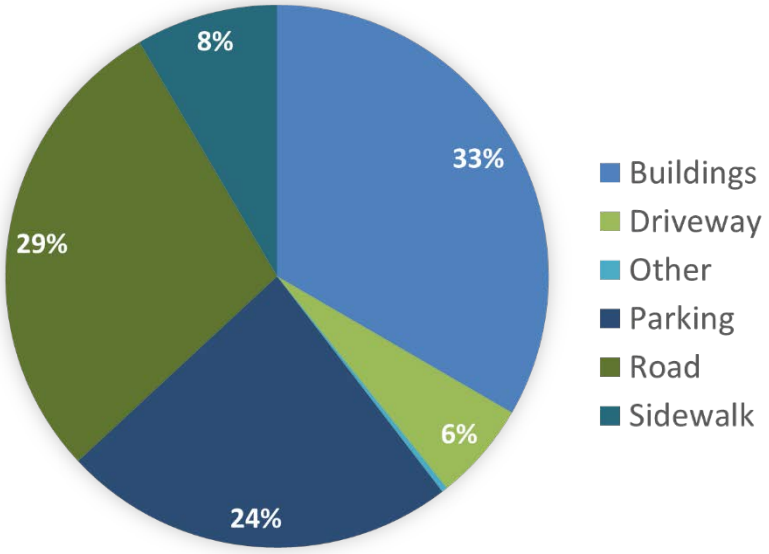


FIGURE ES-2
Impervious Cover in City of Alexandria Storm Sewersheds
City of Alexandria Storm Sewer Capacity Analysis



Results

The hydraulic model predicts that portions of the storm system in the City may experience capacity limitations during the 10-year, 24-hour storm event.

Approximately 22 percent of the system may experience flooding and 16 percent may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 16 percent of the system may be surcharged such that the water surface rises above the crown of the pipe and cause the system to backup. Using criteria determined in collaboration with City staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding locations were identified and prioritized (Figure ES-3). Flooding locations were grouped into high priority problem areas. Overall, 90 problem areas were identified across the City.

FIGURE ES-3
Junction Scores and High Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis

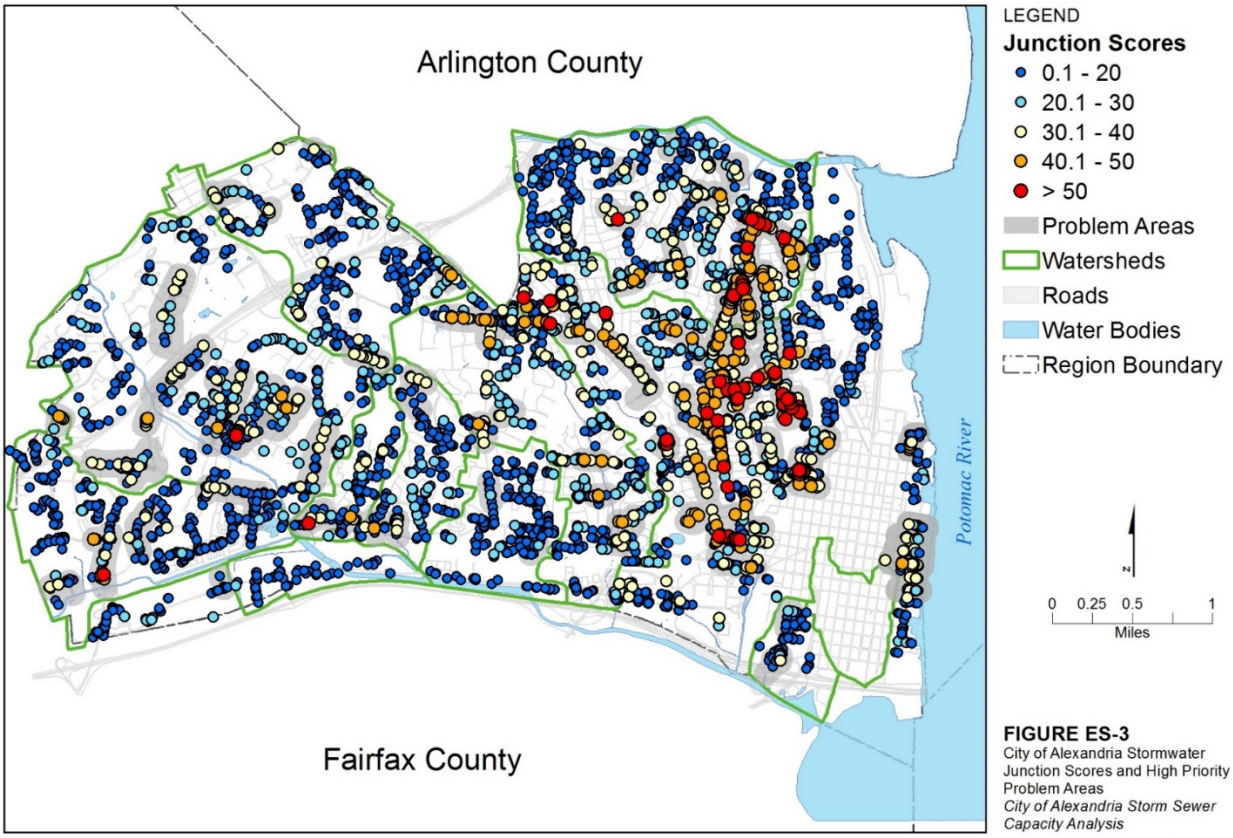


FIGURE ES-3
City of Alexandria Stormwater Junction Scores and High Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis

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Alternatives Analysis

Solutions were developed for each of the problem areas, with the exception of the seven in the Potomac River watershed, where solutions were deferred until after completion of substantial ongoing development in the watershed. For each of the 83 remaining problem areas, up to five solutions were identified and modeled: three levels of GI implementation (high, medium, and low percent impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model

results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest $/gallon of flood reduction in each of the problem areas

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the problem areas

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas.

A preferred alternative was selected for each watershed based on engineering judgement. Table ES-1 summarizes the preferred alternative selected for each watershed and Figure ES-4 shows the project types selected for each of the problem areas in the preferred alternatives. The selected projects were prioritized based on the benefit cost (Figure ES-5).

TABLE ES-1
Watershed-wide Alternatives Scoring and Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis

Watershed	Number of Problem Areas	Total Capital Cost ($ Millions)	Total Benefit Score	Overall Benefit/Cost	Total Flood Reduction (MG)	Cost of Flood Reduction ($/Gallon)	Preferred Alternative
Hooffs Run	23	$18.26	978	54	7.36	$2.48	3
Four Mile Run	23	$24.46	939	38	11.53	$2.12	3
Holmes Run	9	$5.76	433	75	2.78	$2.07	2
Taylor Run	12	$4.89	516	106	4.43	$1.10	2
Cameron Run	8	$3.65	360	99	2.27	$1.61	1
Strawberry Run	3	$0.27	88	322	0.05	$5.77	3
Backlick Run	5	$3.96	229	58	1.39	$2.85	3
Potomac River	7	n/a	n/a	n/a	n/a	n/a	n/a
TOTAL	**90**	**$61.29**	**3543**	**58**	**29.81**	**$2.06**	**n/a**

MG = million gallons
Total existing volume of flooding in the problem areas (not including Potomac River) is 46.02 MG.

FIGURE ES-4
Selected Technology by Problem Area
City of Alexandria Storm Sewer Capacity Analysis

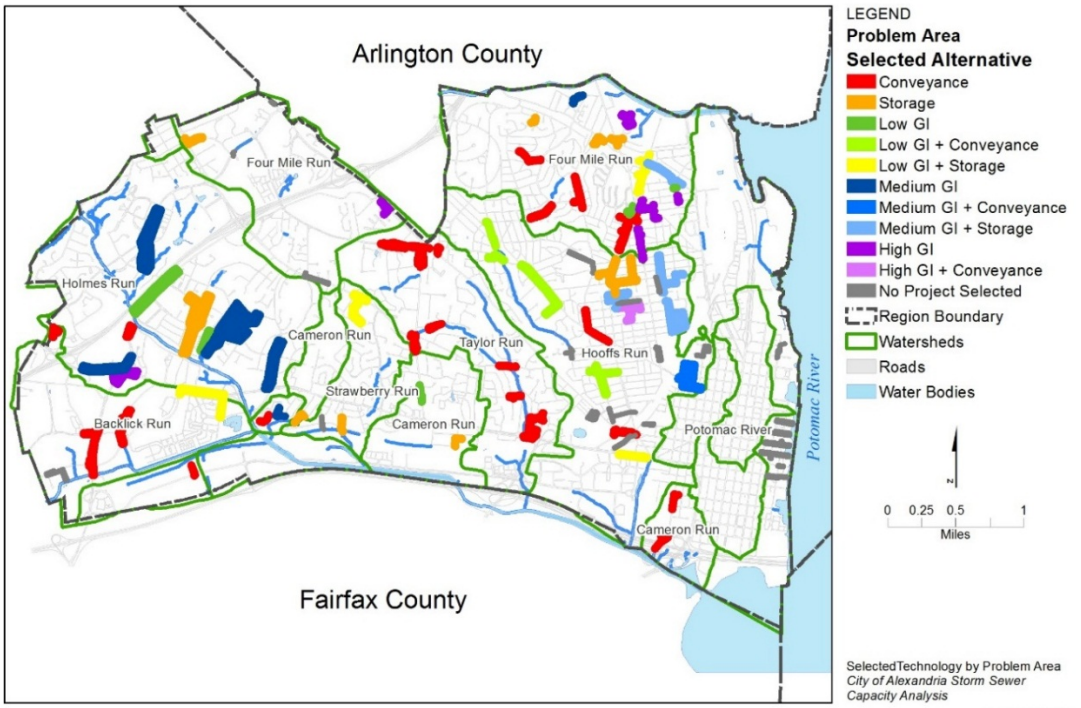
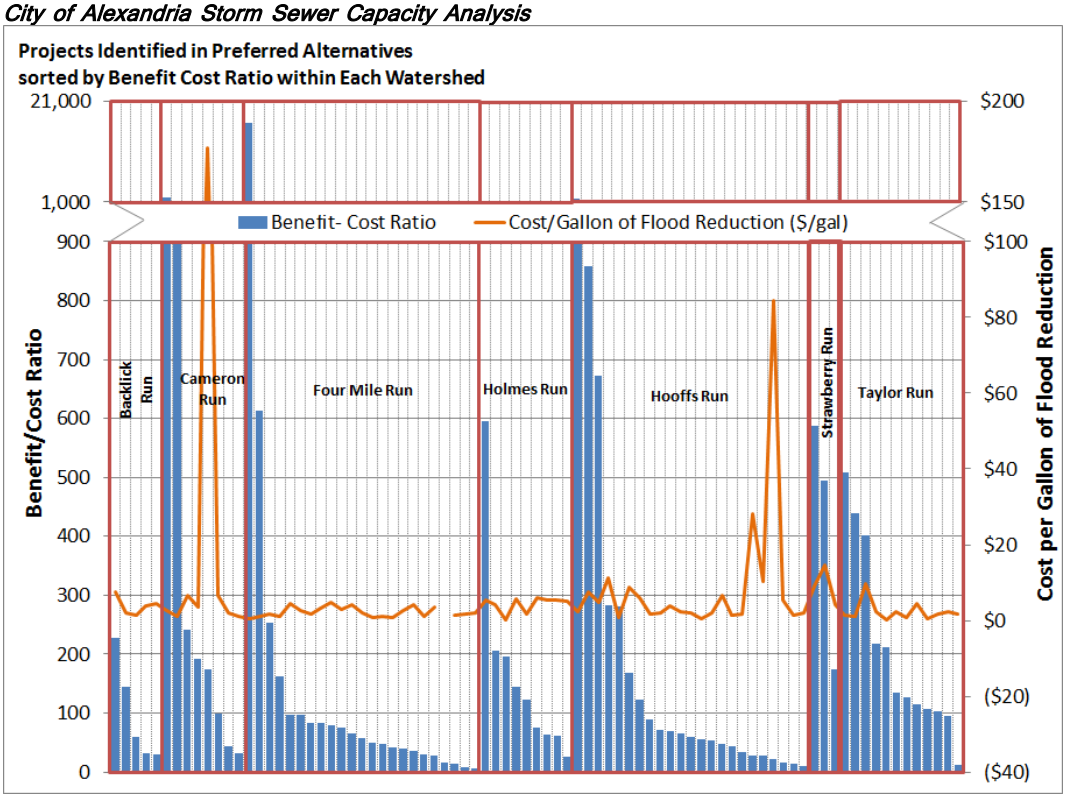


FIGURE ES-5
Recommended Alternative Projects Prioritized by Watershed[2]
City of Alexandria Storm Sewer Capacity Analysis



[2] Problem area 116 in Four Mile Run experiences an increase in flood volume when modeled with the other recommended projects due to increased flow coming from upstream conveyance projects. The cost/gallon of flood reduction is not shown for this project.

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Comparison of Alexandria's Storm Design Criteria to Neighboring Jurisdictions

Updated Precipitation Frequency Results and Synthesis of New IDF Curves for the City of Alexandria, Virginia

Rainfall Frequency and Global Change Model Options for the City of Alexandria, Virginia

Sea Level Rise Potential for the City of Alexandria, Virginia

Consideration of Design Guidelines for Flow-through BMPs and use of Unit Hydrographs

Binder 2: Task 2 Technical Memos

Stormwater Capacity Analysis for Hooffs Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Four Mile Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Holmes Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Taylor Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Cameron Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Backlick Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Strawberry Run, City of Alexandria, Virginia

Stormwater Capacity Analysis for Potomac River, City of Alexandria, Virginia

Supplemental Task 2 Tech Memos:

- Comparison of Model Hyetograph Generation and Hydrologic Computation Methods
- Inlet Capacity Analysis for City of Alexandria Storm Sewer Capacity Analysis
- Summary of Data Gaps and Assumptions in the Hooffs Run Watershed

Binder 3: Task 3 Technical Memos

Hooffs Run Task 3.1 – Pilot Study Area Field Verification – Survey and Inspection

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Four Mile Run Condition Assessment

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Holmes Run Condition Assessment

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Taylor Run Condition Assessment

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Cameron Run Condition Assessment

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Backlick Run Condition Assessment

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Strawberry Run Condition Assessment

City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Potomac River Condition Assessment

Supplemental Task 3 Tech Memos:

- City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Corrugated Metal Pipe Condition Assessment
- City of Alexandria Storm Sewer Capacity Analysis Task Order 2A.04D – Cleaning & CCTV (Business Center Drive & Colvin St)

City of Alexandria Storm Sewer Capacity Analysis Task Order 2B – Cleaning & CCTV (DASH Facility)

City of Alexandria Storm Sewer Capacity Analysis Task Order 2B – Cleaning & CCTV (King St, Beauregard St, and Walter Reed Dr)

City of Alexandria Storm Sewer Capacity Analysis Task Order 2D – Heavy Cleaning & CCTV (N. Beauregard St) Storm Pipe Segment: 001316STMP

Binder 4: Task 4 Reports

Problem and Solution Identification and Prioritization for Hooffs Run, Alexandria, Virginia

Problem and Solution Identification and Prioritization for Four Mile Run, Alexandria, Virginia

Problem and Solution Identification and Prioritization for Holmes Run, Alexandria, Virginia

Problem and Solution Identification and Prioritization for Taylor Run, Alexandria, Virginia

Problem and Solution Identification and Prioritization for Cameron Run, Alexandria, Virginia

Problem and Solution Identification and Prioritization for Backlick Run, Alexandria, Virginia

Problem and Solution Identification and Prioritization for Strawberry Run, Alexandria, Virginia

Problem Area Identification Results for Potomac

Supplemental Task 4 Tech Memos:

Planning Level Cost Information

Task 4 Evaluation Criteria Scoring Systems

Acronyms and Abbreviations

$/gallon	cost per gallon
BMP	best management practices
CCTV	closed-circuit television
CH2M	CH2M HILL, Inc.
City	City of Alexandria, Virginia
CMP	corrugated metal pipe
GCM	general circulation model
GEV	generalized extreme value
GI	green infrastructure
HGL	hydraulic-grade line
IDF	intensity-duration-frequency
LF	linear feet
MHHW	mean higher high water
MS4	municipal separate storm sewer system
MSL	mean seal level
NASSCO	National Association of Sewer Service Companies
NAVD	North American Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PACP	Pipeline Assessment and Certification Program
ROW	right of way
SCREAM	Sewer Condition Risk Evaluation Algorithm Model
SWM	stormwater management
Tc	time of concentration
TM	technical memorandum
TMDL	total maximum daily load
VPS	Video Pipe Services
WIP	Watershed Implementation Plan

SECTION 1

Introduction

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project was implemented in phases by watershed.

The project was accomplished through five tasks:

- **Task 1** - Review rainfall data and the City's stormwater design criteria, develop projections for rainfall and tidal boundary conditions based on climate change, and propose potential revisions as appropriate
- **Task 2** - Analyze the capacity of the City's existing stormwater collection system
- **Task 3** – Perform field verification of selected drainage facilities through survey, manhole inspections, and closed-circuit television (CCTV) inspection
- **Task 4** – Identify and prioritize problem areas (capacity limitations), and develop and prioritize solutions to high-priority problems
- **Task 5** – Coordinate project meetings and public involvement support

This Storm Sewer Capacity Analysis Summary Report provides a summary of the evaluations and results of the analyses conducted throughout the life of the project. Technical Memoranda and Reports from each task and watershed are included in the supplemental binders as follows:

- **Binder 1** – Task 1 Technical Memoranda
- **Binder 2** – Task 2 Technical Memoranda documenting existing condition model for each watershed
- **Binder 3** – Task 3 Technical Memoranda documenting condition assessments by watershed
- **Binder 4** – Task 4 Reports documenting problem areas and solutions by watershed

1.1 Background

Founded in 1749, The City of Alexandria is one of the oldest, and most densely populated cities in Virginia, with a population of more than 150,000 residents living in a 10,000-acre area. The City is bounded by Arlington County to the north, Fairfax County to the west and south, and the Potomac River and Washington, D.C., to the east.

Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The City's storm sewersheds are approximately 43 percent impervious[3], the majority of which is buildings, roads, and parking (Table 1-1). The combination of the high density of development in old neighborhoods with aging infrastructure resulted in flooding that caused economic damage and is a safety hazard (Figure 1-1).

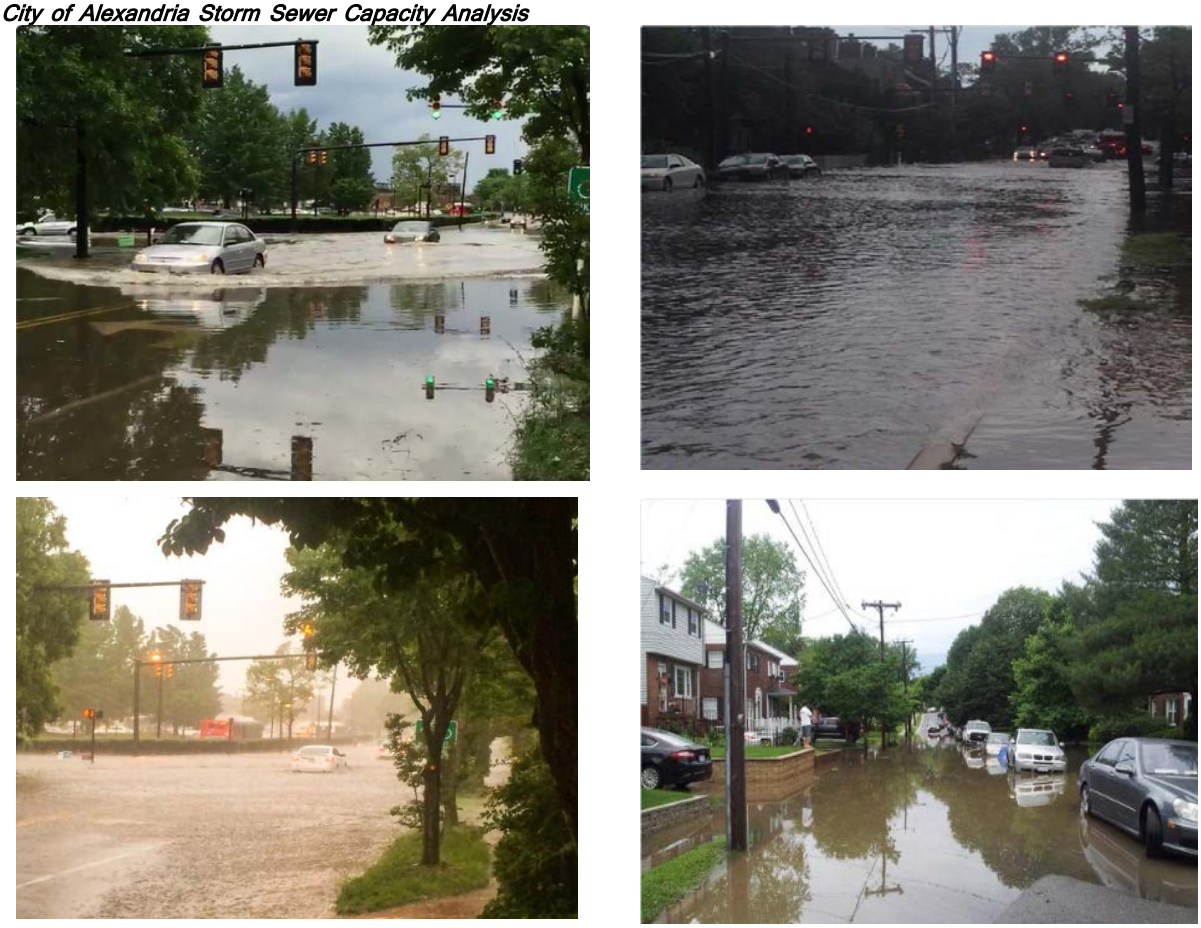
[3] Based on 2011 basemap data provided by the City of Alexandria. More recent (2013) basemap data is available, however the hydrologic models described in this report were developed prior to the release of the 2013 data, therefore information contained within this report is based on 2011 basemap data unless otherwise stated.

TABLE 1-1
Summary of Model Statistics by Watershed
City of Alexandria Storm Sewer Capacity Analysis

Watershed	Drainage Area (Square Miles)[a]	Total Percent Impervious[b]	Percent of Impervious Area				
			Buildings	Driveways	Parking	Road	Sidewalks
Hooffs Run	2.53	44	38	8	15	28	10
Four Mile Run	3.21	44	33	6	22	31	9
Holmes Run	2.88	41	33	4	25	28	9
Taylor Run	1.36	35	31	8	19	34	8
Cameron Run	2.70	44	29	5	31	28	6
Strawberry Run	0.54	32	38	11	13	33	5
Backlick Run	1.22	59	33	4	39	18	6
Potomac River[c]	1.30	45	33	4	19	31	12
TOTAL	**15.75**	**43**	**33**	**6**	**23**	**28**	**8**

[a] Includes drainage area from adjacent municipalities
[b] Impervious areas and total percent impervious are based on the city's 2011 basemap data and the drainage area in the city and does not include drainage areas or imperviousness from adjacent municipalities
[c] Due to extensive recent development in the Potomac Yards area, more recent basemap data (2013) was used to develop impervious cover in the Potomac River watershed

FIGURE 1-1
Flooding in the City of Alexandria on June 1, 2015
City of Alexandria Storm Sewer Capacity Analysis



In addition to the conveyance capacity issues that are the primary objective of this project, the City would also like to use the projects to help meet water quality requirements where appropriate. The City is regulated as a Phase II (small) municipal separate storm sewer system (MS4) under the General Permit for the Discharge of Stormwater from Small MS4 Systems. This year, June 2015-June 2016, is the third year of the current permit term, which ends in June 2018. The current permit requires compliance with the Chesapeake Bay Total Maximum Daily Load (TMDL) and the Virginia Phase I and Phase II Bay TMDL Watershed Implementation Plans (WIP), which allow three 5-year permit cycles to implement necessary reductions. The permit requires meeting 5.0 percent of the total target load reduction by the end of the first permit term. In 2012, a study and report were completed, *Chesapeake Bay TMDL Compliance Analysis and Options Report* (AMEC, 2012), that identified green infrastructure (GI) projects in the public right–of-ways (ROWs) and on public properties as well as pond retrofits to meet the initial permit term requirements. In addition, the report suggests city-wide GI implementation will be needed to meet 50 percent of the total Chesapeake Bay TMDL goal and sites have not yet been identified. The GI projects could provide both water quality and quantity benefits to the City and could help to reduce flooding, if strategically located.

The City separate storm drainage is divided into eight stormwater watersheds that eventually drain to the Potomac River and the Chesapeake Bay (Figure 1-1):

- Backlick Run
- Cameron Run
- Four Mile Run
- Holmes Run
- Hooffs Run
- Potomac River
- Strawberry Run
- Taylor Run

Approximately two-thirds of the City drains south to Cameron Run before entering the Potomac River. The remainder drains north into Four Mile Run or east directly into the Potomac River. Analyses under Tasks 2 through 4 were phased on a watershed basis and individual reports were developed for each task and watershed.

While the focus of this report is on drainage issues associated with drainage conveyance systems in the City of Alexandria that are designed for the 10-year storm, the City recognizes that flooding can also result from flood crest elevations in the surrounding rivers, which result from larger storms and/or storm-surge events and have much longer response times to rainfall. For example, the City has embarked on a flood mitigation project for the Potomac River waterfront and has conducted similar studies for Four Mile Run and Cameron Run that are in various stages of development. The City's Department of Project Implementation has completed schematic designs for the Waterfront Flood Mitigation Project on the Potomac River (URS, 2014), which is based on the Alexandria Waterfront Small Area Plan, completed by the Department of Planning and Zoning in 2012. The Waterfront Flood Mitigation Project includes a number of elements, including a new flood wall or bulkhead, a promenade and park east of Union Street, between Queen Street in the north and Wolf Street to the south, and two new pump stations.

1.2 Project Objectives

The primary objective of the Storm Sewer Capacity Analysis Study was to identify storm sewer capacity limitations and develop solutions to reduce flooding and minimize risk. A secondary objective of the project was to support compliance with the City's MS4 Permit and meeting the Chesapeake Bay TMDL goals. In addition the project was used to update the City's GIS data and provide a planning and design tool for future use by City staff.

FIGURE 1-2
Stormwater Drainage Watersheds, City of Alexandria, Virginia
City of Alexandria Storm Sewer Capacity Analysis

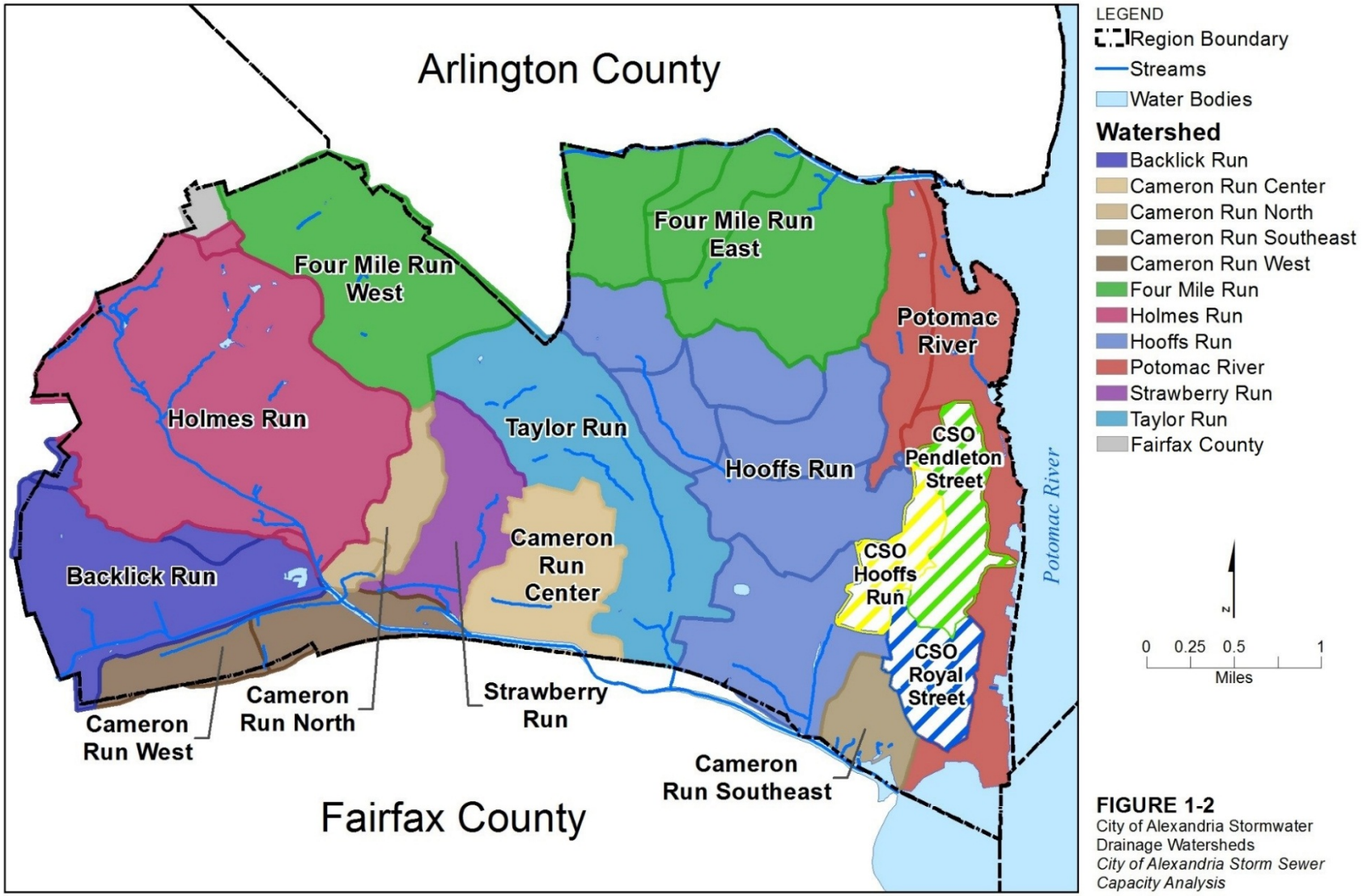


FIGURE 1-2
City of Alexandria Stormwater Drainage Watersheds
City of Alexandria Storm Sewer Capacity Analysis

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SECTION 2

Rainfall and Tide Level Statistics, Climate Projections, and Design Criteria

To understand and analyze the capacity of the City's storm drainage system, it is important to understand what size rainfall event the system was designed for and whether the outfalls at the downstream end are submerged during high tides. Therefore, the first task in the City's Storm Sewer Capacity Analysis Study was to review and update the City's existing rainfall intensity-duration-frequency (IDF) data used to set storm design criteria, and to understand the tidal conditions that may impact the outfalls to the Potomac River, Four Mile Run, and Cameron Run. In addition, it is important to understand how rainfall and tidal conditions will change in the future since storm drains have a very long service life of 50 to 100 years because they are typically built below ground of concrete or similarly inert materials. The following subtasks were conducted to develop recommendations for updating the City's stormwater design criteria:

- Review of Alexandria's storm design criteria and comparison to neighboring jurisdictions
- Update the precipitation frequency results with historical data and synthesis of new IDF curves
- Project changes in rainfall IDF curves
- Project sea level rise impacts on tidal boundary conditions
- Review and determine if changes are needed to design criteria

Results from each of these subtask are summarized below, and technical memoranda (TMs) with details of the analyses are contained in Binder 1.

2.1 Comparison of Alexandria's Storm Design Criteria to Neighboring Jurisdictions

CH2M HILL, Inc. (CH2M) reviewed design criteria and rainfall IDF curves used in nearby communities in Virginia, Maryland and Washington DC for comparison with the City's current criteria. The review of design criteria included understanding design storms used (e.g., recurrence frequency, duration), design parameters (e.g., surcharge levels, gutter spread), and source data for IDF curves.

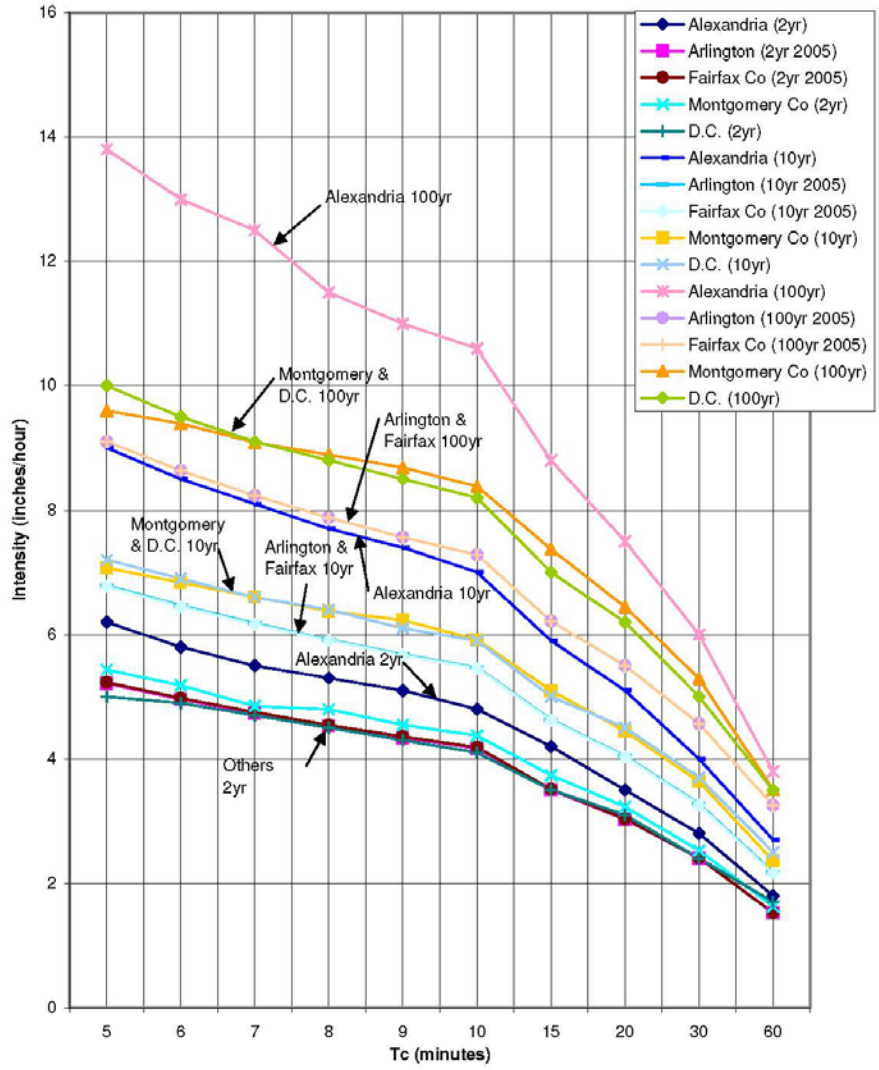
In highly urbanized, impervious areas such as Alexandria, the most common drainage design condition is found to depend on a short time of concentration (Tc). This leads to relatively high instantaneous rainfall intensities and large storm sewers. In this setting, individual land development projects often have a Tc much shorter than 60 minutes and typically around 5 minutes. This is not only a factor for the storm sewer pipe sizing, but also the number and placement of storm drainage inlets or catch basins.

The 10-year, 5-minute intensity is the value with the most implications for site design, while the 10-year, 60-minute intensity has the greatest implications for large storm sewers further downstream. 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.

For each of the design storms, the graph in Figure 2-1 shows three groupings. Alexandria is always alone and the highest, followed by Montgomery County and the District of Columbia close together, followed by the lower values for Arlington and Fairfax counties.

Additional details are documented in Binder 1,TM 1 (Task 1.1).

FIGURE 2-1
Alexandria and Neighboring Jurisdictions IDF Comparison for 5 to 60 minute Time of Concentration
City of Alexandria Storm Sewer Capacity Analysis



2.2 Updated Precipitation Frequency Results and Synthesis of New IDF Curves for the City of Alexandria, Virginia

An analysis was conducted to update the IDF precipitation curves currently used by the City. The approach was to utilize data from precipitation stations that were used by the National Weather Service (NWS) in the update of National Oceanic and Atmospheric Administration (NOAA) Atlas 14, Volume 2, *Ohio River Basin & Surrounding States* (Bonnin et al., 2004). The NOAA Atlas 14 analysis used annual maximum precipitation data through 2000 for several hourly and daily stations in Virginia and Maryland in the vicinity of Alexandria. These stations served as a basis for identifying stations that were applicable in updating the IDF curves for the City. All stations considered for this analysis had in excess of 30 years of record.

Annual maximum data up to 2000 from the NWS were combined with data from 2001 to 2008 to perform frequency analyses using the LMOMENTS statistical package that utilizes five different frequency distributions. The generalized extreme value (GEV) distribution was shown to be most appropriate.

The updated 10- and 100-year IDF curves for Alexandria are given in Table 2-1 (durations of 60-minutes and longer) and Table 2-2 (durations of less than 60 minutes), and are compared to the existing IDF curves for the 2-, 10-, and 100-year events in Figures 2-2, 2-3, and 2-4. All three IDF curves essentially converge at the 24-

hour duration. The 100-year IDF curves are essentially similar for durations of 60 minutes and longer. However, for the 2- and 10-year curves, the existing IDF values are greater than the updated L-moment analysis. The primary reason for this difference is that the period of record (1941 to 1969) for the existing IDF curves is wetter than the long-term period (1948 to 2008). IDF curves for additional return periods are provided in the detailed TM 2 (Task 1.2), Binder 1.

TABLE 2-1
Precipitation Frequency Estimates (in) for the City of Alexandria
Based on the partial duration series for various durations, based on using the mean of the annual maximum events at Reagan Nation Airport and the GEV distribution.
City of Alexandria Storm Sewer Capacity Analysis

Recurrence interval, years	Precipitation (Inches) for Indicated Durations and							
	60-min	120-min	3-hour	6-hour	12-hour	24-hour	48-hour	4-day
Mean at Reagan	**1.502**	**1.740**	**1.844**	**2.212**	**2.665**	**3.164**	**3.522**	**3.975**
10	2.28	2.64	2.80	3.36	4.05	4.81	5.35	6.04
100	3.86	4.47	4.74	5.68	6.85	8.13	9.05	10.22

min = minutes

TABLE 2-2
Precipitation Frequency Estimates for 5-, 10-, 30-, and 60-minute Durations
Based on the partial duration series and the GEV distribution.
City of Alexandria Storm Sewer Capacity Analysis

Recurrence interval, years	5-min (inches)	10-min (inches)	15-min (inches)	30-min (inches)	60-min (inches)
10	0.60	0.96	1.21	1.75	2.28
100	0.91	1.45	1.83	2.80	3.86

FIGURE 2-2
Comparison of Existing IDF Curve for the City of Alexandria to the Updated Historical (L-Moment) Analysis for the 2-year Event
City of Alexandria Storm Sewer Capacity Analysis

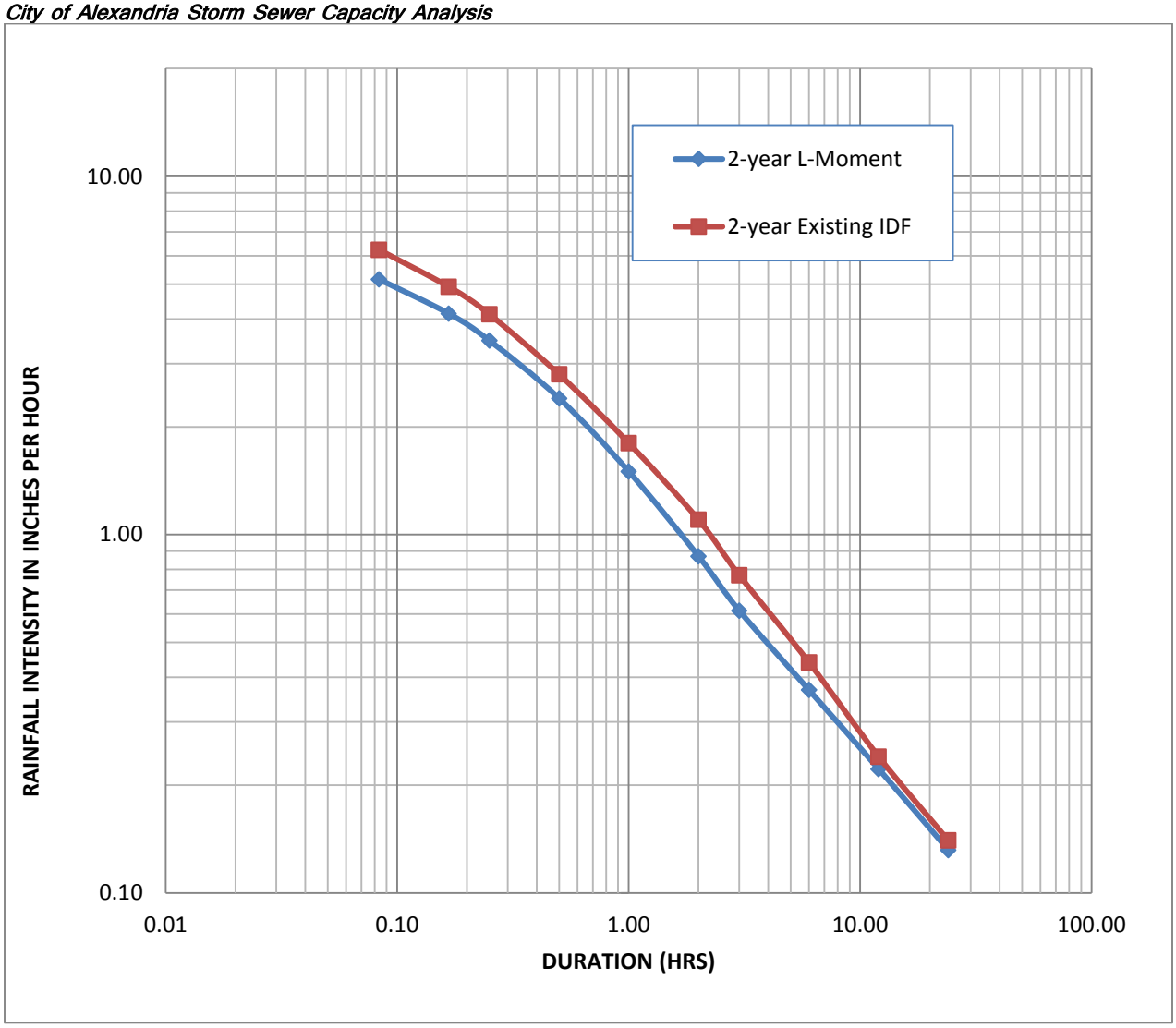


FIGURE 2-3
Comparison of Existing IDF Curve for the City of Alexandria to the Updated Historical (L-Moment) Analysis for the 10-year Event
City of Alexandria Storm Sewer Capacity Analysis

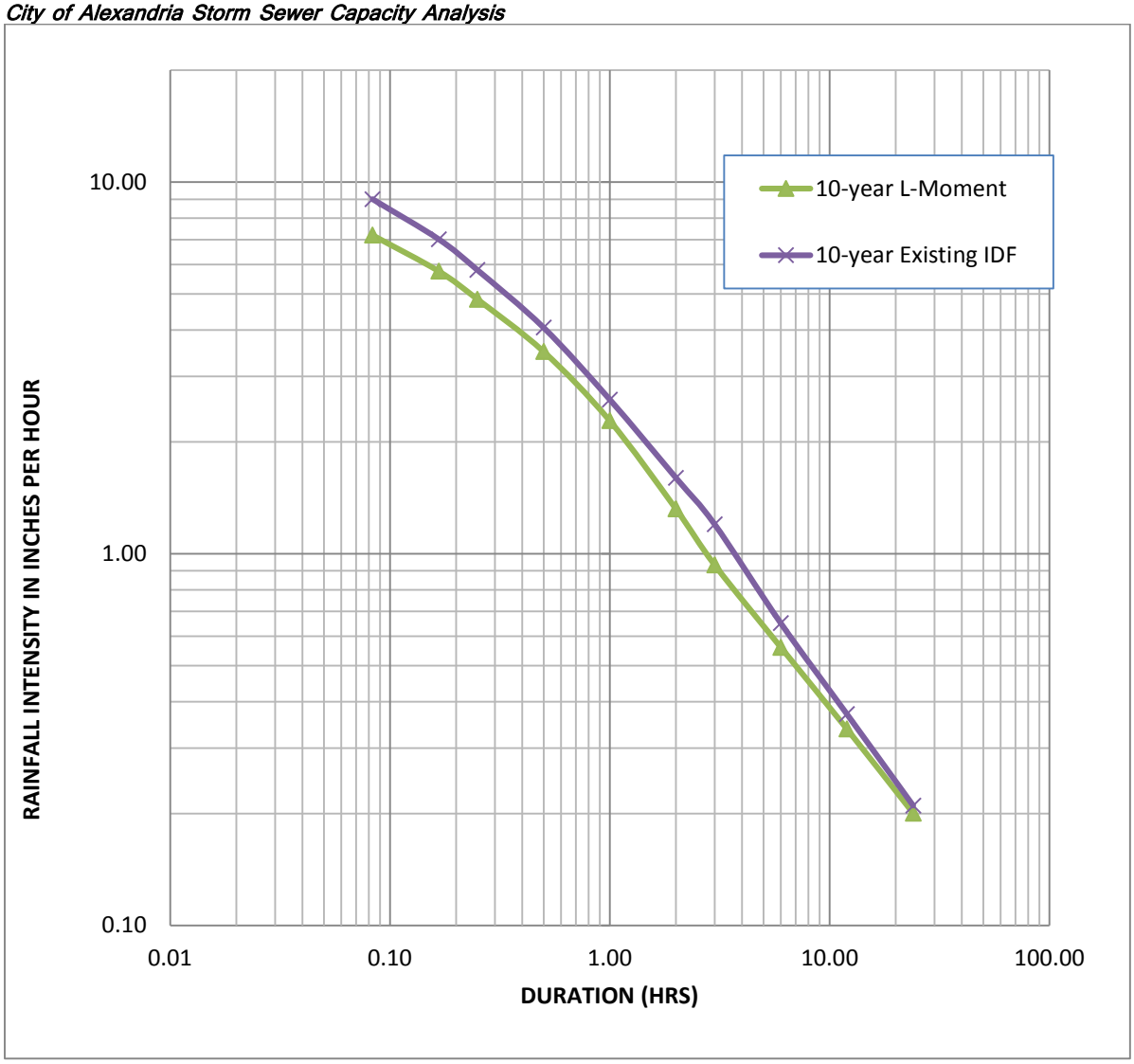
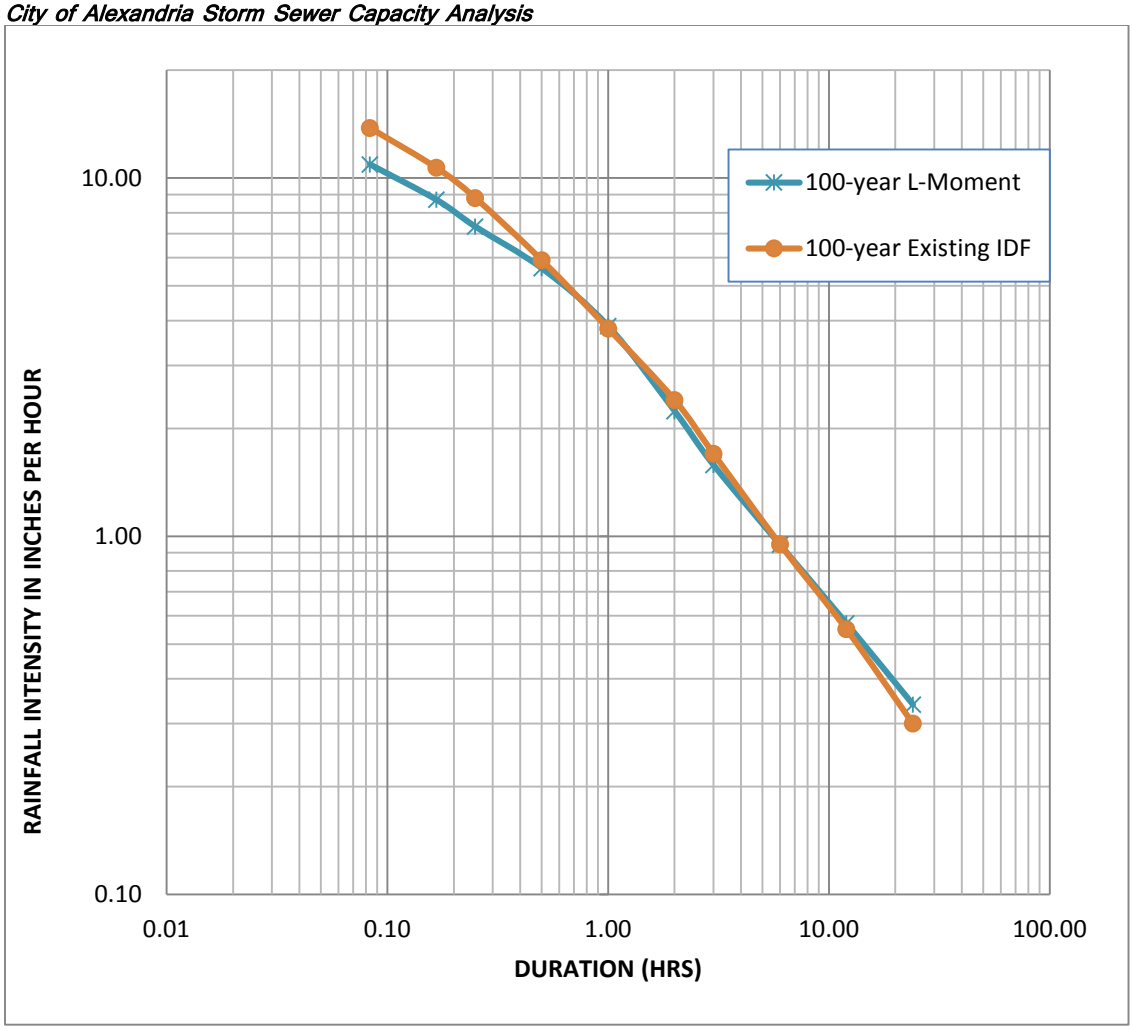


FIGURE 2-4
Comparison of Existing IDF Curve for the City of Alexandria to the Updated Historical (L-Moment) Analysis for the 100-year Event
City of Alexandria Storm Sewer Capacity Analysis



Plots of the 60-minute and 24-hour annual maximums at Reagan National Airport and Beltsville illustrate that the period 1948 to 1969 was generally wetter and experienced larger events than the period after 1969.

Estimates from the updated historical (L-moment) analysis (Table 2-1) were also compared to those from Atlas 14 (Table 2-3). The differences are small because the data used in the two analyses are similar and the same frequency distribution (GEV) was shown to be applicable. The largest differences are for the 50-, 100-, and 500-year estimates for the 60-minute durations, where the updated L-moment estimates range from 15 to 30 percent higher, respectively, than the Atlas 14 estimates. In short, the use of NOAA Atlas 14 would essentially give the same results as using the updated L-moments analysis. Additional details are documented in Binder 1, TM 3 (Task 1.3).

TABLE 2-3
Comparison of the Updated L-Moment Frequency Estimates with NOAA Atlas 14 for Selected Durations
City of Alexandria Storm Sewer Capacity Analysis

Recurrence interval, years	L-moment 60-min (inches)	Atlas 14 60-min (inches)	L-moment 6 hour (inches)	Atlas 14 6-hour (inches)	L-moment 24-hour (inches)	Atlas 14 24-hour (inches)
10	2.28	2.17	3.36	3.29	4.81	4.77
100	3.86	3.21	5.68	5.26	8.13	8.23

Values for additional recurrence intervals are provide in Binder 1, TM 2 (Task 1.2).

2.3 Projected Rainfall IDF Due to Climate Change

In this task potential of changes in precipitation IDF values were developed based on the results of global climate models paired with a range (low to high) in greenhouse gas emission scenarios. Results from 12 daily global circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in daily and annual precipitation for the years 2050 and 2100. The projected changes were applied to the historical daily precipitation record for the period 1945 to 2010 to produce updated IDF values for durations ranging from 5 minutes to 96 hours for return intervals ranging from 2 to 500 years.

Projected precipitation estimates and return intervals for Alexandria for years 2050 and 2100 are shown in Tables 2-4 and 2-5 respectively for durations from 5 minutes to 96 hours. Values for additional recurrence intervals are provided in Binder 1,TM 3 (Task 1.3).

TABLE 2-4
Summary Table of Projected Alexandria, VA IDF Precipitation Amounts (inches) for the Year 2050 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average. Recurrence intervals from 2 to 500 years and durations from 5-minutes to 96-hours.
City of Alexandria Storm Sewer Capacity Analysis

Year 2050	Duration											
Recurrence Interval, Years	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour	48-hour	96-hour
10	0.61	0.99	1.25	1.81	2.35	2.74	2.94	3.57	4.36	5.18	5.85	6.55
100	0.80	1.27	1.61	2.46	3.38	4.09	4.46	5.56	7.11	8.71	10.21	11.76

TABLE 2-5
Summary table of projected Alexandria, VA IDF Precipitation Amounts (inches) for the year 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from a 5-station region average. Recurrence intervals from 2 to 500 years and durations from 5-minutes to 96-hours.
City of Alexandria Storm Sewer Capacity Analysis

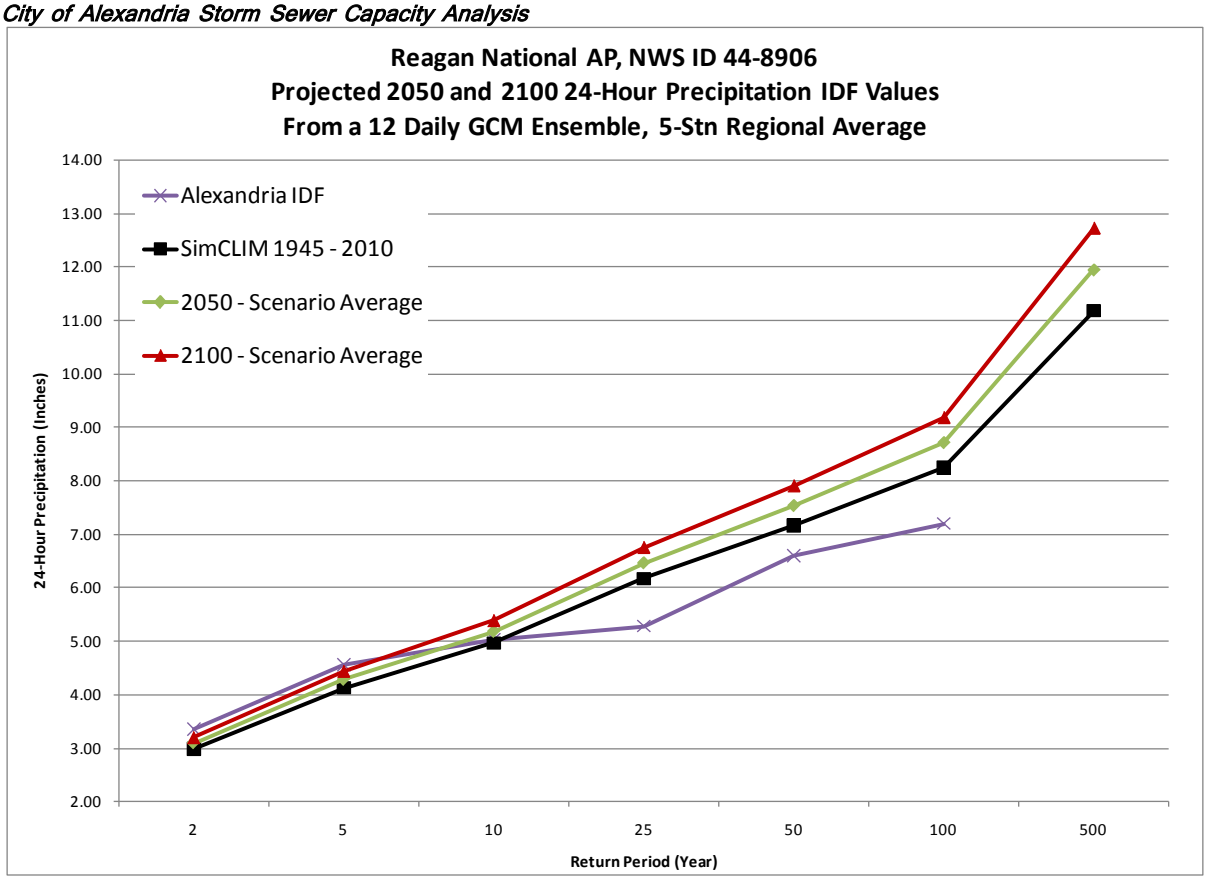
Year 2100	Duration											
Recurrence Interval (Years)	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour	48-hour	96-hour
10	0.64	1.03	1.30	1.88	2.44	2.85	3.06	3.71	4.53	5.39	6.08	6.79
100	0.84	1.33	1.69	2.59	3.56	4.30	4.70	5.86	7.49	9.18	10.76	12.34

As shown in Figure 2-5, the existing Alexandria, Virginia, precipitation IDF curves were found to be conservative, meaning that for most durations less than 12 hours and return periods from 2 to 100 years, the current Alexandria IDF values are greater than the projected IDF amounts for the years 2050 and 2100. For durations greater than 12 hours, projected IDF amounts for 2050 and 2100 are greater than the existing Alexandria IDF amounts for return periods greater than 10 years. These results are not surprising because as noted previously, the City's existing IDF curves were developed using a short and particularly wet period in the historical record (1941 to 1969).

FIGURE 2-5

Summary Plot of Historical Alexandria, VA 24-hour Precipitation IDF Values, SimCLIM estimates of historical IDF (1945 to 2100) and projected IDF precipitation amounts for the year 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average.

City of Alexandria Storm Sewer Capacity Analysis



Because of the potential infrastructure cost implications of changing drainage design criteria, it was initially suggested that the City adopt the Atlas 14 or L-Moment (which are essentially the same, see Table 2-3), which are generally lower than the City's current IDF curves, but are based on a much more complete historical data set and statistical analysis. However, as discussed in Section 2.5, the final recommendation for this project was to stick with the current IDF curves for the 10-year storm drainage criterion (see Table 2-6), because they approximate the projected values for 2050.

TABLE 2-6

Existing Alexandria IDF Precipitation Depth (inches), 5-minutes to 24-hours and return intervals of 2, 10 and 100 years

City of Alexandria Storm Sewer Capacity Analysis

Recurrence Interval (Years)	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour
2	0.52	0.80	1.05	1.40	1.80	2.30	2.28	2.70	3.00	3.36
10	0.75	1.17	1.48	2.00	2.70	3.20	3.60	3.96	4.44	5.04
100	1.15	1.77	2.20	3.00	3.80	4.80	5.25	5.76	6.60	7.20

Additional details are documented in Binder 1, TM 3 (Task 1.3).

2.4 Projected Sea Level Rise Due to Climate Change

In this task, projections of potential sea level rise were developed based on appropriate climate change scenarios. The analysis reviewed historical records for trends and used the SimCLIM application to quantitatively determine sea level rise in the Chesapeake Bay and the Potomac River near Alexandria.

Results from five global circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in mean sea level (MSL) and mean higher high water (MHHW) at the Washington, D.C., gauge near the City for the years 2050 and 2100, as shown in Figures 2-6 and 2.7, respectively.

The projected median MSL from the five general circulation models (GCM) and three greenhouse gas scenarios range from 1.76 to 2.44 feet North American Vertical Datum (NAVD) by the year 2100. The 10-and 90-percent non-exceedance ranges are 1.33 and 3.35 feet NAVD, respectively.

The projected median MHHW from the five GCMs and three greenhouse gas scenarios range from 3.35 to 4.05 feet NAVD by the year 2100. The 10 and 90 percent non-exceedance ranges are 2.94 and 4.96 feet NAVD respectively.

FIGURE 2-6
Projected Mean Sea Level (1990 through 2100) Relative to Observed Historic Values and Trend (1931 through 2008) at Washington, D.C. (8594900)
City of Alexandria Storm Sewer Capacity Analysis

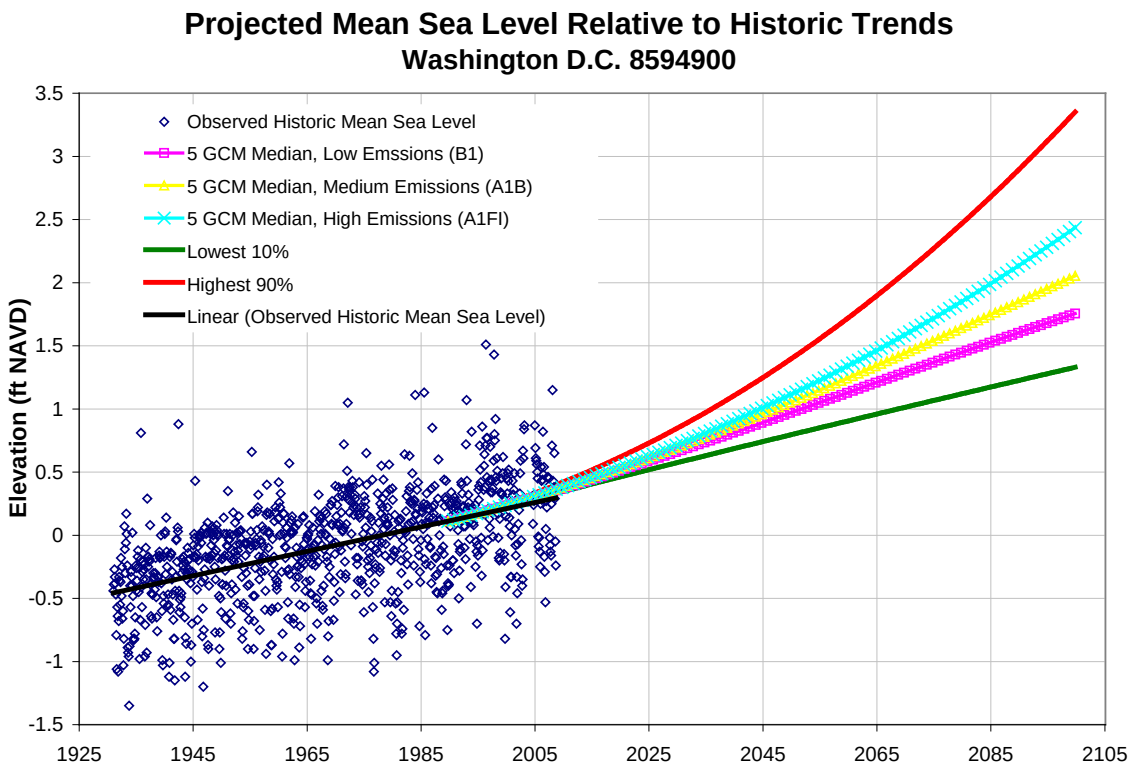
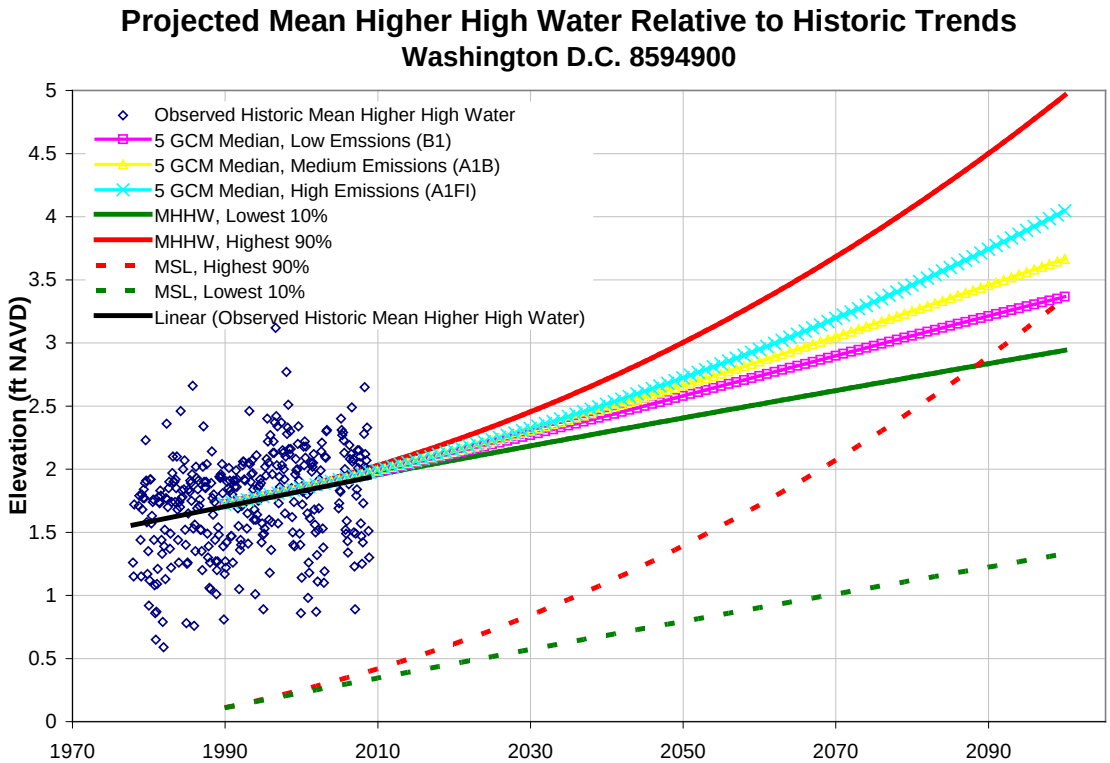


FIGURE 2-7
Derived Projection of Mean Higher High Water Levels (1990 through 2100) Relative to Observed Historic Values and Trend (1978 through 2008) at Washington, D.C. (8594900)
City of Alexandria Storm Sewer Capacity Analysis



A review of relevant literature on sea level rise in the Chesapeake Bay area was conducted. The literature indicated a range of sea level rise from 2.7 to 3.4 feet in one study, and from 1.6 to 4.6 feet in another study by 2100. The literature generally corroborates the projections developed in this report.

Therefore, it is projected that future infrastructure planning take into account possible increases in sea level of between 3.3 and 4.0 feet for MHHW, in addition to water levels projected in the Potomac River, because of storm surge and flood flows in the Potomac River.

With current 10-year water surface elevations in the Potomac River of approximately 5.4 feet NAVD, the projected water surface for the 10-year event with sea level rise is between 8.7 and 9.4 feet NAVD. Similarly, with current 100-year water surface elevations in the Potomac River of approximately 9.9 feet NAVD, the projected water surface for the 100-year event with sea level rise is between 12.2 and 13.9 feet NAVD.

Additional details are documented in Binder 1, TM 4 (Task 1.4).

2.5 Recommendations on Design Criteria

During the Hooffs Run watershed modeling task, three different design storm scenarios and one historic event were investigated: the City's existing IDF curve, the updated IDF curve using the full record of historical precipitation data (1949 to 2008), the IDF curve projected for the year 2100 using various climate change scenarios, and the June 25 through 27, 2006, storm event. The results of the Hooffs Run analyses showed that the existing IDF design hyetograph was the most conservative of the design storms (produced the greatest amount of stormwater runoff and flooding), and produced a similar amount of the system flooding to the results from the historic event. Consequently, this scenario was chosen to be used to complete the stormwater capacity analysis for the other watersheds. During this analysis a current and future tidal boundary conditions were also considered. The existing boundary condition was selected for use in the remainder of the project. Details on this analysis are provided in the Stormwater Capacity Analysis for Hooffs Run, City of Alexandria, Virginia, located in Binder 2.

SECTION 3

Design Guidelines for Flow-through BMPs and use of Unit Hydrographs

The City requested evaluation and development of design criteria to be set forth by the City for flow-through type best management practices (BMPs) to facilitate updates to the City's drainage criteria. This section documents the information gathered on these topics and resulting recommendations.

3.1.1 Unit Hydrographs

Given the limited amount of data available, the fact that the characteristics of the City watersheds (slope and depression storage) are not particularly atypical, and the standard use of the NRCS hydrograph in the industry, the development of an Alexandria-specific unit hydrograph is not recommended at this time. Therefore, CH2M recommends that the City clarify in its drainage criteria that the NRCS unit hydrograph method should be used with a shape factor of 484 unless an applicant can demonstrate that a different method (or shape factor) is justified for a particular development.

3.1.2 Flow-Through BMP Design Guidelines

The Claytor and Schueler 1996 method appears to have become a commonly accepted approach for converting a water quality volume into a peak discharge. It formed the basis of the method recommended in the *Virginia Stormwater Management Handbook, Second Edition* (VDEQ, 2013). The approach is logical and consistent with VA DEQ recommendations and is therefore recommended for use in the City. Using TR-55, an NRCS Type II 24-hour storm, and the 0.95 inches of runoff for impervious areas is an acceptable alternative for most sites which produces very similar results.

Additional details are documented in Binder 1, TM 5 (Task 1.5), along with specific summary and a sample application of the recommended design methodology.

SECTION 4

Existing Stormwater Capacity Analysis

Task 2 focused on the hydrologic and hydraulic analyses of the existing storm sewer collection system. The objective of this phase of the study was to identify the deficient stormwater collection system elements in the City during a 10-year return period rainfall event.

4.1 Modeling Approach

Individual hydrologic and hydraulic models have been developed for each watershed using the xpswmm software to simulate rainfall-runoff processes as well as the hydraulic performance of the stormwater collection system during a 10-year design storm event. The watersheds were divided into smaller catchments and the hydrologic parameters such as area, slope, width, and percent impervious were estimated using ArcGIS, Arc Hydro Tools, and ArcGIS version of HEC-GeoHMS. In most parts of the system, the model ends at the point where the storm sewer outfalls into open channel; however, where the storm sewer system discharges to an open channel that re-enters the closed-pipe collection system downstream, the open channel was included in the model to connect the upstream and downstream pipe systems. One example of this is Timber Branch in Hooffs Run Watershed.

The scope of work included modeling approximately 20 percent of inlets in the storm sewer system, so not all pipes in the storm network were analyzed. The extent of the system analyzed in the model includes a total of 7,160 drainage junction points (catch basins, culvert points, drainage inlets, manholes, nodes [blind connections], and pipe inlet/outlets) and 6,878 segments of sewer pipes. This equates to approximately 128 miles of pipe, representing 63 percent of the total storm sewers in the City. Table 4-1 summarizes some of the statistics for the GIS and analyzed representation of each watershed.

TABLE 4-1
Summary of Model Statistics by Watershed
City of Alexandria Storm Sewer Capacity Analysis

			GIS Data			System Analyzed with Models		
Watershed	**Drainage Area Square Miles**	**Percent impervious**	**Number of Junctions**	**Number of Pipes**	**Length of Pipes**	**Number of Junctions**	**Number of Pipes**	**Length of Pipes**
Hooffs Run	2.53	44	3,496	3,068	208,824	1,555	1,535	140,095
Four Mile Run	3.21	44	3,906	3,454	242,438	1,708	1,683	158,758
Holmes Run	2.88	41	2,279	2,135	172,327	896	822	98,019
Taylor Run	1.36	35	1,266	1,158	78,947	741	709	58,308
Cameron Run	2.70	44	1,589	1,465	112,493	851	790	82,086
Strawberry Run	0.54	32	489	461	36,293	260	240	25,038
Backlick Run	1.22	59	1,158	1,105	96,628	495	481	57,255
Potomac River	1.30	45	1,861	1,720	129,466	654	615	66,060
TOTAL	**15.24**	43	**16,044**	**14,566**	**1,077,416**	**7,160**	**6,875**	**685,619**

4.2 Existing Collection System Capacity

The hydraulic models were used to predict water surface elevations within the collection system to identify flooding or potential for flooding due to capacity limitations of the pipes. The hydraulic models predicted the storm sewer system is experiencing capacity deficiencies at several areas within each of the watersheds. The

model results predict that 22 percent of the analyzed pipes flood the ground surface, 16 percent have a hydraulic grade line within 2 feet of the surface, and 16 percent surcharge above the crown of the pipe and 47 percent have sufficient capacity. In addition, flows generated from the hydrologic model were compared to the estimated inlet capacity to evaluate potential limitations in inlet capacity. The results indicate that 50 percent of the catchments in the city may have insufficient inlet capacity. Model results for each individual watershed are summarized in Table 4-2. Exhibit 1 presents capacity limitations identified across the City and Exhibits 3A through 10 present the capacity limitations identified within each watershed. Maps and profiles of flooding areas are presented in the individual watershed TMs in Binder 2 to assist in locating problem areas and understanding the capacity deficiencies of the drainage system.

The hydraulic modeling results presented in this report should be reviewed with the understanding that several assumptions were made to fill data gaps, primarily assumptions of inverts in pipes with diameters less than 24 inches.

TABLE 4-2
Summary of Hydraulic Model Results (in Percent)
City of Alexandria Storm Sewer Capacity Analysis

Watershed	Total Conduit Length (Linear Feet)	Percent of Total Length				Runoff Input Points with Insufficient Inlet Capacity
		Sufficient Capacity	Surcharged	Insufficient Freeboard	Flooded	
Hooffs Run	140,095	32	11	20	37	40
Four Mile Run	158,758	46	14	16	24	60
Holmes Run	98,019	47	19	16	18	44
Taylor Run	58,308	37	18	17	27	48
Cameron Run	82,086	57	17	14	12	76
Strawberry Run	25,038	54	17	13	16	42
Backlick Run	57,255	48	30	13	9	50
Potomac River	66,060	70	13	9	9	26
TOTAL	**685,619**	**47**	**16**	**16**	**22**	**50**

SECTION 5

Condition Assessment and Field Verification

As part of the City's CASSCA project, a visual inspection of the storm sewer infrastructure within seven local watersheds (Four Mile Run, Holmes Run, Taylor Run, Backlick Run, Strawberry Run, Potomac River, and Cameron Run) was conducted between 2012 and 2014. This section summarizes the methods and results of the field investigations.

The inspections were performed by Video Pipe Services (VPS) using the "lamping" technique. Lamping involves the use of a pole-mounted optical zoom camera to visually assess the condition of the buried infrastructure. The lamping method is an unconfined space inspection procedure that does not require entry into a manhole. The use of an optical zoom camera allows field crews to remain at ground level of a storm structure and screen the structure and its connecting pipes for defects. The lamping technique is a preliminary inspection tool to assess the condition of buried infrastructure and determine if further investigation or repair is warranted. In addition to visually inspecting the stormwater structures and pipes, field crews from VPS obtained the size and invert measurements of storm pipes.

CCTV pipe inspections were also conducted in the seven investigated watersheds for the corrugated metal pipe (CMP) segments. The number of CMP segments represents a small fraction (less than 1 percent) of the total storm infrastructure length in the watersheds. The results of the CMP inspections were delivered to the City under separate cover.

The storm sewer structures and pipes were inspected utilizing the Pipeline Assessment and Certification Program (PACP) coding standards developed by the National Association of Sewer Service Companies (NASSCO), and were assessed further using the Sewer Condition Risk Evaluation Algorithm Model (SCREAM). The data collected from the field work was logged into a database using the *SCREAM Manhole and Lamping Inspection Field Tool.*

SCREAM is a system of assessment algorithms and tables that synthesizes data collected in the field and assigns a score to each structure or pipe segment, based on the inspection results. A scoring scale of 0 to 100 for each defect is automatically assigned when the operator enters the defect code. A score of 1 represents a very minor defect and a score of 100 represents the most severe defect. To represent the overall condition of a pipe or manhole, an overall score is derived from the scores of the individual defects utilizing the SCREAM program, as shown in Table 5-1. Note that the examples provided are meant to show a typical defect found in an asset that would result in the condition category rating.

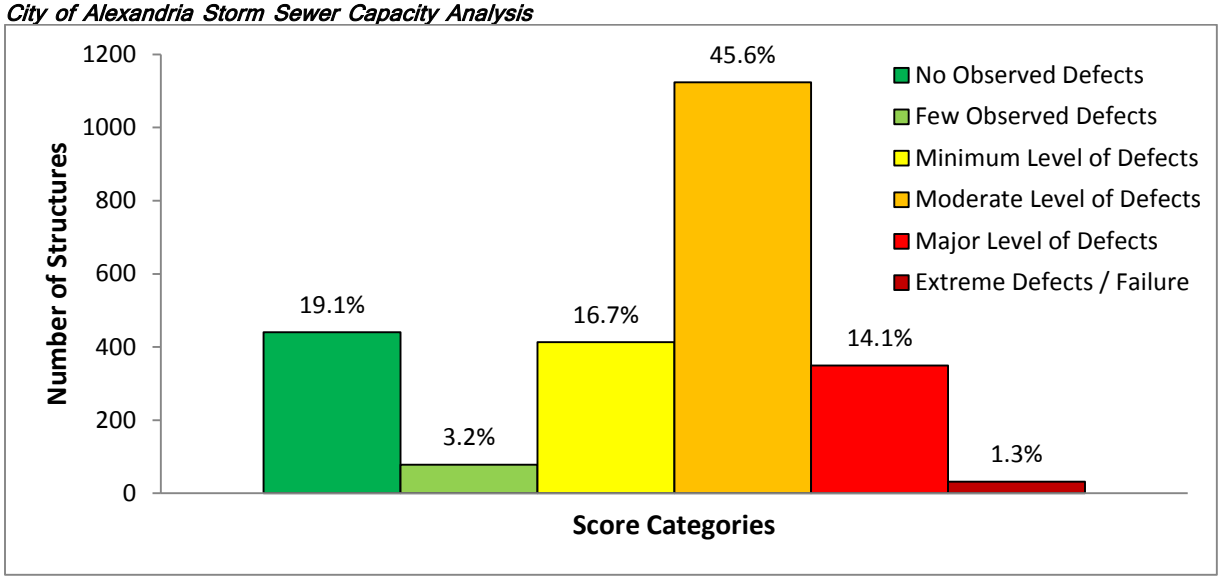
TABLE 5-1
SCREAM Defect Categories
City of Alexandria Storm Sewer Capacity Analysis

Defect Category	Score Range	Example
None	0	n/a
Few	1-20	Infiltration weeper
Minimum	21-40	Manhole cracks less than 1/8-inch
Moderate	41-60	Spalling of chamber wall, large infiltration flow
Major	61-80	Large cracks in cover or frame
Extreme	81-100	Collapsed pipe

5.1 Structure Inspections

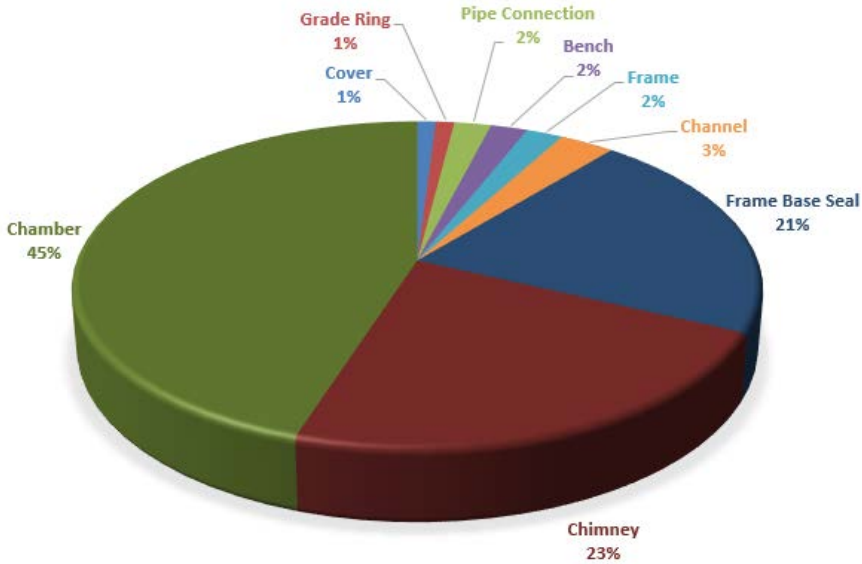
In total, over 2,400 storm structures were inspected in the seven watersheds of the City. Figure 5-1 presents the number and percentage of structures within each defect category. Approximately one percent of the structures inspected citywide had defects within the "Extreme" defect category. Nineteen percent of the structures had no observed defects. The average structure defect score for each watershed ranged from 29 (Potomac River) to 45 (Four Mile Run and Holmes Run). Refer to the separate Condition Assessment Memoranda for additional details about the condition of structures within a specific watershed.

FIGURE 5-1
Structure Inspections Summary
City of Alexandria Storm Sewer Capacity Analysis



To further assess the condition of the structures, the inspection results of the structures were broken down by structure component. Defects were most frequently observed in the chamber, chimney, and frame base seal components of storm structures throughout the City. Other components, such as the cover and pipe connections, had a smaller share of the observed defects but tended to be more severe when defects were observed. Figure 5-2 outlines the percentages of the observed component defects.

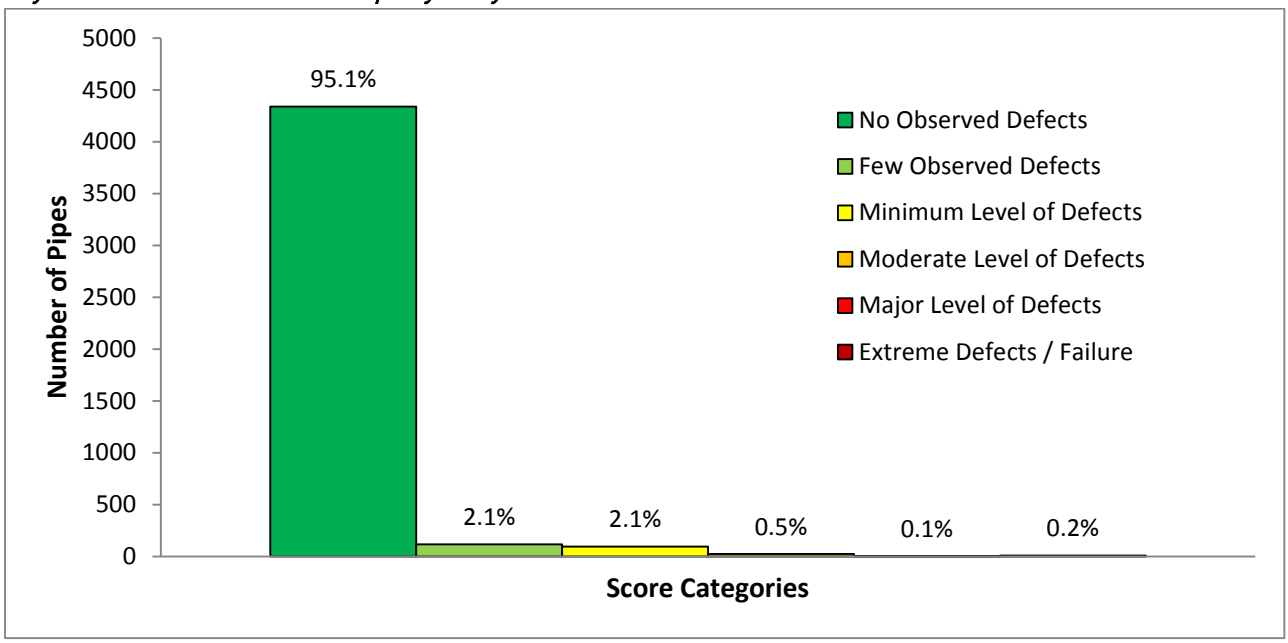
FIGURE 5-2
Summary of Defects by Manhole Component
City of Alexandria Storm Sewer Capacity Analysis



5.2 Pipeline Inspections

Over 4,500 storm sewer pipe segments were inspected as a part of the condition assessment effort. Inspection results in the City's watersheds showed that the pipe segments were observed to be in generally good condition, with no defect observed in approximately ninety-five percent of the pipes. Figure 5-3 presents the number and ratio of pipe segments within each defect category. Approximately four percent of the pipes were found to have "few" or "minimum" defects. Less than one percent of the pipe segments inspected had defects in either the "moderate", "major", or "extreme" categories. The average pipe segment defect score for each watershed ranged from 0.2 (Backlick Run) to 2.4 (Four Mile Run). Refer to the separate Condition Assessment Memoranda for additional detail about the condition of structures within a specific watershed.

FIGURE 5-3
Pipeline Inspections Summary
City of Alexandria Storm Sewer Capacity Analysis



SECTION 6

Problem and Solution Identification and Prioritization

Task 4 focused on problem and solution identification for capacity issues identified during Task 2 and was completed on a watershed basis as Task 2 modeling was completed. The objectives of this phase of the study were to identify and prioritize capacity problems based on modeling results from Task 2 of this project, and to develop and prioritize solutions to address those problems.

6.1 Problem Identification and Prioritization

The first objective was accomplished in two steps. The first step included evaluating each stormwater junction in the drainage network using a scoring system to identify problems based on several criteria, including the severity of flooding, proximity to critical infrastructure and roadways, identification of problems by City staff and the public, and opportunity for overland relief. In the next step of this objective, high-scoring junctions (that is, higher-priority problems) were grouped together to form high-priority problem areas. In total, 90 high-priority problem areas were identified across the City. Flooding locations falling outside of the high-priority problem areas were either flooding at isolated structures, or did not score high on the problem identification scoring criteria. These flooding problems were not addressed in this project. Figure 6-1 shows the junction scores and resulting high priority problem areas across the City. It is apparent when looking at the City as a whole that the highest density of flooding of the most concern is in Hooffs Run and Four Mile Run.

6.2 Solution Identification and Prioritization

The second objective involved developing and prioritizing solutions to address capacity limitations within the high-priority problem areas. This task was completed for each of the problem areas, with the exception of the seven in the Potomac River watershed, where solutions were deferred until after completion of substantial ongoing development in the watershed. To accomplish this objective, several strategies involving different technologies were examined, including improving conveyance by increasing hydraulic capacity, reducing capacity limitations by adding distributed storage to the system, and reducing stormwater inflows by implementing GI. Each of these strategies required a different modeling approach. Conveyance improvements were modeled by increasing pipe diameter in key locations within the problem area, storage was added as storage nodes based on a preliminary-siting exercise, and GI was modeled as a reduction in impervious area at three different implementation levels (high, medium, and low). A single model run was set up and run for each strategy addressing all of the high-priority problem areas in a given watershed and the results were compiled for the alternatives and prioritization evaluation. Solutions were evaluated based on several criteria, including drainage improvement/flood reduction, environmental compliance, sustainability and social benefits, asset management and maintenance implications, constructability, and public acceptance. Planning-level capital costs were developed for each solution to facilitate a benefit/cost analysis and prioritization process.

FIGURE 6-1
Junction Scores and High Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis

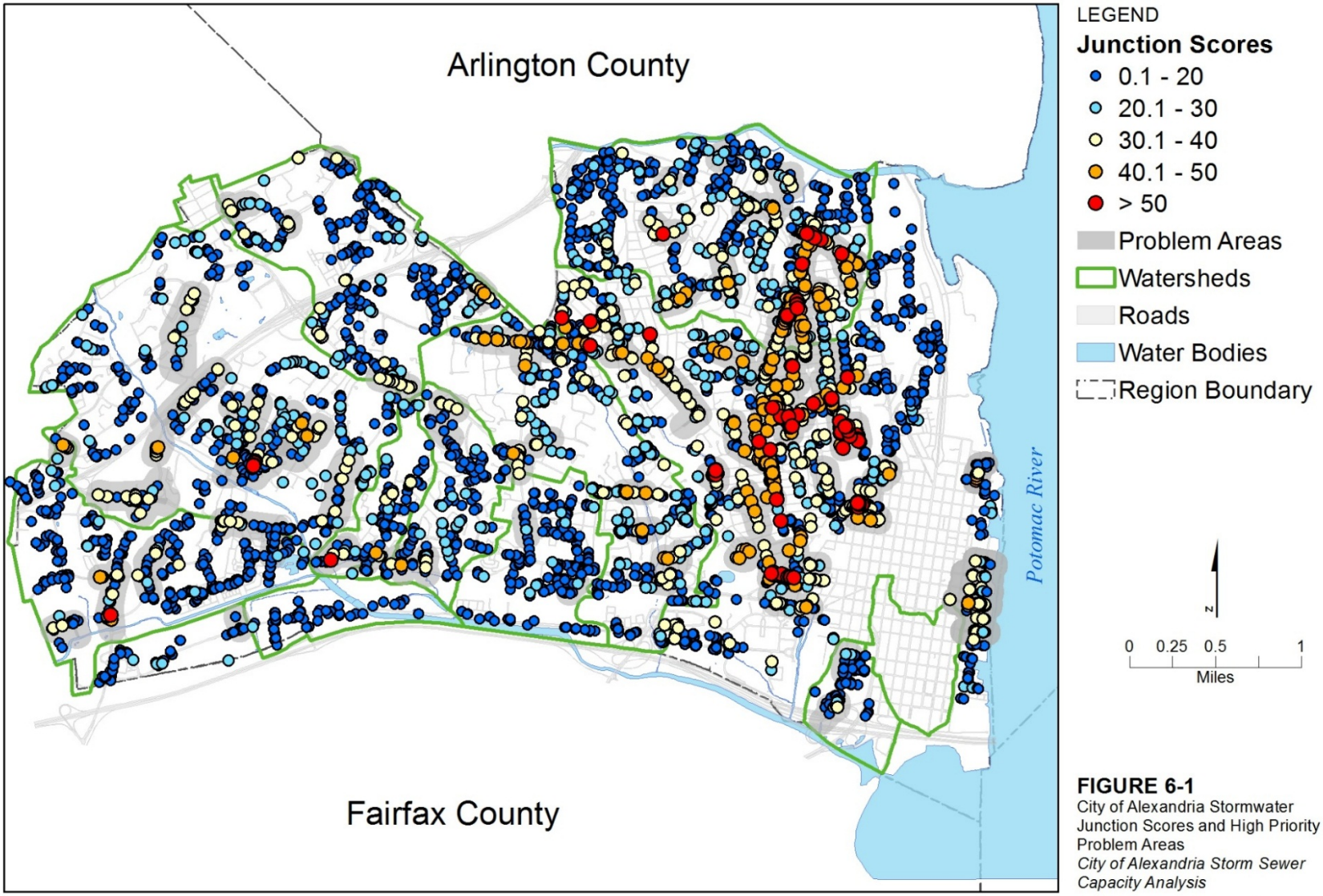


FIGURE 6-1
City of Alexandria Stormwater Junction Scores and High Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis

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The results of the solution identification and prioritization analysis show the following general results across the City:

- In terms of solution technology performance:
  - GI solutions generally have the greatest overall benefit.
  - Conveyance, Storage, and High GI solutions generally provide significant flood reduction for the problem areas analyzed.
  - The combination of conveyance or storage projects and GI generally provides the greatest benefit and flood reduction.
- In terms of costs:
  - A low level of GI implementation generally has the greatest benefit/cost score, but did not usually provide significant enough flood reduction.
  - Combination of conveyance and GI generally provides the greatest overall benefit/cost score.
  - The cost per gallon ($/gallon) of flood reduction is highly dependent on the problem area, but in general, conveyance and storage projects provide the most economical stormwater volume reduction in terms of $/gallons of flood reduction within a high-priority problem area.

Three watershed-wide alternatives were developed, including:

- Alternative 1: Most cost-effective solution for each problem area (lowest $/gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to address the worst problem areas to the extent practicable

The results for each alternative reflect the objective upon which it was built to some degree. A preferred alternative was selected for each watershed based on best engineering judgement. A summary of the results for the preferred alternative for each watershed is provided in Table 6-1. Model results for the existing conditions model and the preferred watershed-wide alternative are presented citywide in Exhibits 1 and 2 and for each watershed in Exhibits 3A/B through 10A/B.

TABLE 6-1
Watershed-wide Alternatives Scoring and Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis

Watershed	Number of Problem Areas	Total Capital Cost ($ Millions)	Total Benefit Score	Overall Benefit/ Cost	Total Flood Reduction (MG)	Cost of Flood Reduction ($/Gallon)	Preferred Alternative
Hooffs Run*	23	$18.26	978	54	7.36	$2.48	3
Four Mile Run	23	$24.46	939	38	11.53	$2.12	3
Holmes Run	9	$5.76	433	75	2.78	$2.07	2
Taylor Run	12	$4.89	516	106	4.43	$1.10	2
Cameron Run	8	$3.65	360	99	2.27	$1.61	1
Strawberry Run	3	$0.27	88	322	0.05	$5.77	3
Backlick Run	5	$3.96	229	58	1.39	$2.86	3
Potomac River	7	n/a	n/a	n/a	n/a	n/a	n/a
TOTAL	90	$61.29	3543	58	29.81	$2.06	n/a

MG = million gallons
Total existing volume of flooding in the problem areas (not including Potomac River) is 46.02 MG.

The preferred technology for a problem areas depended significantly on its location within the watershed and the severity of flooding. Conveyance solutions increase the capacity of the pipe and send large flow

downstream, which can increase flooding in downstream problem areas. If there was limited collection system downstream the conveyance solutions were more likely to be selected. GI solutions require implementation throughout the upstream watershed. The smaller the upstream watershed, the lower the cost, and the more cost effective the solution can be. Therefore GI solutions tended to be more common where the problem area drainage areas are smaller. Based on the preferred alternatives a total of 38 conveyance projects, 16 storage projects and 29 GI projects were selected. Figure 6-2 shows the selected technology for each problem area.

As part of evaluating the cost and potential for implementing GI within the City, a desktop evaluation was conducted to identify the land areas that presented the greatest opportunities. Several GI technologies were considered feasible within the City, including:

- **Bioretention/Planters** – Planted depression or constructed box with vegetation that typically receives runoff from roadways or rooftops; includes vegetation and soil media over an underdrain and filtration fabric. The City does not typically encourage infiltration; therefore, rain gardens, which typically do not have an underdrain, are not encouraged.
- **Cisterns** – A tank for storing water, typically connected to a roof drain that can be either above or below ground. Water from a cistern is typically reused or slowly infiltrated into the soil rather than discharged to a storm sewer.
- **Green/Blue Roofs** - A roof of a building that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane (green roof) or a roof that is capable of storing and then slowly releasing rainwater (blue roof).
- **Porous Pavement** - Paving surfaces designed to allow stormwater infiltration; may or may not include underground storage component.
- **Surface Storage** – Retrofit of inlets and catch basins to include flow regulators on streets with a standard curb and gutter system so that stormwater can be stored within the roadway and slowly released back into the storm sewer system.
- **Amended Soils** – Altering soils to improve water retention, permeability, infiltration, drainage, aeration, and/or structure.

These technologies were grouped into GI programs based on the land uses where they could be applied. A program combines a set of technologies into an implementation strategy for different types of sites and land use categories. Programs being considered are described as follows:

- **Green Streets/Alleys** – Includes bioretention/planters and porous pavement combined along the public ROW between buildings and roadways; can include parking lane and curb cuts.
- **Green Roofs** – Includes green/blue roofs, sometimes in combination with cisterns.
- **Green Schools** – Use of school properties to implement one-to-many GI management strategies, including bioretention/planters, cisterns, green/blue roofs, and porous pavement.
- **Green Parking** – Bioretention/planters and porous pavement in parking lots.
- **Green Buildings** – Use of bioretention/planters, cisterns, and/or downspout disconnection on public or private buildings.
- **Blue Streets** – Short-term surface storage on streets with relatively flat slopes and standard curb and gutter systems.
- **Open Spaces** – Use of open spaces to store and/or infiltrate stormwater using a combination of detention, amended soils, bioretention/planters, and/or porous pavement; may also include stream daylighting where appropriate.

FIGURE 6-2
Selected Technology by Problem Area
City of Alexandria Storm Sewer Capacity Analysis

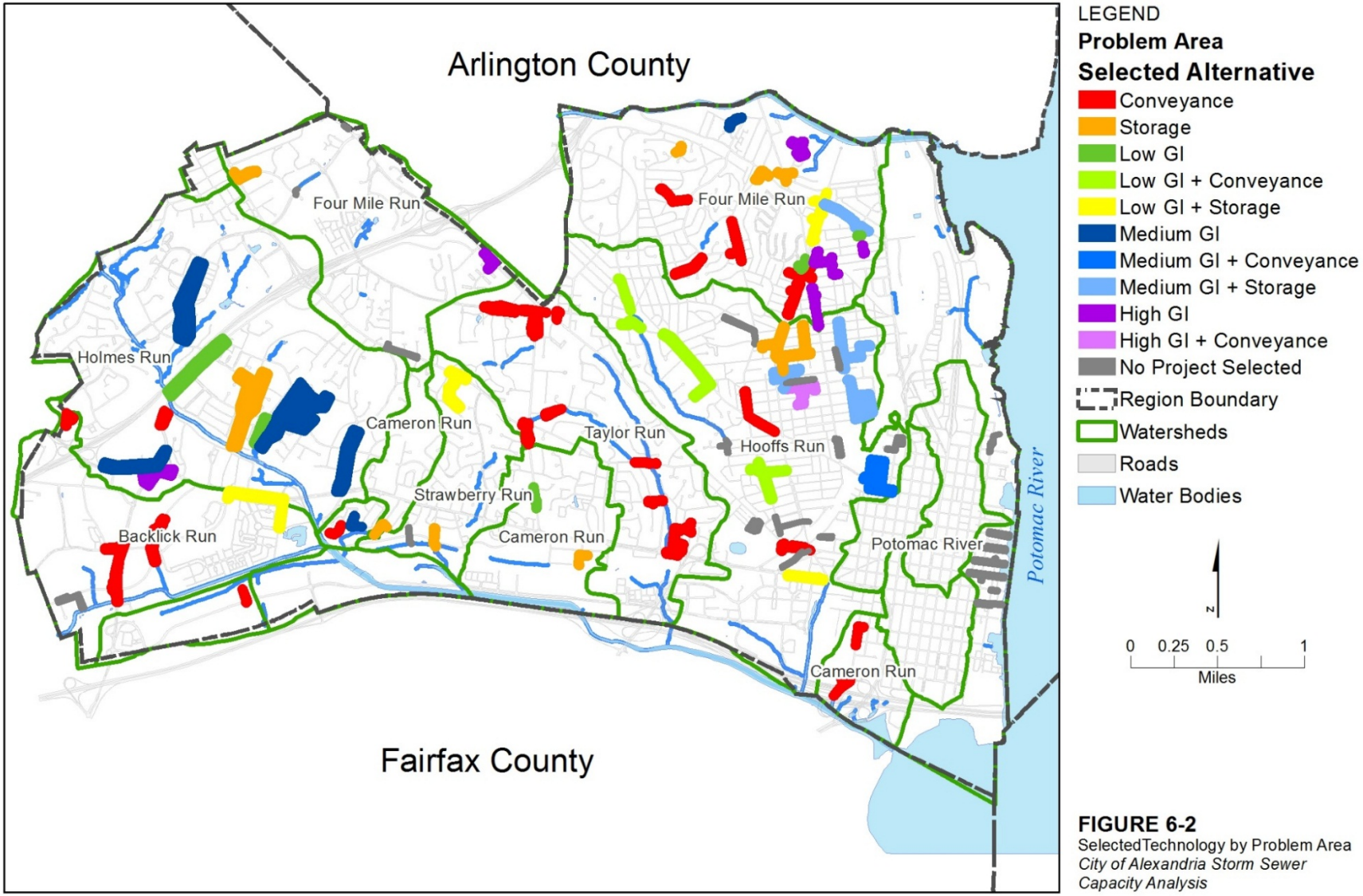

FIGURE 6-2
SelectedTechnology by Problem Area
City of Alexandria Storm Sewer Capacity Analysis

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Figure 6-3 maps the opportunities identified during the desktop analysis, based on existing landuse and constraints such as slope and street width. This map was used to determine the potential mix of GI technologies that could be implemented within a given watershed.

GI Concept Plans were also developed for each watershed as an example of the different green infrastructure programs. These plans could be used as a starting point for demonstration projects or conversations with landowners. Figure 6-4 shows the locations of the Concept Plans. The Concept Plans, along with addition details about each site are provided in each of the individual reports.

When developing a Capital Improvement Plan, the benefit/cost or cost efficiency ($/gallon of flood reduction) are typically used to guide the order in which projects are implemented. Solutions within each watershed-wide alternative were prioritized for each watershed and are presented in Figure 6-5.

It should be noted that the model does not include analysis on private property, but applies assumed runoff loads as inputs to the public conveyance system. The City chose not to include existing private or public stormwater management (SWM) facilities upstream of the modeled collection system because of the limited available information on these facilities and a concern that the facilities may not be performing as designed. When the City moves forward into detailed evaluation and design of selected projects, it will be important to fully evaluate and account for the benefits of any existing SWM facilities.

The hydraulic modeling results and proposed solutions and costs presented in this report were developed on a planning level.

6.3 Hooffs Run Analyses

Because it was the initial watershed analyzed and because of some of the site-specific conditions there were some unique analyses completed in Hooffs Run.

6.3.1 Major Capacity Solutions

In the Task 2 modeling results, two areas in the Hooffs Run Watershed (Hooffs Culvert and Braddock & West Intersection) experience extreme capacity limitations with long backwater impacts. Because the backwater impacts limit the ability to identify and prioritize solutions for localized capacity limitations, major capacity projects were developed to improve backwater conditions prior to evaluating problems and solutions in the watershed. A conveyance and a storage option were evaluated for each of major capacity problem areas.

In addition to the major capacity projects, 9 baseline projects were identified in the Hooffs Run Watershed. Baseline projects were identified in locations where significant changes in the hydraulic-grade line (HGL) were observed due to sudden diameter or slope change. The baseline improvement projects include replacement of approximately 1,910 linear feet of pipe, for an estimated capital cost of $0.83 million. Because many of the baseline projects include short lengths of pipe with extreme or sudden slope or diameter change, it is possible that the data contains errors; therefore all nine projects may not be necessary.

6.3.2 Evaluation of Ordinance Changes

The intent of the current study was to identify existing capacity limitations in the system and potential solutions, however future land use changes were not considered. The City stormwater ordinances focus on development and redevelopment projects, therefore would not affect the results of this study. However, the City has modified City Ordinance Section XIII to comply with new state requirements, and the more stringent requirements included in the ordinance creates an avenue for implementation of the projects that are identified in this report. More details on this analysis are provided in the Hooffs Run report in Binder 4.

FIGURE 6-3
Green Infrastructure Opportunities based on Desktop Analysis
City of Alexandria Storm Sewer Capacity Analysis

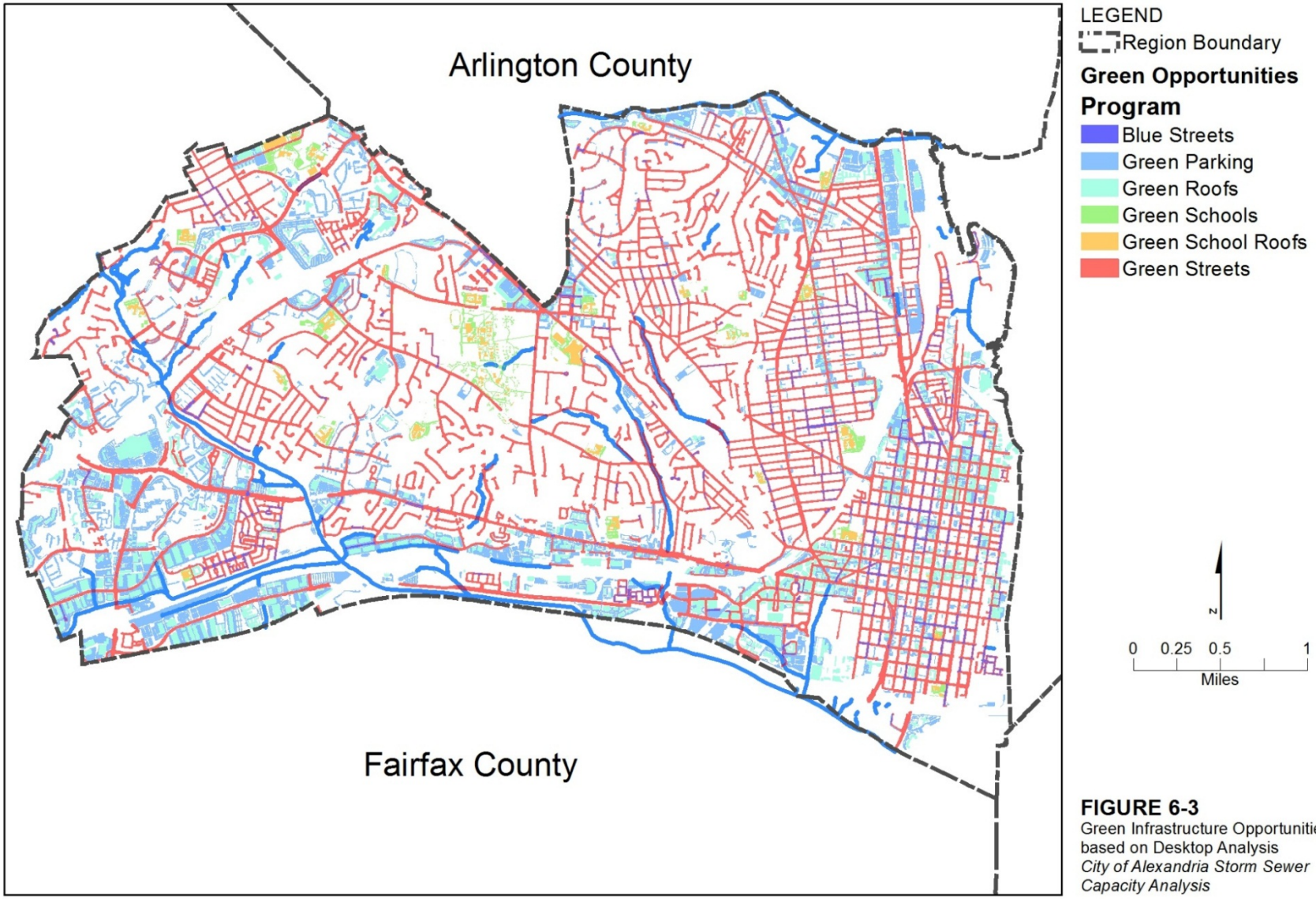

FIGURE 6-3
Green Infrastructure Opportunities based on Desktop Analysis
City of Alexandria Storm Sewer Capacity Analysis

CH2MHILL

FIGURE 6-4
Concept Area Locations
City of Alexandria Storm Sewer Capacity Analysis

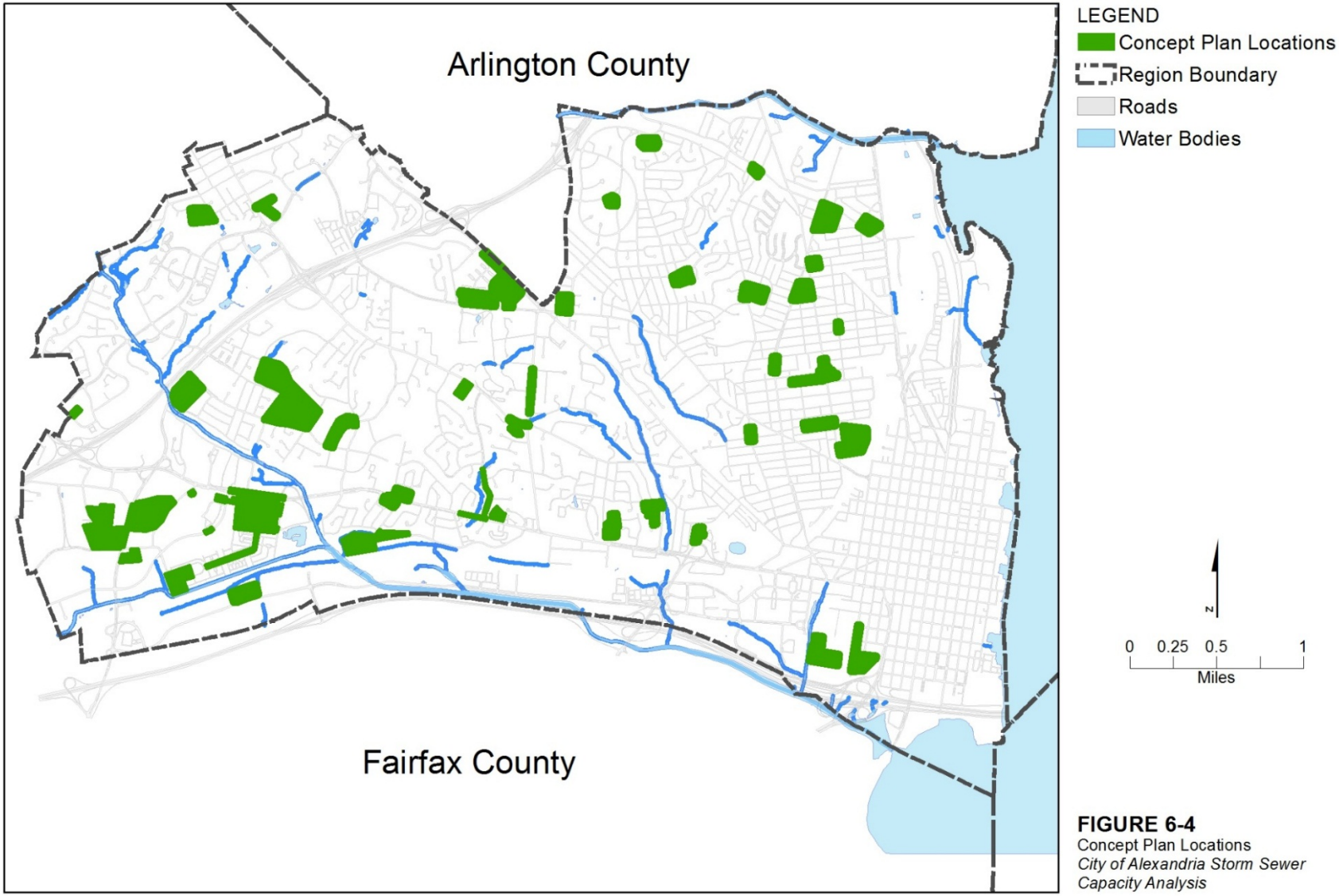

FIGURE 6-4
Concept Plan Locations
City of Alexandria Storm Sewer Capacity Analysis

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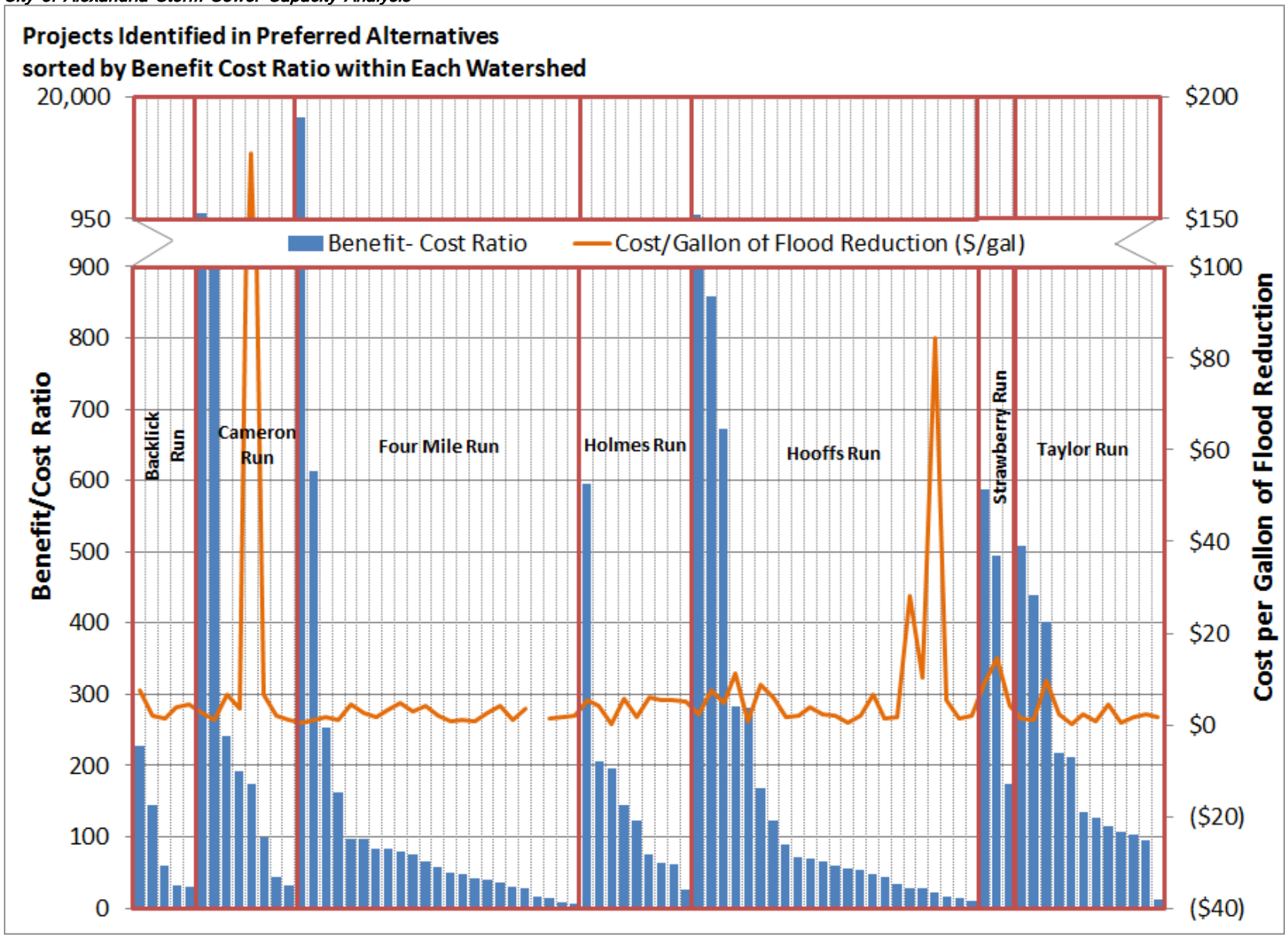
FIGURE 6-5
Recommended Alternative Projects Prioritized Projects by Watershed
City of Alexandria Storm Sewer Capacity Analysis



SECTION 7

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SECTION 8

Public Involvement Materials

As a culmination of the work within each watershed a summary fact sheet was developed for use in outreach within the City staff, as well as to the public. Fact sheets were also developed to help describe the features of each of six different green infrastructure technologies: Bioretention, Blue Streets, Cisterns, Green Roofs\Blue Roofs, Porous Pavement, and Soil Amendment. These fact sheets are provided in in the following pages.

Watershed Summary Fact Sheets

CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS

HOOFFS RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Hooffs Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Hooffs Run watershed covers approximately 1,650 acres (2.6 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Hooffs Run watershed is 43% impervious, the majority of which is buildings and roads. Stormwater runoff is conveyed to the Hooffs Run stream through a network of over 200,000 linear feet of pipe and streams, including Timber Branch and Old Cameron Run. Approximately 140,095 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Hooffs Run Watershed

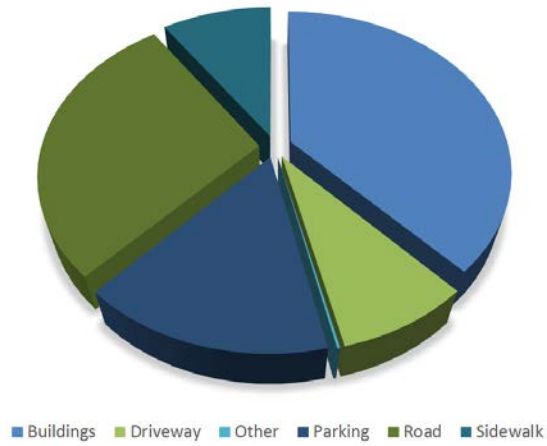
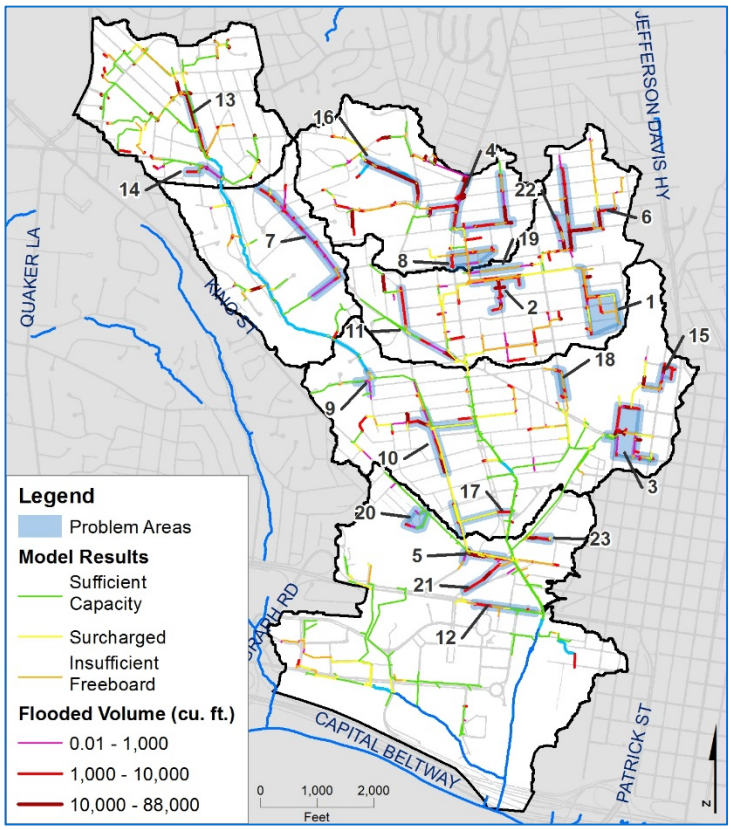


TABLE 1 Modeled Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 160"
Number of Pipe Segments	806	381	173	175
Length of Pipe (LF)	57,197	44,067	20,298	18,533

FIGURE 2
Hooffs Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Hooffs Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 37% of the system may experience flooding and 20% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 11% of the system may be surcharged such that the water surface rises above the crown of the pipe and cause the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 23 problem areas in the Hooffs Run watershed were identified for solution development (see Figure 2; problem areas annotated with numbers 1-23).

ALTERNATIVES ANALYSIS

For each of the 23 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 23 problem areas

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 23 problem areas

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas (1 to 14).

Alternative 3 was recommended as the preferred solution to alleviate flooding in Hooffs Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$19.65	$18.10	$18.26
Total Benefit Score	811	984	978
Overall Benefit/ Cost	41	54	54
Total Flood Reduction (Million Gal.)	6.90	6.82	7.36
Cost of Flood Reduction ($/Gallon)	$2.85	$2.65	$2.48

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Phone: 703.746.4057
email: brian.rahal@alexandriava.gov

FIGURE 3
Hooffs Run Watershed Alternative 3 Solution Benefit Cost Analysis

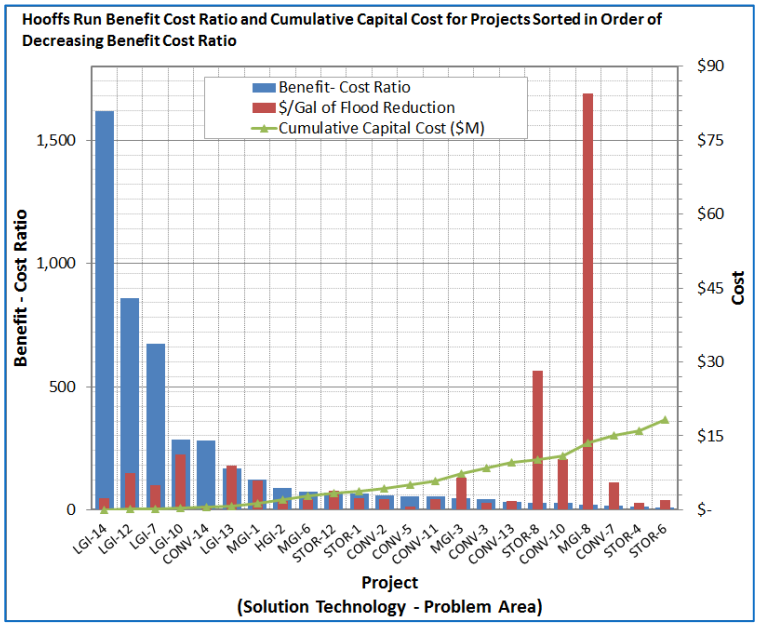
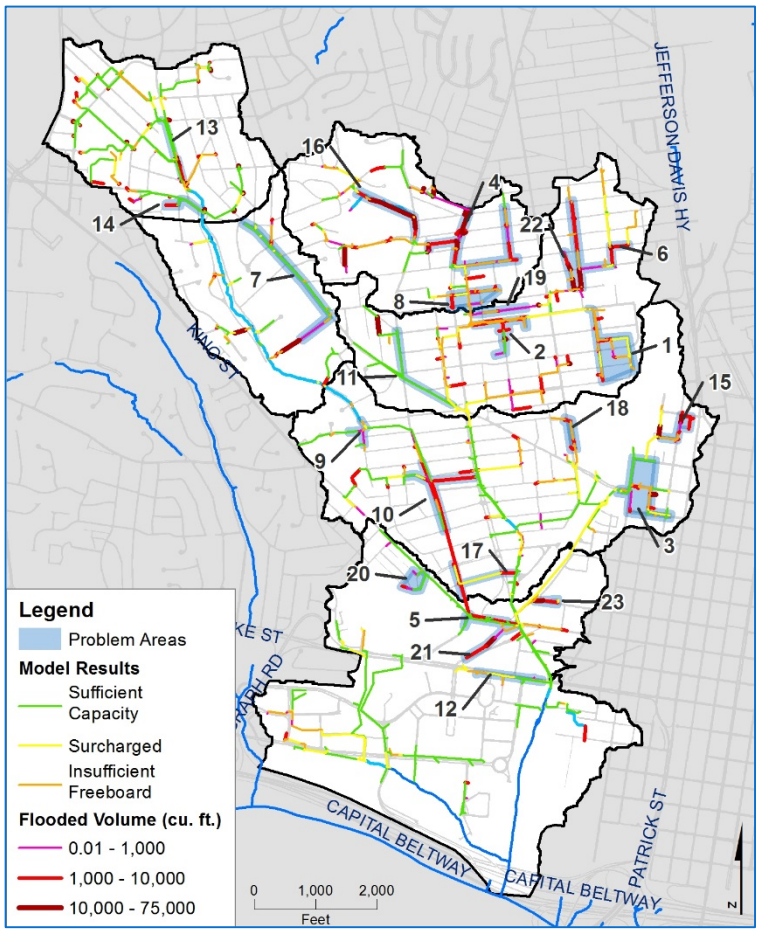
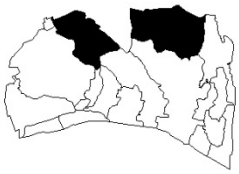


FIGURE 4
Hooffs Run Watershed Alternative 3 Solution Results



CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS



FOUR MILE RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Four Mile Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Four Mile Run watershed covers approximately 1,920 acres (3.0 mi^2) of the City of Alexandria. The FMR watershed within the City is composed of two hydrologically-separate areas referred to as FMR East (1.6 mi^2) and FMR West (1.4 mi^2). The Four Mile Run watershed is 47% impervious, the majority of which is buildings and roads. Stormwater runoff is conveyed to the Four Mile Run stream through a network of over 242,000 linear feet of pipe and streams and natural channels. Approximately 158,758 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Four Mile Run Watershed

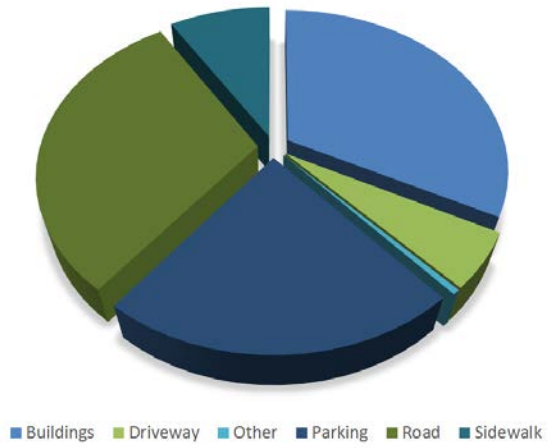
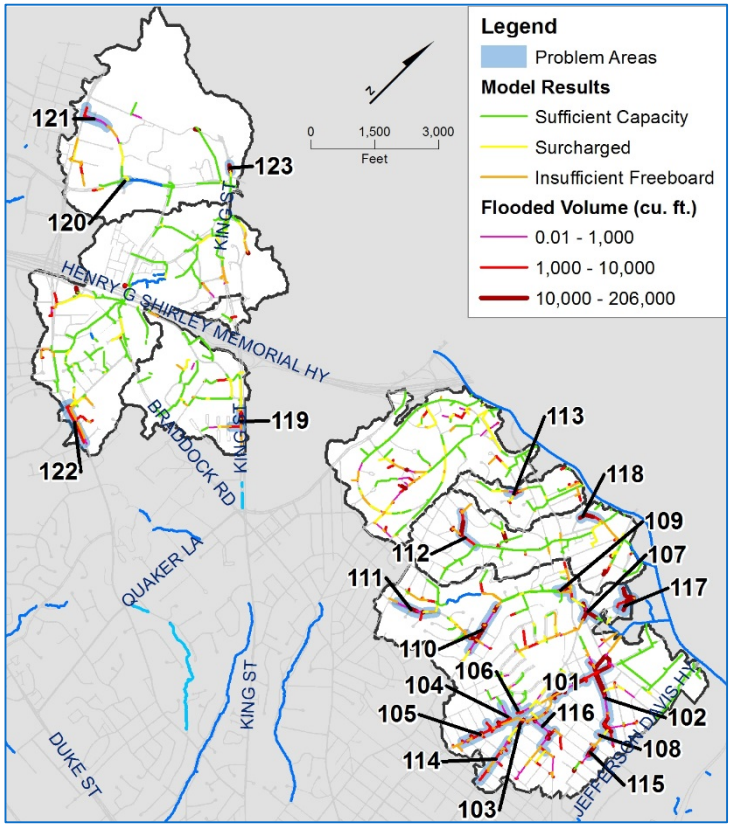


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 120"
Number of Pipe Segments	922	356	309	96
Length of Pipe (LF)	70,865	39,328	36,638	11,927

FIGURE 2
Four Mile Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Four Mile Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 24% of the system may experience flooding and 16% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 14% of the system may be surcharged such that the water surface rises above the crown of the pipe and causes the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 23 problem areas in the Four Mile Run watershed were identified for solution development (see Figure 2; problem areas annotated with numbers 101-123).

ALTERNATIVES ANALYSIS

For each of the 23 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 23 problem areas.

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 23 problem areas.

Alternative 3 – Highest-Priority Problems: a set of 23 projects that address the worst flooding in the highest priority problem areas.

Alternative 3 was recommended as the preferred solution to alleviate flooding in Four Mile Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$21.7	$19.8	$24.5
Total Benefit Score	754	954	939
Overall Benefit/ Cost	34.7	48.2	38.4
Total Flood Reduction (Million Gal.)	10.84	7.90	11.53
Cost of Flood Reduction ($/Gallon)	$2.00	$2.50	$2.12

FIGURE 3
Four Mile Run Watershed Alternative 3 Solution Benefit Cost Analysis

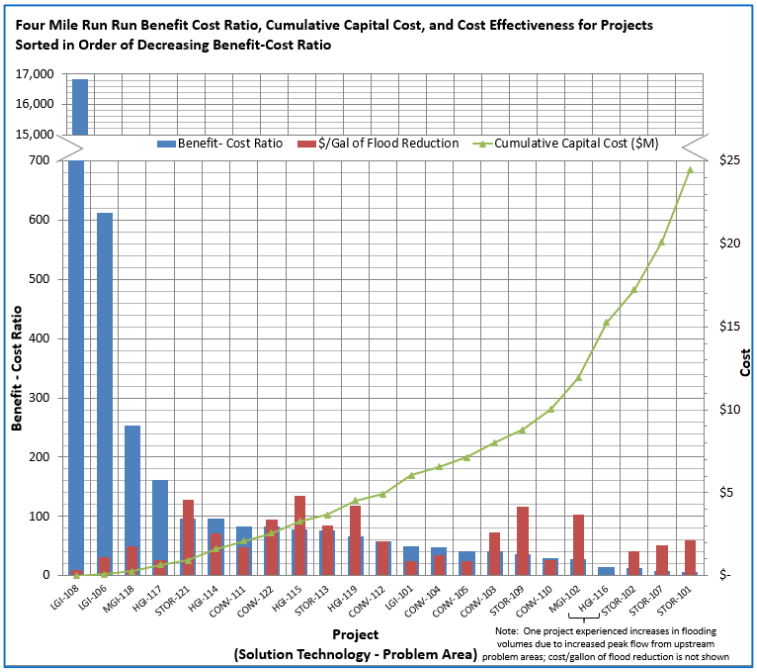
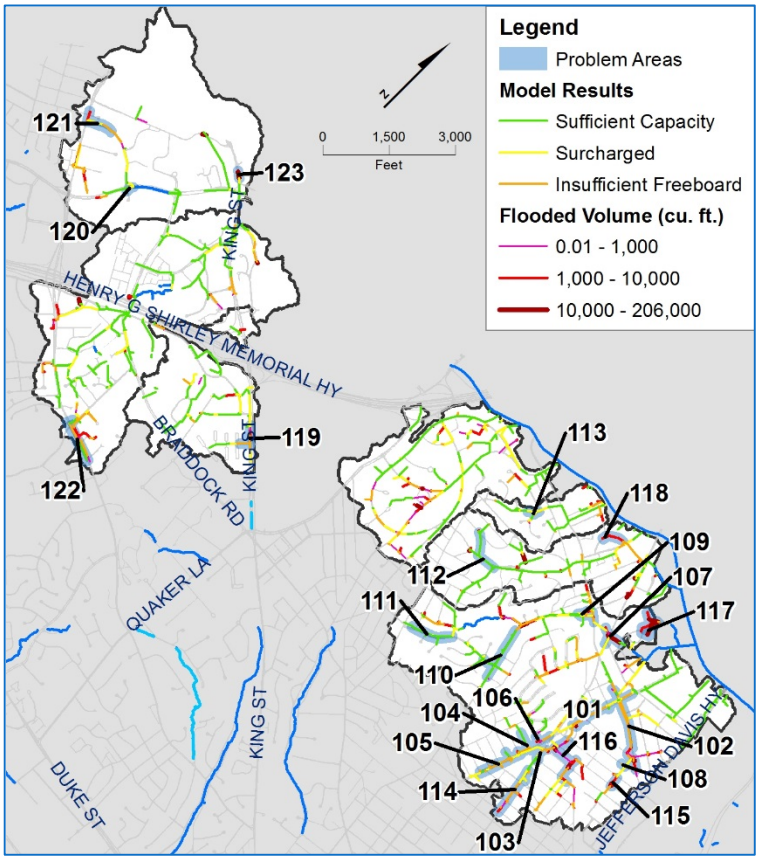


FIGURE 4
Four Mile Run Watershed Alternative 3 Solution Results



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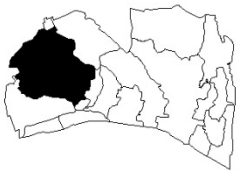
CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS



HOLMES RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Holmes Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Holmes Run watershed covers approximately 1,840 acres (2.9 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Holmes Run watershed is 39% impervious, the majority of which is buildings, parking lots and roads. Stormwater runoff is conveyed to the Holmes Run stream through a network of over 172,000 linear feet of pipe. Approximately 98,019 feet of pipes were analyzed.

FIGURE 1
Impervious Cover in Holmes Run Watershed

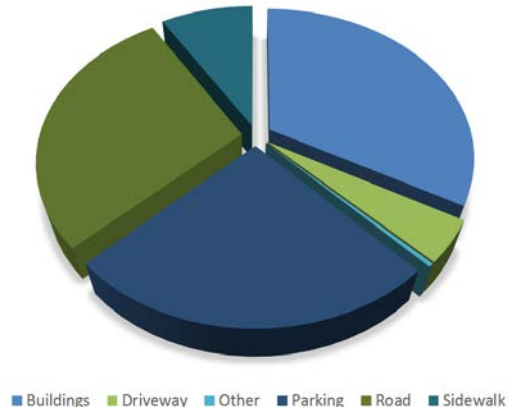
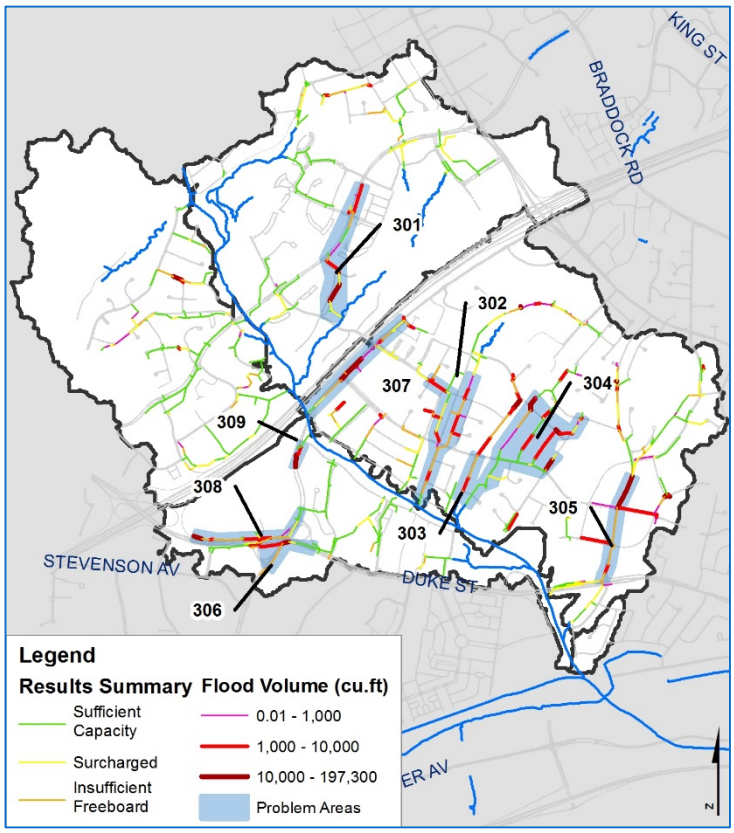


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 160"
Number of Pipe Segments	402	180	219	21
Length of Pipe (LF)	44,546	22,561	28,433	2,479

FIGURE 2
Holmes Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Holmes Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 18% of the system may experience flooding and 16% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 19% of the system may be surcharged such that the water surface rises above the crown of the pipe and causes the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 9 problem areas in the Holmes Run watershed were identified for solution development (see Figure 2; problem areas annotated with numbers 1-9).

ALTERNATIVES ANALYSIS

For each of the 9 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 9 problem areas

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 9 problem areas

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas (1 to 9).

Alternative 2 was recommended as the preferred solution to alleviate flooding in Holmes Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$8.30	$5.76	$18.97
Total Benefit Score	404	433	445
Overall Benefit/ Cost	48.7	75.1	23.5
Total Flood Reduction (Million Gal.)	3.620	2.780	4.743
Cost of Flood Reduction ($/Gallon)	$2.29	$2.07	$4.00

FIGURE 3
Holmes Run Watershed Alternative 2 Solution Benefit Cost Analysis

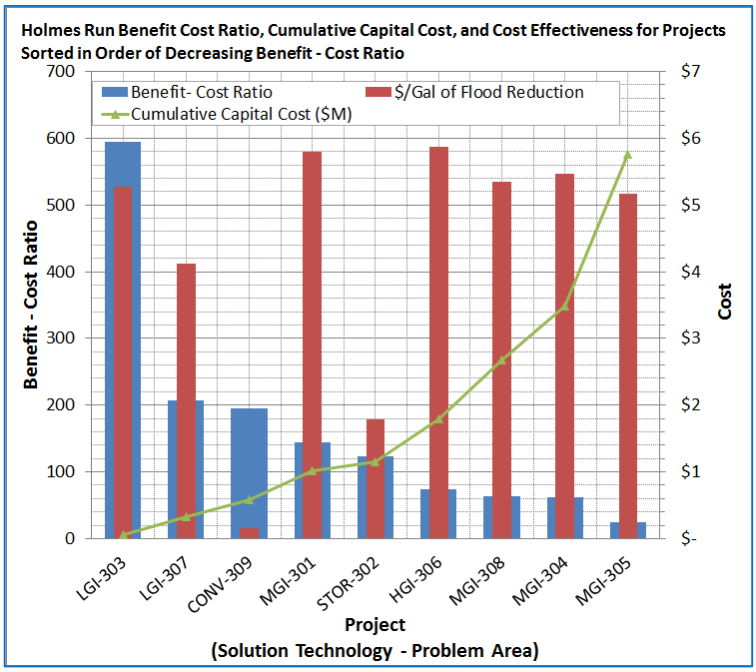
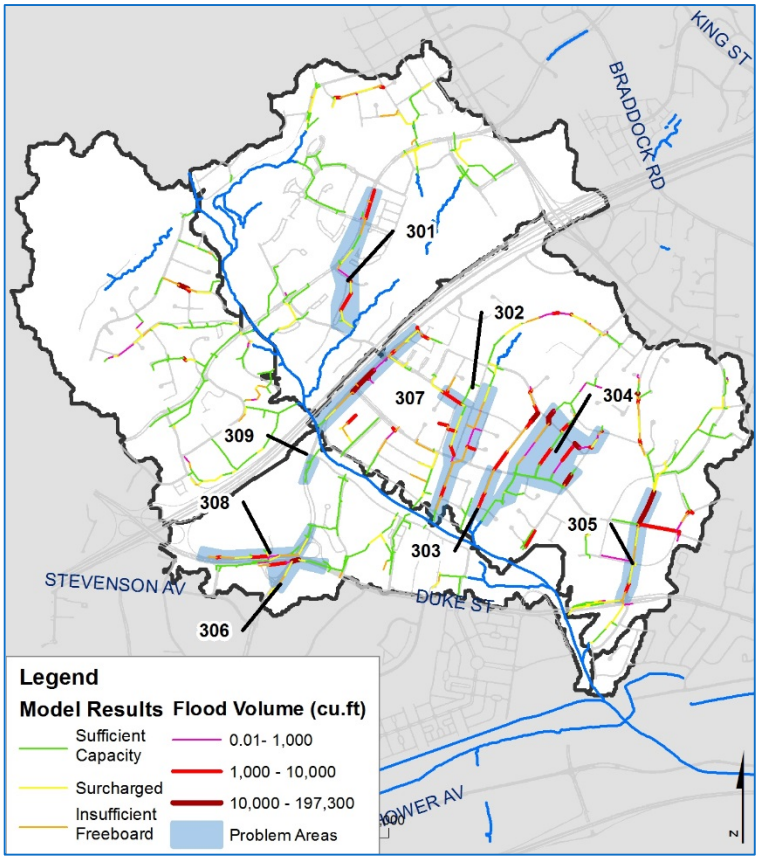


FIGURE 4
Holmes Run Watershed Alternative 2 Solution Results



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CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS

TAYLOR RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Taylor Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Taylor Run watershed covers approximately 868 acres (1.4 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Taylor Run watershed is 35% impervious, the majority of which is buildings, parking lots and roads. Stormwater runoff is conveyed to the Taylor Run stream through a network of over 80,000 linear feet of pipe. Approximately 58,308 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Taylor Run Watershed

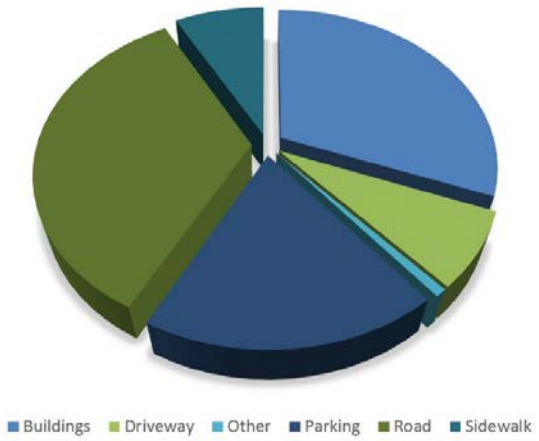
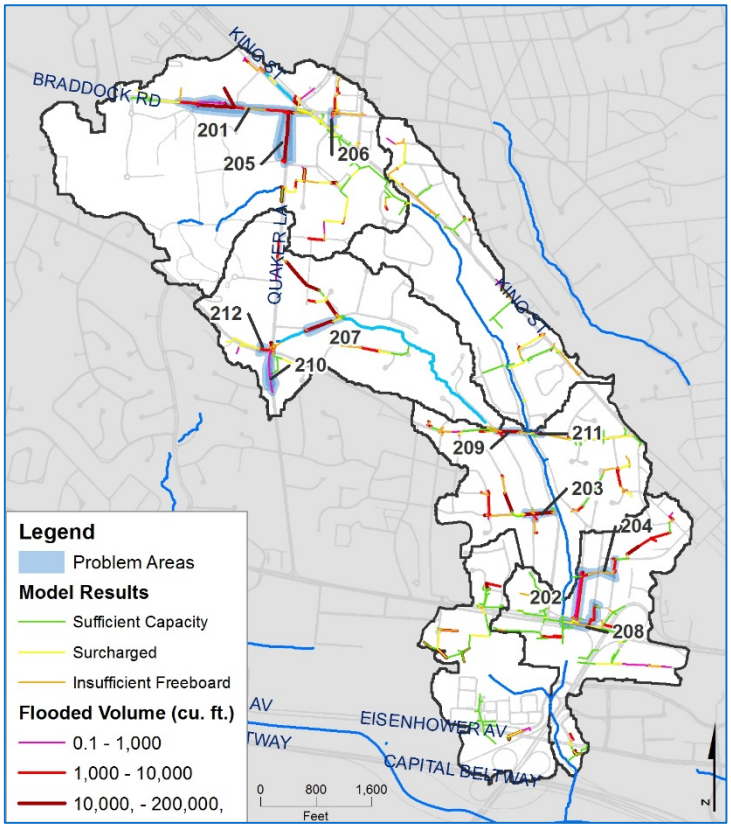


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 160"
Number of Pipe Segments	467	143	70	29
Length of Pipe (LF)	32,601	14,808	7,617	3,282

FIGURE 2
Taylor Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Taylor Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 27% of the system may experience flooding and 17% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 18% of the system may be surcharged such that the water surface rises above the crown of the pipe and causes the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 12 problem areas in the Taylor Run watershed were identified for solution development (see Figure 2; problem areas annotated with numbers 1-12).

ALTERNATIVES ANALYSIS

For each of the 12 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 12 problem areas

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 12 problem areas

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas (201 to 204).

Alternative 2 was recommended as the preferred solution to alleviate flooding in Taylor Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$4.87	$4.89	$7.36
Total Benefit Score	501	516	538
Overall Benefit/ Cost	103	106	73
Total Flood Reduction (Million Gal.)	4.47	4.43	4.66
Cost of Flood Reduction ($/Gallon)	$1.10	$1.10	$1.58

FIGURE 3
Taylor Run Watershed Alternative 2 Solution Benefit Cost Analysis

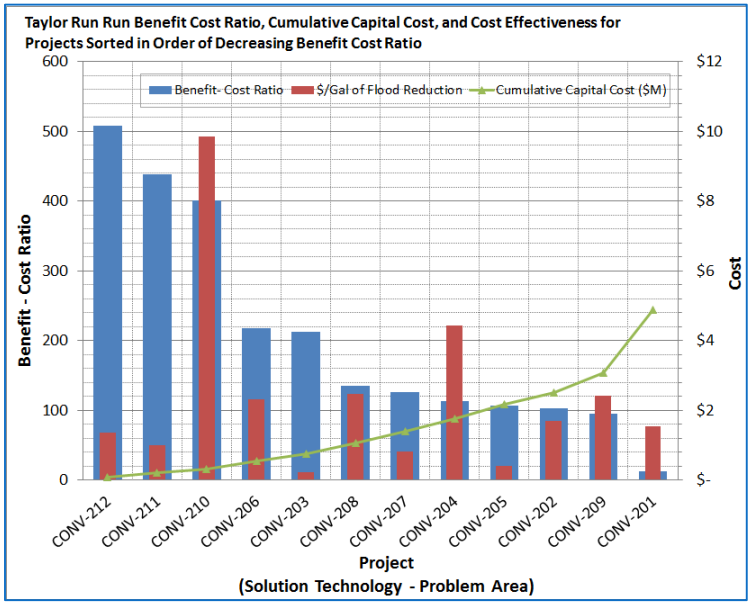
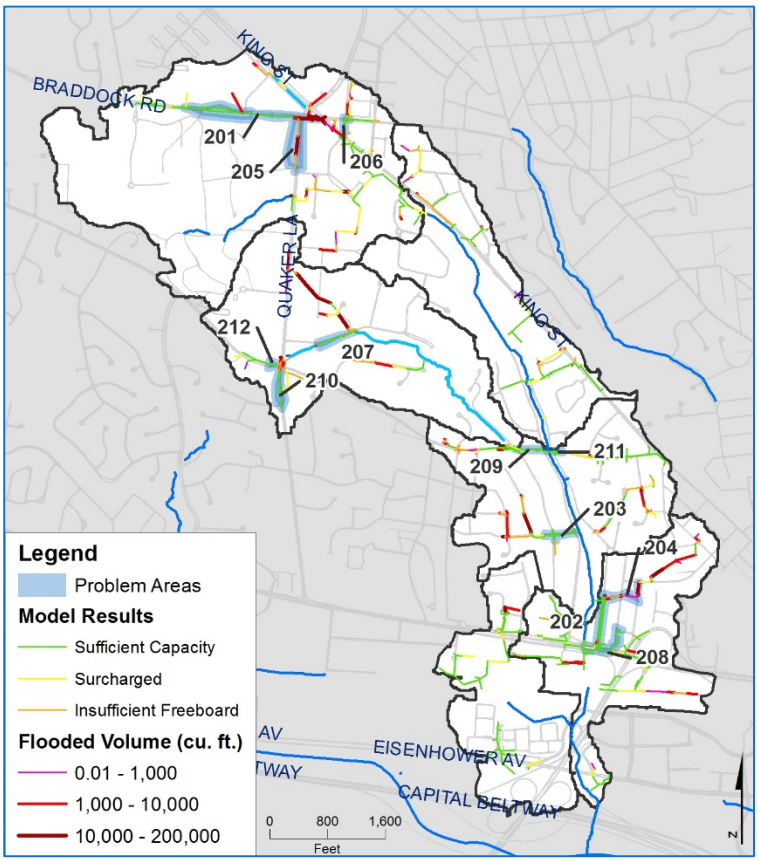


FIGURE 4
Taylor Run Watershed Alternative 2 Solution Results



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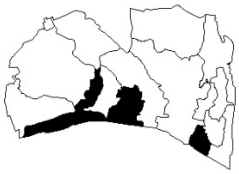
CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS



CAMERON RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Cameron Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Cameron Run watershed is made up of four hydrologically-separated areas designated by Cameron Run West, Center, Southeast, and North and covers a total of approximately 1,500 acres (2.35 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Cameron Run watershed is 43% impervious, the majority of which is buildings and roads. Stormwater runoff is conveyed to the Cameron Run stream and its tributaries through a network of over 116,500 linear feet of pipe and streams. Approximately 82,086 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Cameron Run Watershed

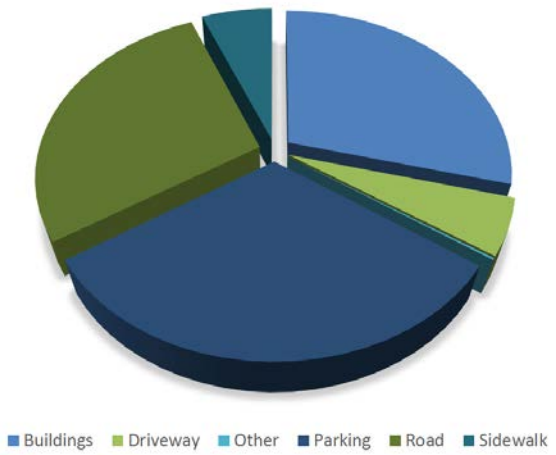
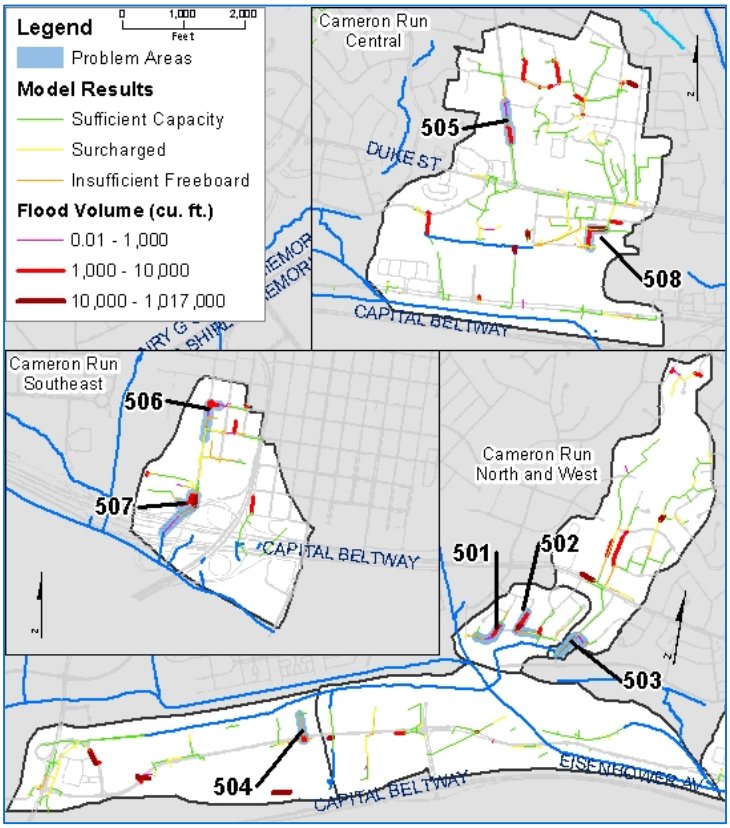


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 120"
Number of Pipe Segments	419	165	148	58
Length of Pipe (LF)	35,064	17,996	19,459	9,567

FIGURE 2
Cameron Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Cameron Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 12% of the system may experience flooding and 14% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 17% of the system may be surcharged such that the water surface rises above the crown of the pipe and cause the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 8 problem areas were identified in the Cameron Run watershed for solution development (see Figure 2; problem areas annotated with numbers 501-508).

ALTERNATIVES ANALYSIS

For each of the 8 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 8 problem areas.

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 8 problem areas.

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas.

Alternative 1 was recommended as the preferred solution to alleviate flooding in the Cameron Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$3.65	$3.39	$4.57
Total Benefit Score	360	394	410
Overall Benefit/ Cost	99	116	90
Total Flood Reduction (Million Gal.)	2.27	1.13	2.67
Cost of Flood Reduction ($/Gallon)	$1.61	$3.01	$1.71

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FIGURE 3
Cameron Run Watershed Alternative 1 Solution Benefit Cost Analysis

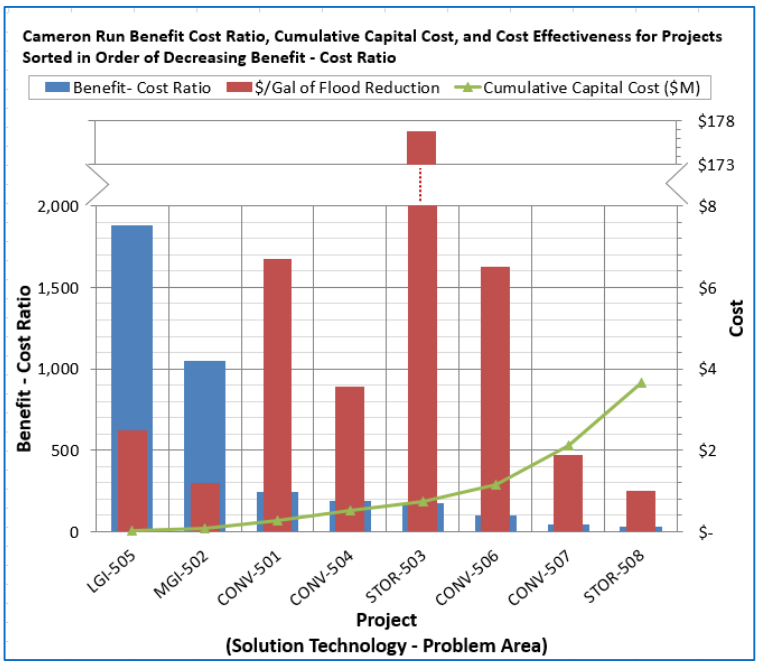
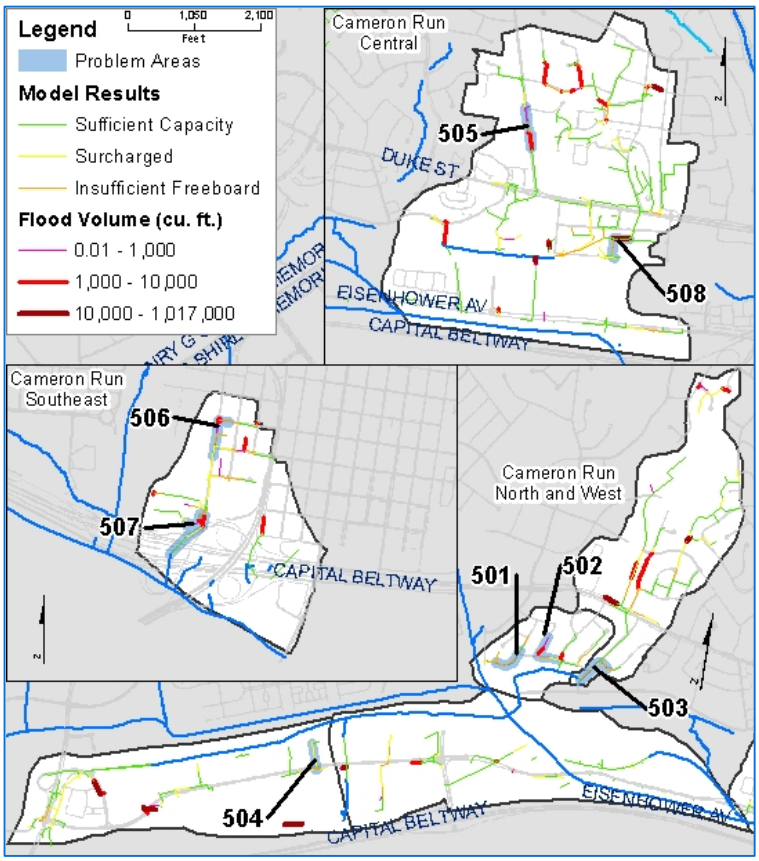
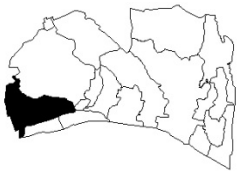


FIGURE 4
Cameron Run Watershed Alternative 1 Solution Results



CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS



BACKLICK RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Backlick Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Backlick Run watershed covers approximately 780 acres (1.2 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Backlick Run watershed is 63% impervious, the majority of which is buildings, parking lots and roads. Stormwater runoff is conveyed to the Backlick Run stream through a network of over 96,600 linear feet of pipe. Approximately 57,255 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Backlick Run Watershed

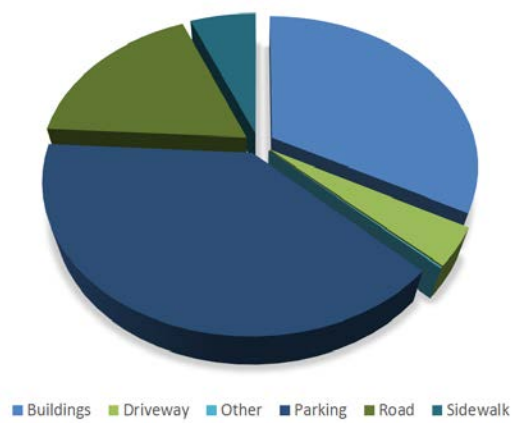
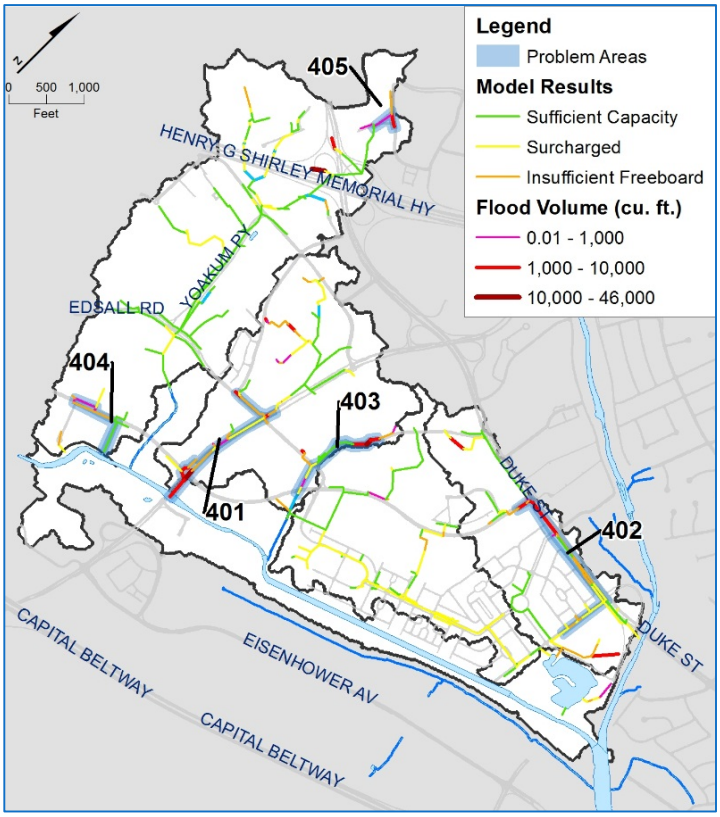


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 160"
Number of Pipe Segments	146	144	125	66
Length of Pipe (LF)	14,920	14,712	16,863	10,760

FIGURE 2
Backlick Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Backlick Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 9% of the system may experience flooding and 13% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 30% of the system may be surcharged such that the water surface rises above the crown of the pipe and causes the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 5 problem areas in the Backlick Run watershed were identified for solution development (see Figure 2; problem areas annotated with numbers 401-405).

ALTERNATIVES ANALYSIS

For each of the 5 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 5 problem areas

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 5 problem areas

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas.

Alternative 3 was recommended as the preferred solution to alleviate flooding in Backlick Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$4.00	$4.12	$3.96
Total Benefit Score	222	256	229
Overall Benefit/ Cost	56	62	58
Total Flood Reduction (Million Gal.)	1.39	0.89	1.39
Cost of Flood Reduction ($/Gallon)	$2.88	$4.63	$2.85

FIGURE 3
Backlick Run Watershed Alternative 3 Solution Benefit Cost Analysis

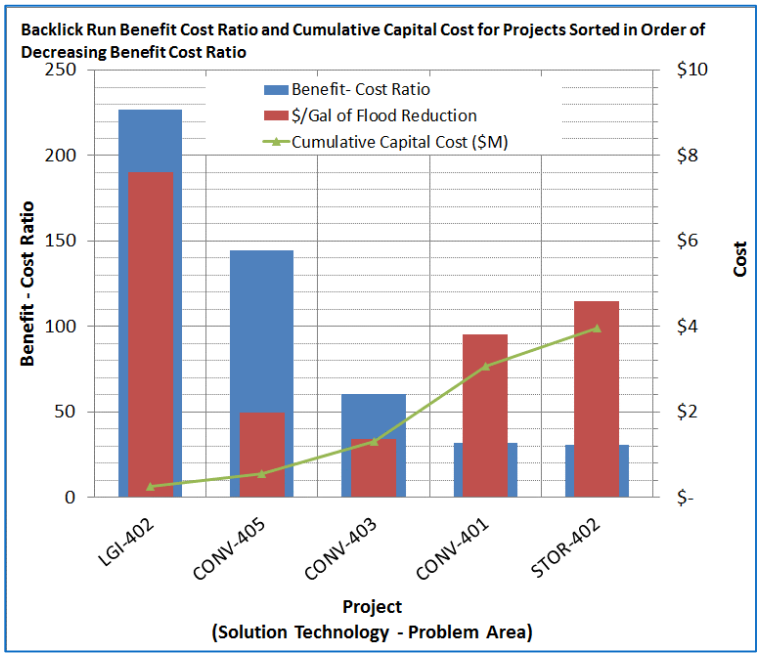
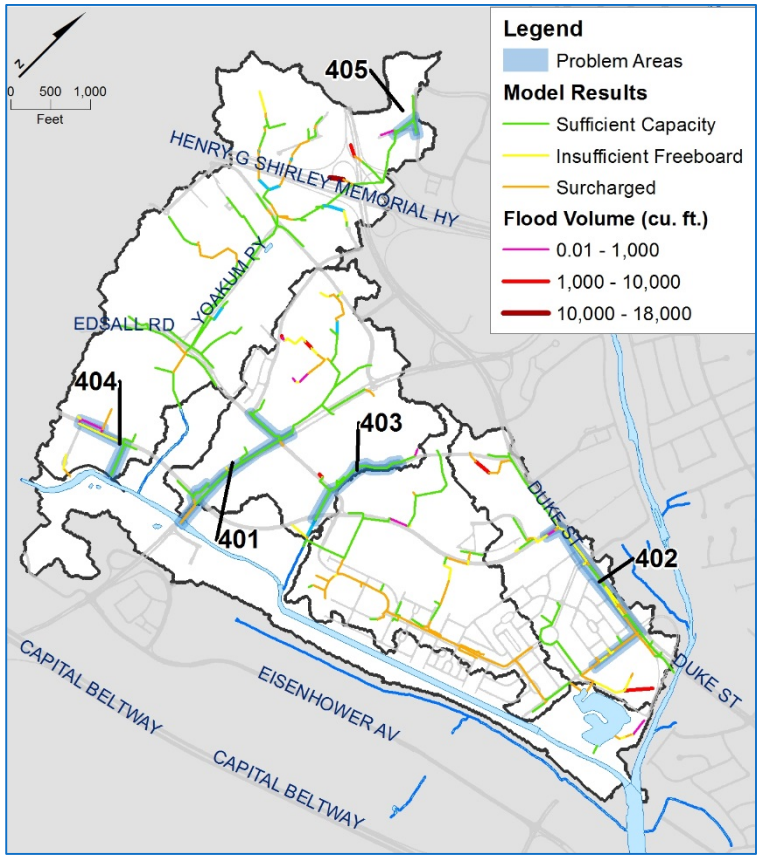


FIGURE 4
Backlick Run Watershed Alternative 3 Solution Results



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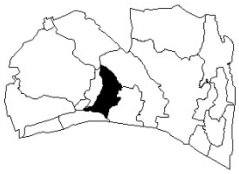
CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS



STRAWBERRY RUN WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Strawberry Run were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Stormwater management solutions, including green infrastructure, storage, and conveyance improvements, were identified, evaluated and prioritized using a cost benefit analysis. Three watershed wide alternatives for managing stormwater were developed and presented as possible solutions.

WATERSHED CHARACTERISTICS

The Strawberry Run watershed covers approximately 348 acres (0.5 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Strawberry Run watershed is 32% impervious, the majority of which is buildings, parking lots and roads. Stormwater runoff is conveyed to the Strawberry Run stream through a network of over 36,200 linear feet of pipe. Approximately 25,038 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Strawberry Run Watershed

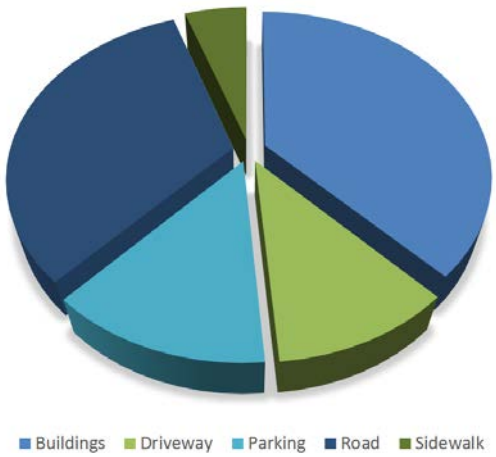
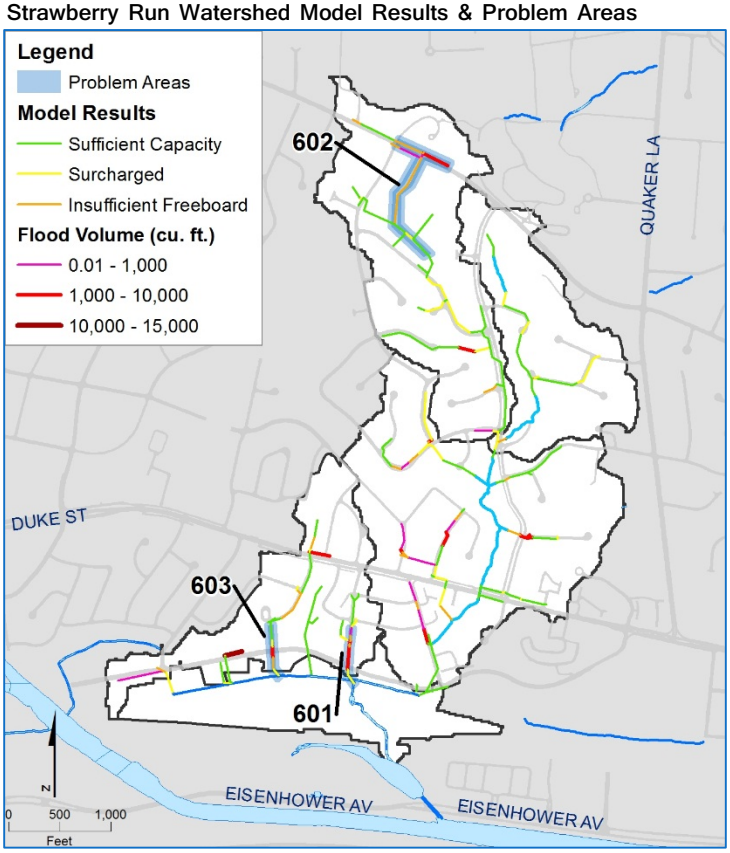


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" and up
Number of Pipe Segments	152	28	47	13
Length of Pipe (LF)	15,443	3,550	4,973	1,072

FIGURE 2
Strawberry Run Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Strawberry Run watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 16% of the system may experience flooding and 13% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 17% of the system may be surcharged such that the water surface rises above the crown of the pipe and causes the system to backup. Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 3 problem areas in the Strawberry Run watershed were identified for solution development (see Figure 2; problem areas annotated with numbers 601-603).

ALTERNATIVES ANALYSIS

For each of the 3 problem areas, up to 5 solutions were identified and modeled: 3 levels of green infrastructure implementation (high, medium, and low % impervious area managed), conveyance improvements, and storage construction. Planning level costs were developed and a benefit score was assigned to each of the solutions. Benefit scoring criteria, which includes urban drainage/flooding, sustainability, social benefits, and public acceptance, among others, were selected with City staff. The model results, cost, and benefit score were used to generate three watershed wide scenarios to address flooding in a cost effective and beneficial manner.

Alternative 1 – Best Cost Efficiency: the projects that achieve the lowest cost/gallon of flood reduction in each of the 3 problem areas

Alternative 2 – Best Benefit/Cost Ratio: the projects that have the highest benefit score to cost ratio in each of the 3 problem areas

Alternative 3 – Highest-Priority Problems: a set of projects that address flooding in the highest priority problem areas (601 to 602).

Alternative 3 was recommended as the preferred solution to alleviate flooding in Strawberry Run watershed.

TABLE 2 Watershed-wide Alternative Scoring & Prioritization Results	Alternative 1	Alternative 2	Alternative 3
	Best Cost Efficiency	Best Benefit/ Cost Ratio	Highest-priority Problems
Total Capital Cost ($ Millions)	$0.55	$0.62	$0.27
Total Benefit Score	90	144	88
Overall Benefit/ Cost	164	232	322
Total Flood Reduction (Million Gal.)	0.06	0.04	0.05
Cost of Flood Reduction ($/Gallon)	$8.58	$14.76	$5.77

FIGURE 3
Strawberry Run Watershed Alternative 3 Solution Benefit Cost Analysis

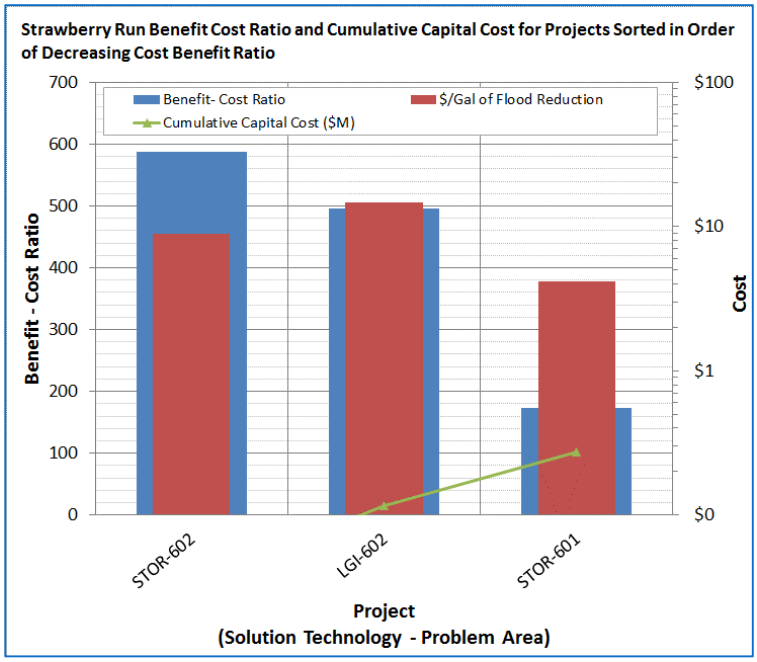
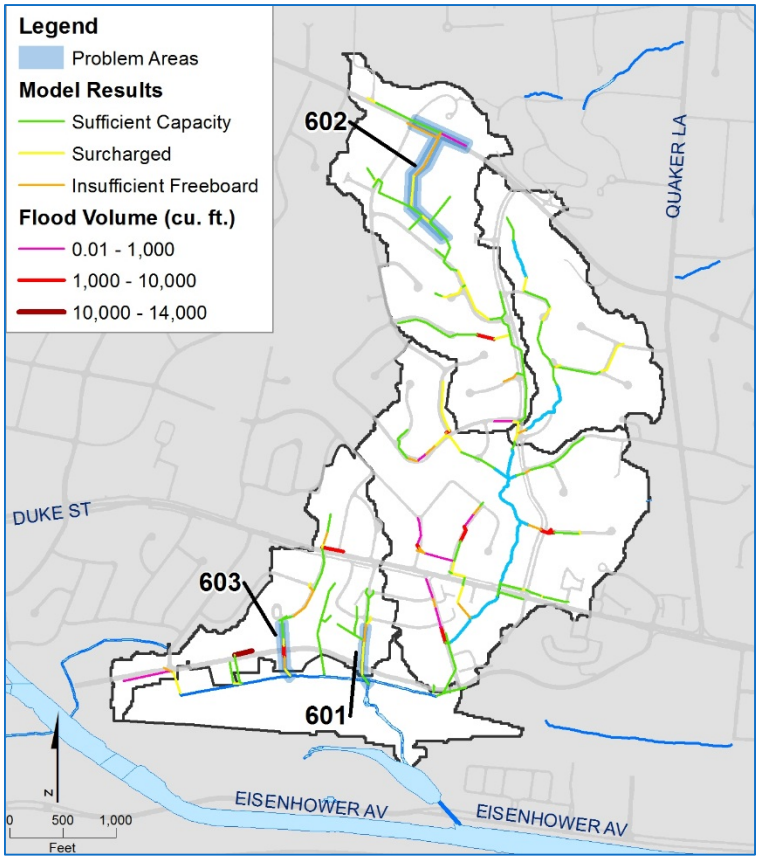


FIGURE 4
Strawberry Run Watershed Alternative 3 Solution Results



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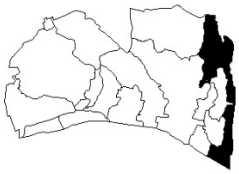
CITY OF ALEXANDRIA STORM SEWER CAPACITY ANALYSIS



POTOMAC RIVER WATERSHED FACTSHEET

INTRODUCTION

The City of Alexandria, Virginia (City), has experienced repeated and increasingly frequent flooding from storm events attributable to old infrastructure, inconsistent design criteria, and possibly, climate change. The purpose of the stormwater capacity analysis project is to analyze storm sewer system, identify problem flooding areas, and develop and prioritize solutions.

The stormwater runoff and hydraulics of the storm sewer system in Potomac River were modeled for a 10 year, 24 hour storm event (the City's recommended design event) using industry standard approach and the results were used to identify and prioritize flooding areas. Due to ongoing development in the Potomac River watershed as well as existing studies focused on flooding in the Potomac River resulting from larger storms or storm surge events, solutions were not developed for problem areas identified in the Potomac River watershed.

WATERSHED CHARACTERISTICS

The Potomac River watershed covers approximately 835 acres (1.3 mi^2) of the City of Alexandria. Stormwater runoff is generated when precipitation flows over land or impervious surfaces. The Potomac River watershed is 45% impervious, the majority of which is buildings, roads, and parking. Stormwater runoff is conveyed to the Potomac River and its tributaries through a network of over 105,000 linear feet of pipe and streams. Approximately 66,060 feet of pipe were analyzed.

FIGURE 1
Impervious Cover in Potomac River Watershed

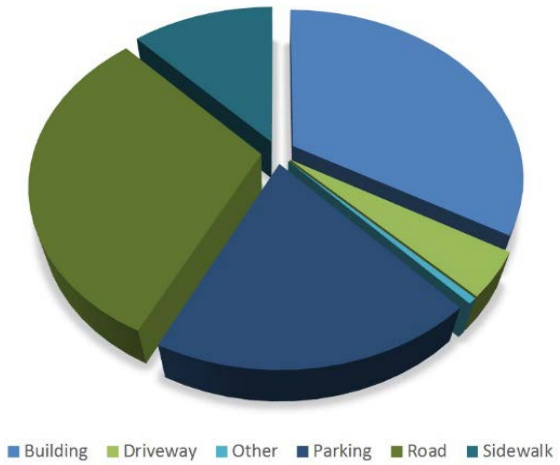
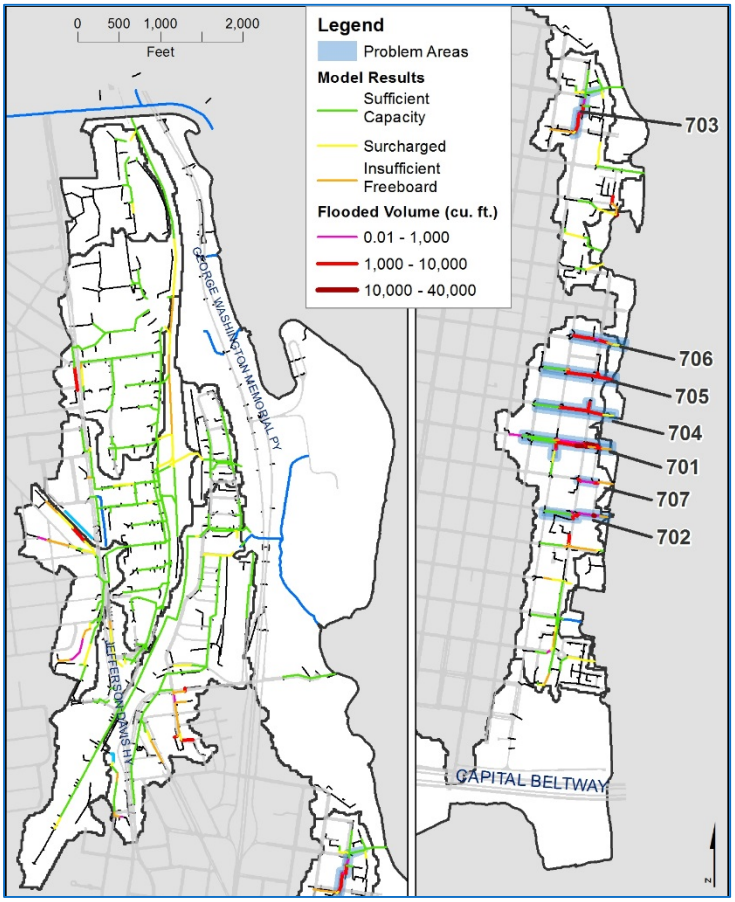


TABLE 1 Analyzed Pipe Summary	Pipe Diameter (inch)			
	Less than 24"	24" to 33"	36" to 59"	60" to 96"
Number of Pipe Segments	230	182	164	39
Length of Pipe (LF)	20,839	15,810	21,896	7,515

FIGURE 2
Potomac River Watershed Model Results & Problem Areas



RESULTS

The hydraulic model predicts that portions of the storm system in the Potomac River watershed may experience capacity limitations during the 10 year, 24 hour storm event.

Approximately 9% of the system may experience flooding and 9% may have a water level within 2 feet below the surface, referred to as insufficient freeboard, at some point during the storm. Also 13% of the system may be surcharged such that the water surface rises above the crown of the pipe and cause the system to backup.

Flooding in the Potomac River watershed is generally limited to the waterfront area and older storm sewer systems, whereas newly developed areas in and around Potomac Yards appear to have sufficient capacity. Modeling results are shown in Figure 2.

PROBLEM IDENTIFICATION

Using criteria selected with City of Alexandria staff, including but not limited to proximity to critical infrastructure and roads, predicted magnitude of flooding, and problems reported by the public and city staff, problem flooding areas were identified and prioritized. Overall, 7 problem areas were identified in the Potomac River watershed (see Figures 2 and 3; problem areas annotated with numbers 701-707).

While this study focused on drainage issues associated with stormwater conveyance systems that are designed for the 10-year storm, the City recognizes that flooding can also result from flood crest elevations in the surrounding rivers resulting from larger storms and/or storm surge events that have much longer rainfall response times. The City has embarked on a flood mitigation project for the Potomac River waterfront that includes a number of elements, including a new flood wall or bulkhead, a promenade, and two new pump stations.

CONTACT INFORMATION

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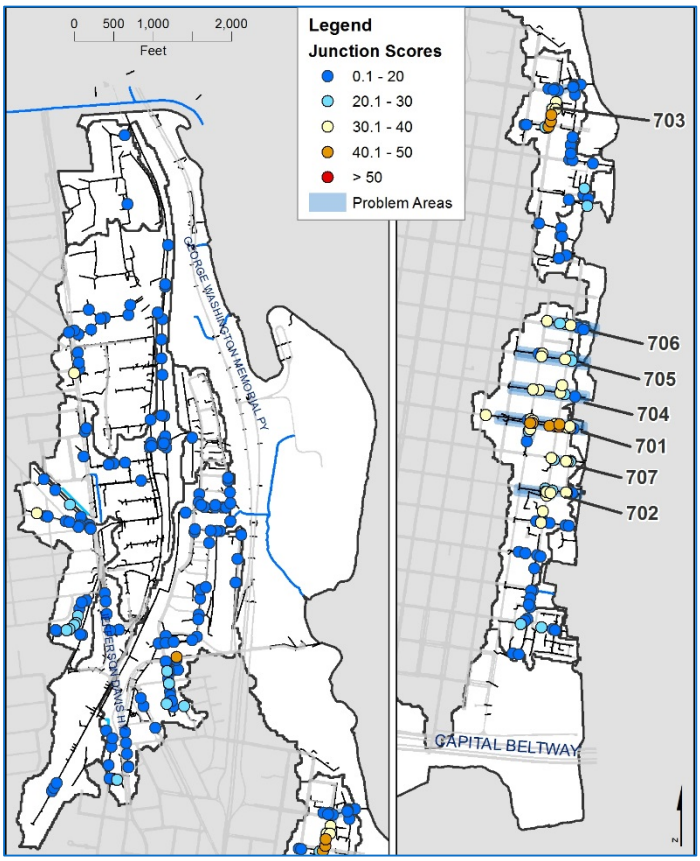
FIGURE 3
Potomac River Watershed Problem Identification Results



Green Infrastructure Technology Fact Sheets

FACT SHEET: BIORETENTION AND STORMWATER PLANTERS

Rain garden in a public park setting in Lancaster, PA

Right-of-way bioretention planting in Syracuse, NY

Bioretention areas (often called Rain Gardens) are shallow surface depressions planted with specially selected native vegetation to treat and capture runoff and are sometimes underlain by sand or a gravel storage/infiltration bed. Bioretention is a method of managing stormwater by pooling water within a planting area and then allowing the water to infiltrate into the garden soils. In addition to managing runoff volume and mitigating peak discharge rates, this process filters suspended solids and related pollutants from stormwater runoff.

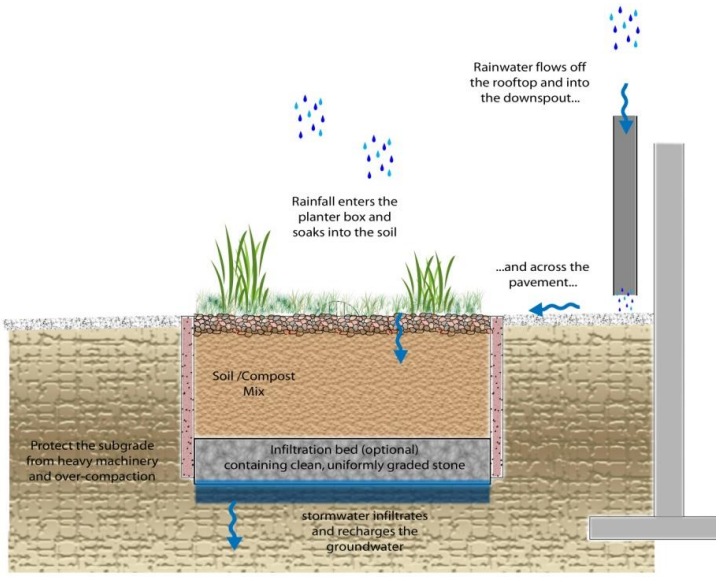
Bioretention can be designed into a landscape as a garden feature that helps to improve water quality while reducing runoff quantity. Rain Gardens can be integrated into a site with a high degree of flexibility and can balance nicely with other structural management systems including porous pavement parking lots, infiltration trenches, and non-structural stormwater BMPs. Bioretention areas typically require little maintenance once fully established and often replace areas that were intensively landscaped and required high maintenance.

A Stormwater Planter is a container or enclosed feature located either above ground or below ground, planted with vegetation that captures stormwater within the structure itself.

BENEFITS

- Volume control & GW recharge, moderate peak rate control
- Versatile w/ broad applicability
- Enhanced site aesthetics and habitat
- Potential air quality & climate benefits

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Yes (Planters)
Industrial	Yes
Retrofit	Yes
Recreational	Yes
Public/Private	Yes



Conceptual cross-section showing planter with infiltration

VARIATIONS

- Subsurface storage/infiltration bed
- Use of underdrain and/or impervious liner
- Planters – Contained (above ground), infiltration (below ground), flow-through
- Pre-treatment incorporated into design

KEY DESIGN FEATURES

- Ponding depths 6 to 18 inches for drawdown within 48 hours
- Plant selection (native vegetation that is tolerant of hydrologic variability, salts, and environmental stress)
- Amended or engineered soil as needed
- Stable inflow/outflow conditions and positive overflow for extreme storm events
- Planters may require flow bypass during winter
- Planters - Captured runoff to drain out in 3 to 4 hours after storm even unless used for irrigation

SITE FACTORS

- Water Table/ Bedrock Separation: 2-foot minimum, 4-foot recommended (N/A for contained planter)
- Soils: HSG A and B preferred; C & D may require an underdrain (N/A for contained planter)
- Feasibility on steeper slopes: medium
- Potential Hotspots: yes with pretreatment and/or impervious liner, yes for contained planter
- Maximum recommended drainage area loading: 15:1; not more than 1 acre to one rain garden

MAINTENANCE

- Often requires watering during establishment
- Spot weeding, pruning, erosion repair, trash removal, mulch reapplication (as needed) required 2-3x/growing season
- Maintenance tasks and costs are similar to traditional landscaping

COST

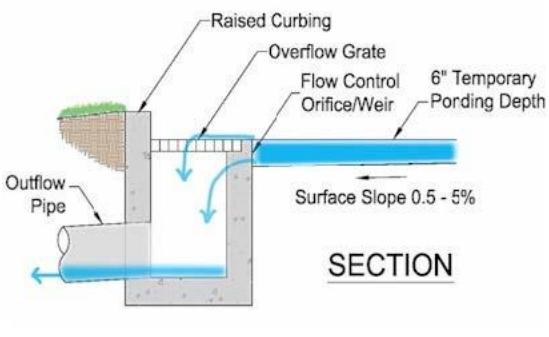
- Bioretention costs will vary depending on size/vegetation type/storage elements; typical costs $10-25/ sq. ft.

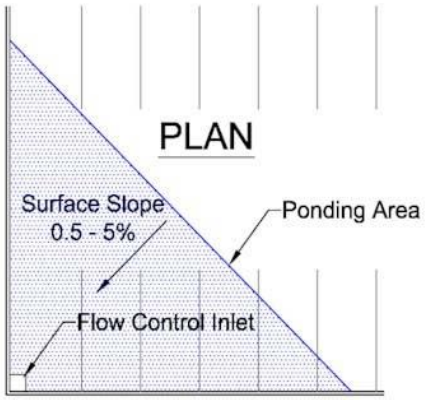
POTENTIAL LIMITATIONS

- Higher maintenance until vegetation is established
- Limited impervious drainage area to each BMP
- Requires careful selection & establishment of plants

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	High	TSS	High	Capital Cost	Medium
Groundwater Recharge	High	TP	High	Maintenance	Low/Medium
Peak Rate	Medium	TN	Medium	Winter Performance	Medium
Erosion Reduction	Medium	Temperature	Medium/High	Fast Track Potential	Medium
Flood Protection	Medium			Aesthetics	High

FACT SHEET: BLUE STREETS





Blue streets refer to the practice of temporarily detaining stormwater, delaying its release and reducing its peak flow rate into the storm sewer system.

Surface storage practices have been used traditionally on rooftops (i.e. blue roofs) and in parking lots but can also be implemented in residential streets and right-of-ways with lower traffic volumes. These "blue streets" can be a cost-effective way to manage stormwater and address surcharging without significant subsurface excavation and construction interventions.

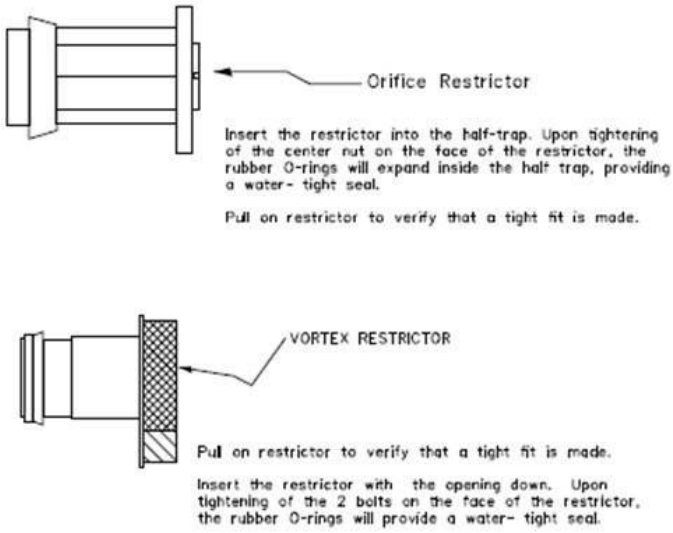
Surface storage is typically accomplished using drainage structures and retrofitting existing catch basins to feature devices such as orifice restrictors or vortex restrictors. Blue streets also emphasize minimizing the number of catch basins to the extent practical.

Blue streets (surface storage techniques) are often best implemented in alleys, low volume roads, and on private sites, for public perception and safety reasons.

BENEFITS

- Reduces stress on drainage system
- Mitigates peak rate flow
- Cost-effective technique to manage stormwater
- Short duration storage
- Reduces need for subsurface excavation and construction

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Limited
Industrial	Yes
Retrofit	Yes
Highway/Road	Limited for Highway
Recreational	Yes
Public/Private	Yes/Yes



Drainage structure restrictors are key features of surface storage and blue streets. Source: City of Chicago design manual

VARIATIONS

- Flow control structures
- Orifice restrictors
- Vortex restrictors
- Reduction in number of catch basins/inlets on a street

KEY DESIGN FEATURES

- Emergency overflows typically required
- Maximum ponding depths (less than one foot)
- Adequate surface slope to outlet
- Traffic volume, public safety, and user inconvenience must be taken into account

SITE FACTORS

- Water table to bedrock depth – N/A
- Soils – N/A
- Slope – Requires relatively low slopes to provide appreciable storage
- Potential hotspots – yes
- Maximum drainage area – relatively small DA to individual inlets (similar to conventional inlets)

MAINTENANCE

- Clean drainage structures and repair/replace parts as needed

COST

- Drainage structures restrictors range in cost, for example installing a vortex restrictor can be approximately $1000 per inlet

POTENTIAL LIMITATIONS

- Not suitable for heavily-used roadways without adequate median/shoulder space
- Excess ponding on roadways may freeze in winter conditions
- Public safety perceptions and concerns
- Does not inherently address water quality and quantity – should generally be combined with other BMPs

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Low	TSS	Low	Capital Cost	Low
Groundwater Recharge	Low	TP	Low	Maintenance	Low/Medium
Peak Rate	Medium	TN	Low	Winter Performance	Medium
Erosion Reduction	Low	Temperature	Low	Fast Track Potential	High
Flood Protection	Medium			Aesthetics	Low

FACT SHEET: CISTERNS/RAIN BARRELS

Example of above-ground cistern with vegetation screening

Cisterns (or rain barrels) are structures designed to intercept and store runoff from rooftops to allow for its reuse, reducing volume and overall water quality impairment. Stormwater is contained in the cistern structure and typically reused for irrigation or other water needs. This GI technology reduces potable water needs while also reducing stormwater discharges.

Cisterns can be located above or below ground and are containers or tanks with a larger storage capacity than a rain barrel, and often used to supplement grey water needs (i.e. toilet flushing) in a building, as well as irrigation. Rain barrels are above-ground structures connected to rooftop downspouts that collect rainwater and store it until needed for a specific use, such as landscape irrigation.

Cisterns and rain barrels can be used in suburban and urban areas where the need for supplemental onsite irrigation or other high water uses is especially apparent.

BENEFITS

- Provides supplemental water supply
- Wide applicability
- Reduces potable water use
- Related cost savings and environmental benefits
- Reduces stormwater runoff impacts

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Yes, if demand exists
Industrial	Yes
Retrofit	Yes
Highway/Road	No
Recreational	Limited
Public/Private	Yes/Yes

Rain barrel prototype example

VARIATIONS

- Cisterns – can be either underground and above ground
- Water storage tanks
- Storage beneath a usable surface using manufactured stormwater products (chambers, pipes, crates, etc.)
- Various sizes, materials, shapes, etc.

KEY DESIGN FEATURES

- Small storm events are captured with most structures
- Provide overflow for large storms events
- Discharge/use water before next storm event
- Consider site topography, placing structure upgradient of plantings (if applicable) in order to eliminate pumping needs

SITE FACTORS

- Water table to bedrock depth – N/A (although must be considered for subsurface systems)
- Soils – N/A
- Slope – N/A
- Potential hotspots – typically N/A for rooftop runoff
- Maximum drainage area – typically relatively small, based on storage capacity

MAINTENANCE

- Use stored water and/or discharge before next storm event
- Clean annually and check for loose valves, leaks, etc. monthly during active season
- May require flow bypass valves or be taken offline during the winter

COST

- Cisterns typically cost from $3 to $8/gallon/ Rain Barrels range from $75 to $300 each

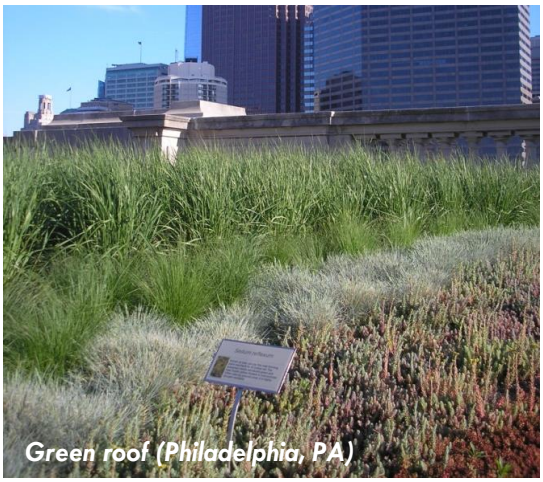
POTENTIAL LIMITATIONS

- Manages only relatively small storm events which requires additional management and use for the stored water.
- Typically requires additional management of runoff
- Requires a use for the stored water (irrigation, gray water, etc.)

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Low/Medium	TSS	Medium	Capital Cost	Medium
Groundwater Recharge*	Low/Medium	TP	Medium	Maintenance	Medium
Peak Rate*	Low	TN	Low	Winter Performance	Low
Erosion Reduction	Low	Temperature	Low	Fast Track Potential	Medium/High
Flood Protection*	Low			Aesthetics	Low/Medium

**Although stand-alone cisterns are expected to have lower benefits in these categories, if combined with downspout disconnection to landscaped areas the benefits can be increased significantly.*

FACT SHEET: VEGETATED (GREEN) ROOFS AND BLUE ROOFS



Blue roof (NYC) / Photo – Gowanus Canal Conservancy

A green roof is a veneer of vegetation that is grown on and covers an otherwise conventional flat or pitched roof, endowing the roof with hydrologic characteristics that more closely match surface vegetation. The overall thickness of the veneer typically ranges from 2 to 6 inches and may contain multiple layers, such as waterproofing, synthetic insulation, non-soil engineered growth media, fabrics, and synthetic components. Vegetated roofs can be optimized to achieve water quantity and water quality benefits. Through the appropriate selection of materials, even thin vegetated covers can provide significant rainfall retention and detention functions.

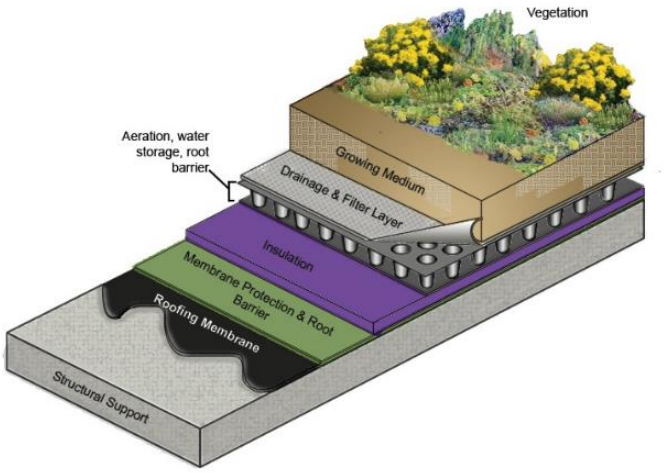
Depending on the plant material and planned usage for the roof area, modern vegetated roofs can be categorized as systems that are intensive (usually > 6 inches of substrate), semi-intensive, or extensive (<4 inches). More maintenance, higher costs and more weight are the characteristics for the intensive system compared to that of the extensive vegetated roof.

Another GI rooftop technology - **Blue roofs -** are non-vegetated systems that employ stormwater control devices to temporarily store water on the rooftop and then release it into the drainage system at a relatively low flow rate. Storage can be provided by modifying roof drains or through the use of detention trays that sometimes have a lightweight gravel media. Blue roof and green roof technologies can also be combined in a design to achieve

BENEFITS

- High volume reduction (annual basis)
- Moderate ecological value and habitat (green roofs)
- High aesthetic value (green roofs)
- Energy benefits (heating/cooling)
- Urban heat island reduction

POTENTIAL APPLICATIONS	
Residential	Limited
Commercial	Yes
Ultra-Urban	Yes
Industrial	Yes
Retrofit	Yes
Highway/Road	No
Recreational	Limited
Public/Private	Yes/Yes



Cross-section showing components of vegetated roof system

VARIATIONS

- Green roofs - single media system, dual media system (with synthetic liner)
- Green roofs - Intensive, Extensive, or Semi-intensive

KEY DESIGN FEATURES

- Engineered media should have a high mineral content and is typically 85% to 97% nonorganic.
- 2-6 inches of non-soil engineered media; assemblies that are 4 inches and deeper may include more than one type of engineered media.
- Irrigation is generally not required (or even desirable) for optimal stormwater management
- Internal building drainage, including provision to cover and protect deck drains or scuppers, must anticipate the need to manage large rainfall events without inundating the vegetated roof system.
- Assemblies planned for roofs with pitches steeper than 2:12 (9.5 degrees) must incorporate supplemental measures to insure stability against siding.
- The roof structure must be evaluated for compatibility with the maximum predicted dead and live loads. Typical dead loads for wet extensive vegetated covers range from about 12 to 36 pounds per square foot.
- Waterproofing must be resistant to biological and root attack. In many instances a supplemental root barrier-layer is installed to protect the primary waterproofing.
- Blue roofs: roof structure, waterproofing, accommodation for larger storm events/emergency overflows

MAINTENANCE

- Once vegetation is fully established, little maintenance needed for the extensive system
- Maintenance cost is similar to native landscaping, $0.10-$0.35 per square foot
- Blue roof maintenance is similar to conventional roof maintenance (cleaning roof and drains as necessary)

COST

- Green roofs: $10 - $35 per square foot, including all structural components, soil, and plants; more expensive than traditional roofs, but have longer lifespan; generally less expensive to install on new roof versus retrofit on existing roof
- Blue roofs: Typically add only $1-$5 per square foot compared to traditional roofs

POTENTIAL LIMITATIONS

- Green roofs have higher maintenance needs until vegetation is established
- Need for adequate roof structure and waterproofing; can be challenging on retrofit application

STORMWATER QUANTITY FUNCTIONS*		STORMWATER QUALITY FUNCTIONS*		ADDITIONAL CONSIDERATIONS	
Volume	Medium/High	TSS	Low/Medium	Capital Cost	High
Groundwater Recharge	Low	TP	Low/Medium	Maintenance	Medium
Peak Rate	Medium	TN	Low	Winter Performance	Medium
Erosion Reduction	Low/Medium	Temperature	Medium	Fast Track Potential	Low
Flood Protection	Low/Medium			Aesthetics	High

**For green roofs, blue roofs primarily function for peak rate control and flood protection.*

FACT SHEET: POROUS PAVEMENT

Porous asphalt basketball courts (Lancaster, PA)

Porous (pervious) pavement is a Green Infrastructure (GI) technique that combines stormwater infiltration, storage, and a structural pavement consisting of a permeable surface underlain by a storage/infiltration bed. Porous pavement is well suited for parking areas, walking paths, sidewalks, playgrounds, plazas, basketball courts, and other similar uses.

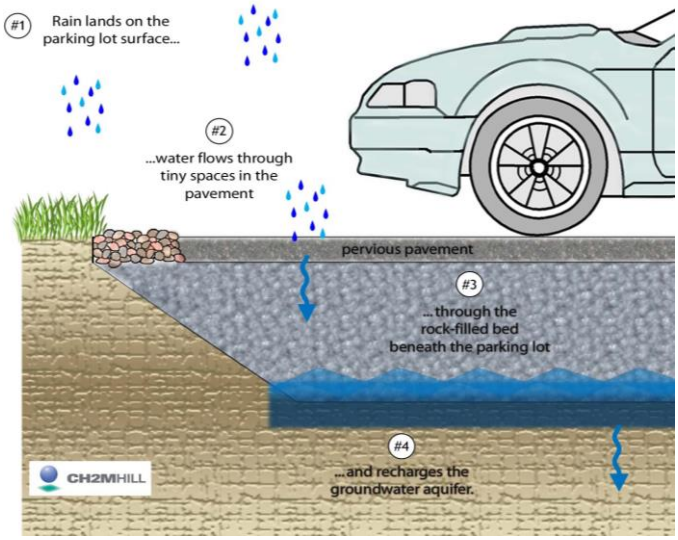
A porous pavement system consists of a pervious surface course underlain by a storage bed, typically placed on uncompacted subgrade to facilitate stormwater infiltration. The subsurface storage reservoir may consist of a stone bed of uniformly graded, clean and washed course aggregate with a void space of approximately 40% or other manufactured structural storage units. Porous pavement may be asphalt, concrete, permeable paver blocks, reinforced turf/gravel, or other emerging types of pavement.

BENEFITS

- Volume control & GW recharge, moderate peak rate control
- Versatile with broad applicability
- Dual use for pavement structure and stormwater management
- Pavers come in range of sizes and colors
- Opportunity for public education/demonstration

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra Urban	Yes
Industrial	Limited
Retrofit	Yes
Highway	Limited
Recreational	Yes
Public/Private	Yes/Yes

Porous pavers (San Diego)



Conceptual diagram showing how porous pavement functions

KEY DESIGN FEATURES

- Soil testing required for infiltration designs
- Limit amount of adjacent areas that drain directly onto the surface of the porous pavement
- Uncompacted soil subgrade for infiltration
- Level storage bed bottoms
- Provide positive storm water overflow from bed
- Surface permeability greater than 20 inches per hour
- Secondary inflow mechanism recommended
- Pretreatment for sediment-laden runoff, limit sources of sediment/debris deposition

SITE FACTORS

- Water Table/Bedrock Separation: 2-foot minimum
- Soils: HSG A&B preferred; HSG C&D may require underdrains
- Feasibility on steeper slopes: Low
- Potential Hotspots: Not without design of pretreatment system/impervious liner

MAINTENANCE

- Clean inlets
- Vacuum biannually
- Maintain adjacent landscaping/planting beds
- Periodic replacement of aggregate in paver block joints (if applicable)
- Careful winter maintenance (no sand or other abrasives, careful plowing)

COST

- Varies by porous pavement type
- Local quarry needed for stone filled infiltration bed
- Typically $7-$15 per square foot, including underground stormwater storage bed
- Generally more than standard pavement, but saves on cost of other BMPs and traditional drainage infrastructure

POTENTIAL LIMITATIONS

- Careful design & construction required
- Pervious pavement not suitable for all uses/not suitable for steep slopes
- Higher maintenance needs than standard pavement

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	High	TSS*	High	Capital Cost	Medium
Groundwater Recharge	High	TP	High	Maintenance	Medium
Peak Rate	Medium/High	TN	Medium	Winter Performance	Medium/High
Erosion Reduction	Medium/High	Temperature	High	Fast Track Potential	Low/Medium
Flood Protection	Medium/High			Aesthetics	Low to High

** While porous pavements typically result in low TSS loads, sources of sediment should be minimized to reduce the risk of clogging.*

FACT SHEET: SOIL AMENDMENTS

Healthy soils help vegetation thrive while also increasing soil infiltration rates Photo: S.Coronado

Soil amendments can include a variety of practices that reduce the generation of runoff by improving vegetation growth, increasing water infiltration, and improving water holding capacity. For example, on existing turf grass, soil amendments can include placing a thin layer of compost or other materials and spreading them evenly over existing vegetation. Amendments on existing turf grass areas can be applied for several years to improve soil over time. Soil testing can indicate how many applications are appropriate. Existing grass areas can also be aerated to improve water transmission and allow for deeper incorporation of compost.

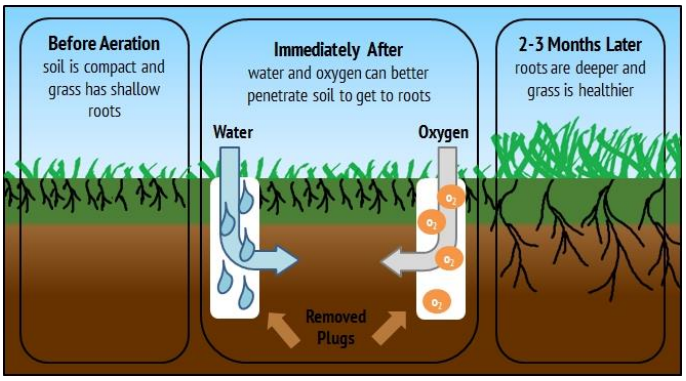
On new construction, redevelopment, and restoration projects, compost can be applied and deeply tilled into compacted soils to restore their porosity before the areas are re-vegetated (potentially with native landscaping, combining the benefits of both GI strategies).

BENEFITS

- Enhanced soil health and vegetation growth/root depth
- Improved soil infiltration rates
- Enhanced soil water holding capacity
- Reduced stormwater runoff from soil surface

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Limited
Industrial	Yes
Retrofit	Yes
Highway/Road	Yes
Recreational	Yes
Public/Private	Yes/Yes

A variety of soil amendments are available depending on the specific soil conditions and desired result. Photo: Pahls Market



Physical aeration (tilling) can also help improve soil health and soil permeability/porosity. Image: GreenMaxLawns

VARIATIONS

- Treating turf grass or areas with more intensive plant palettes
- Combining amended soil areas with downspout disconnection
- Physical aeration/tilling of turf grass/vegetated areas can help to remedy soil compaction
- Compost, sand, microbes, mycorrhizae, gypsum, biochar, manure, worm castings, etc.
- Amendments can improve soil aggregation, increase porosity, and improve aeration and rooting depth

KEY DESIGN FEATURES

- Soil bulk density and soil nutrient testing required
- Existing soil conditions should be evaluated before forming an amendment strategy

SITE FACTORS

- Water table to bedrock depth – N/A
- Soils – Bulk density and nutrient levels
- Slope – Not recommended for use on slopes greater than 3:1
- Potential hotspots – N/A
- Maximum drainage area – N/A

MAINTENANCE

- Replenishment of amendments on a regular basis may be required
- Aeration of soil often done at same time

COST

- The cost of soil amendments ranges widely depending on the size and type. Larger projects are estimated to cost approximately $5,000 per acre.

POTENTIAL LIMITATIONS

- Viability depends upon soil testing results
- Certain types of soil may not be favorable for success with amendments
- Not a regulated industry – testing of amendment may be needed to ensure specifications
- Physical aeration should not be done near existing tree roots

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Medium	TSS*	Medium	Capital Cost	Low
Groundwater Recharge	Medium	TP*	Medium	Maintenance	Low/Medium
Peak Rate	Medium	TN*	Medium	Winter Performance	Medium
Erosion Reduction	High	Temperature	Low	Fast Track Potential	Medium
Flood Protection	Low/Medium			Aesthetics	Medium

**Water quality benefits expected to vary widely depending on the condition of the soil/landscape prior to soil amendments.*

Exhibits

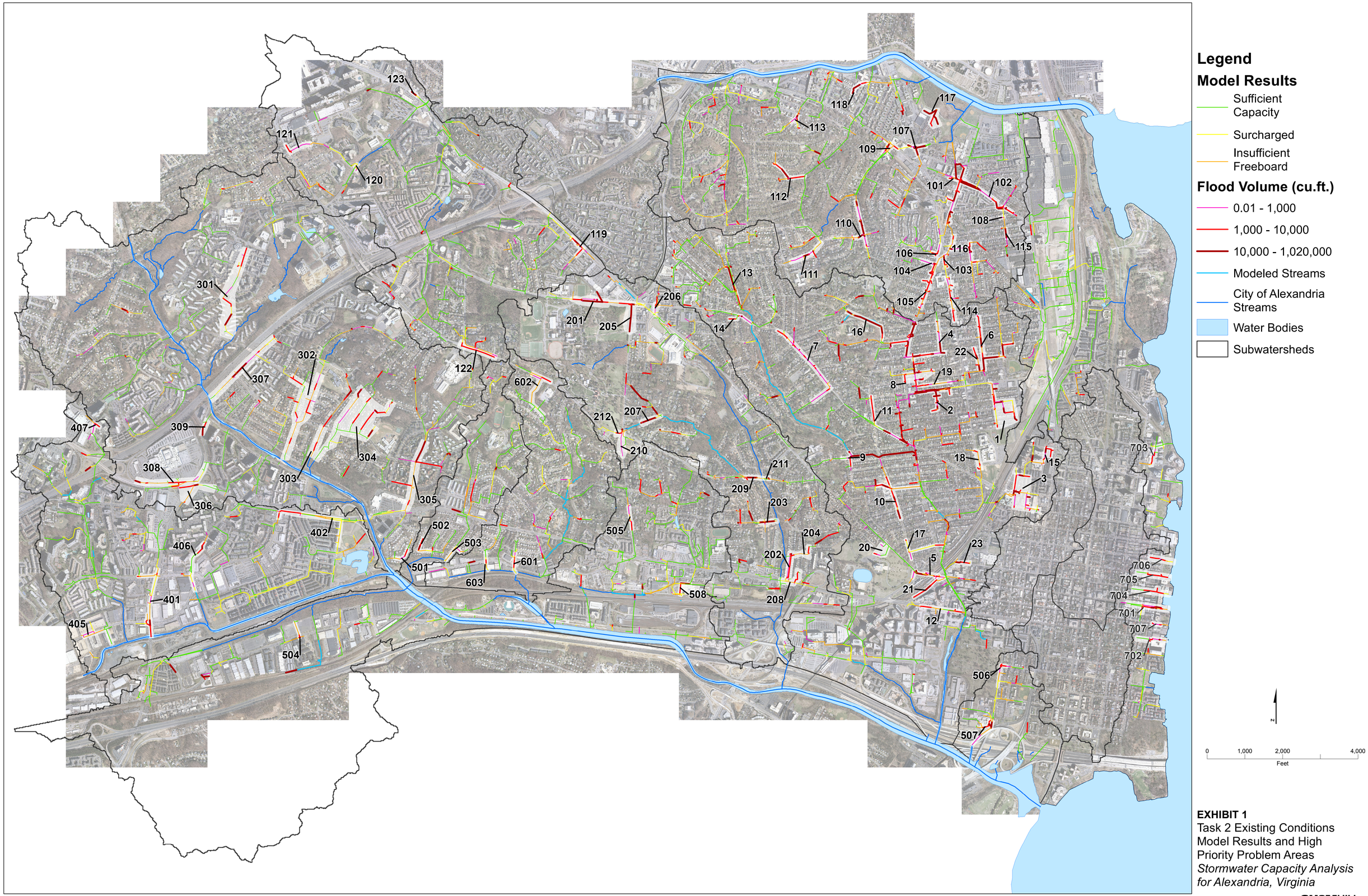
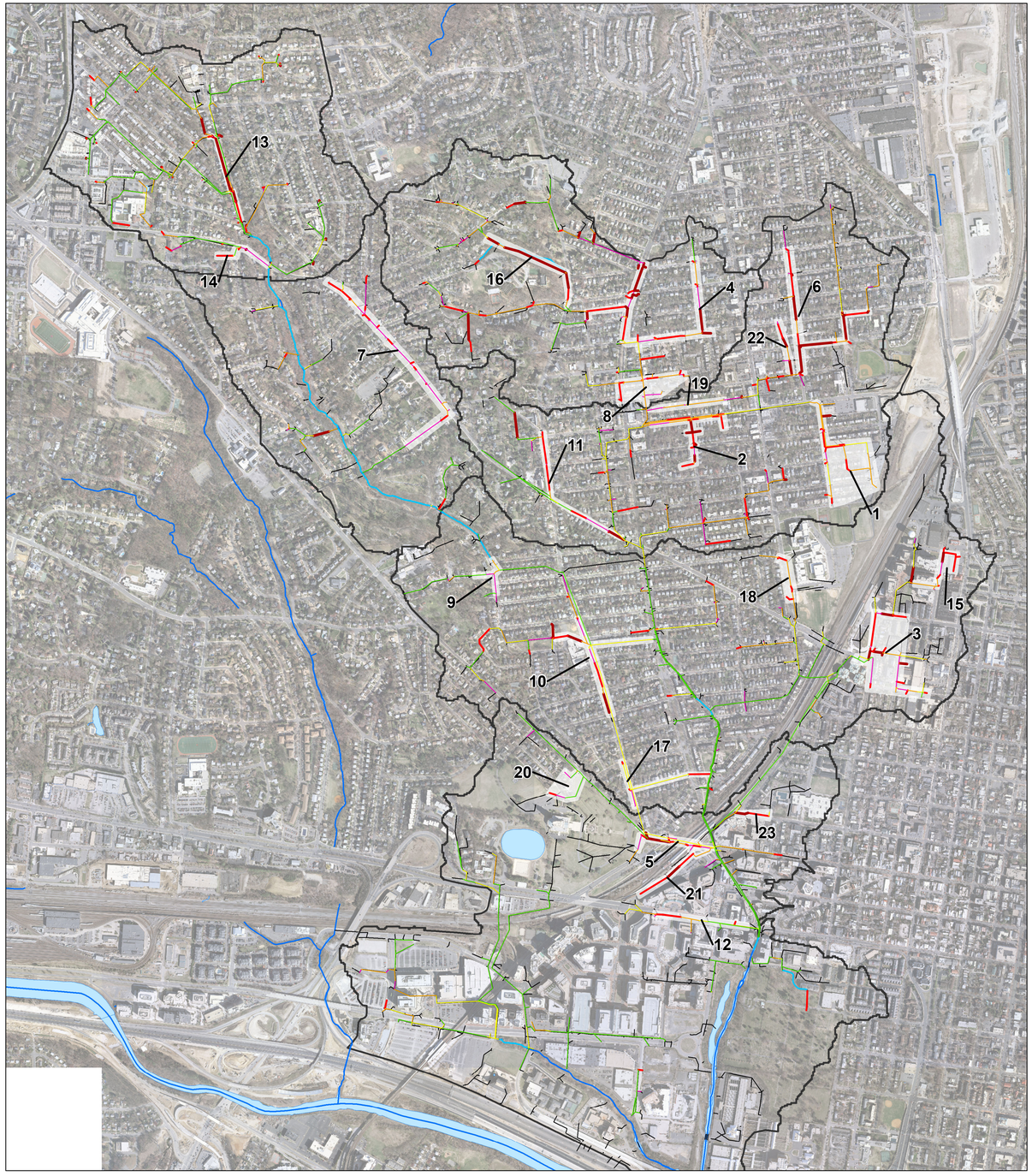


EXHIBIT 1
Task 2 Existing Conditions Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Alexandria, Virginia

CH2MHILL

EXHIBIT 2
Recommended Alternative Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Alexandria, Virginia

CH2MHILL



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)
- 0.01- 1,000
- 1,000 - 10,000
- 10,000 - 88,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

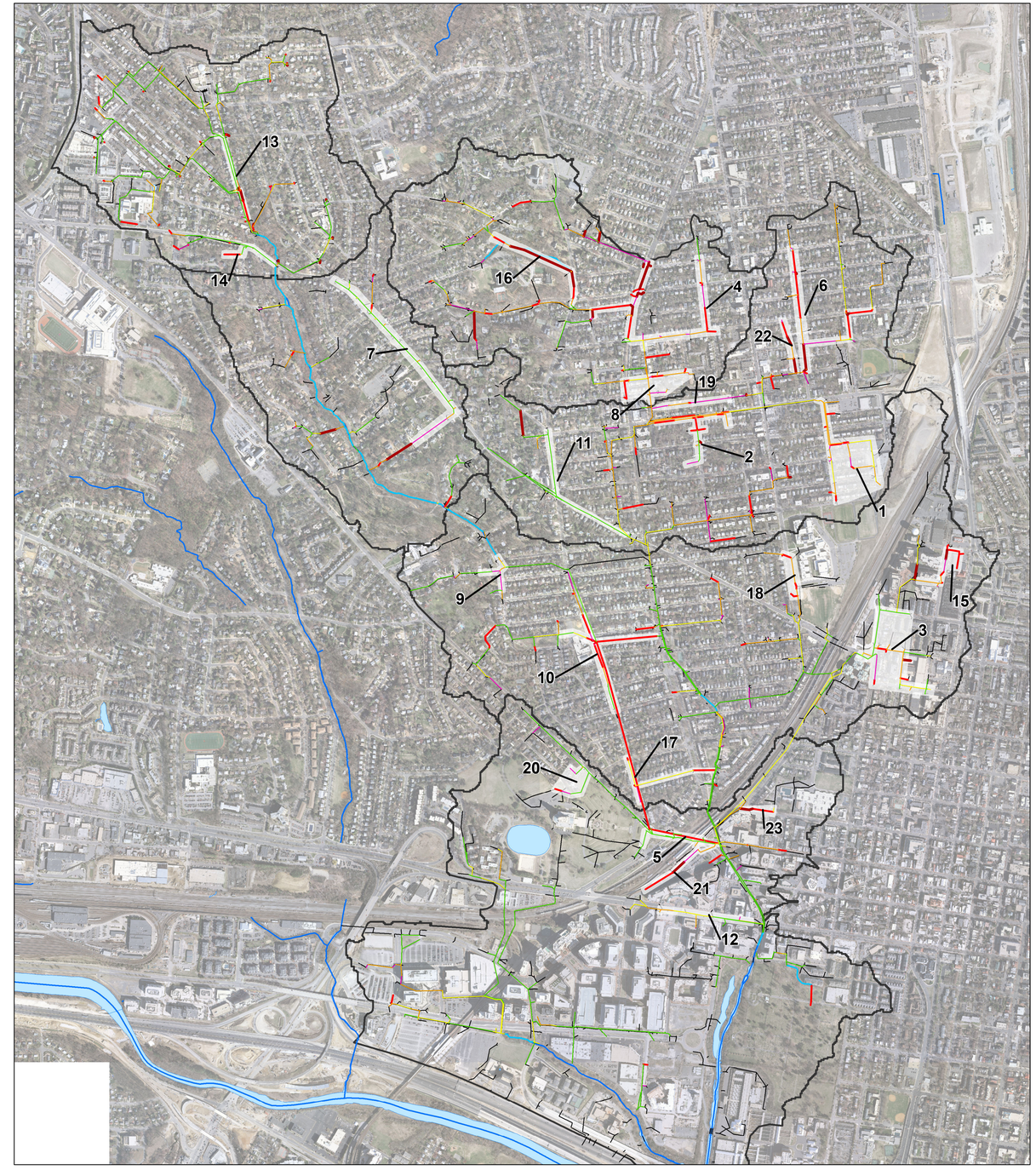
EXHIBIT 3A

Major Conveyance Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Hooffs Run Watershed, Alexandria, Virginia

0 500 1,000 2,000
Feet

CH2MHILL



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)
- 0.01- 1,000
- 1,000 - 10,000
- 10,000 - 88,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

EXHIBIT 3B

Watershed-wide Alternative 3 Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Hooffs Run Watershed, Alexandria, Virginia

0 500 1,000 2,000
Feet

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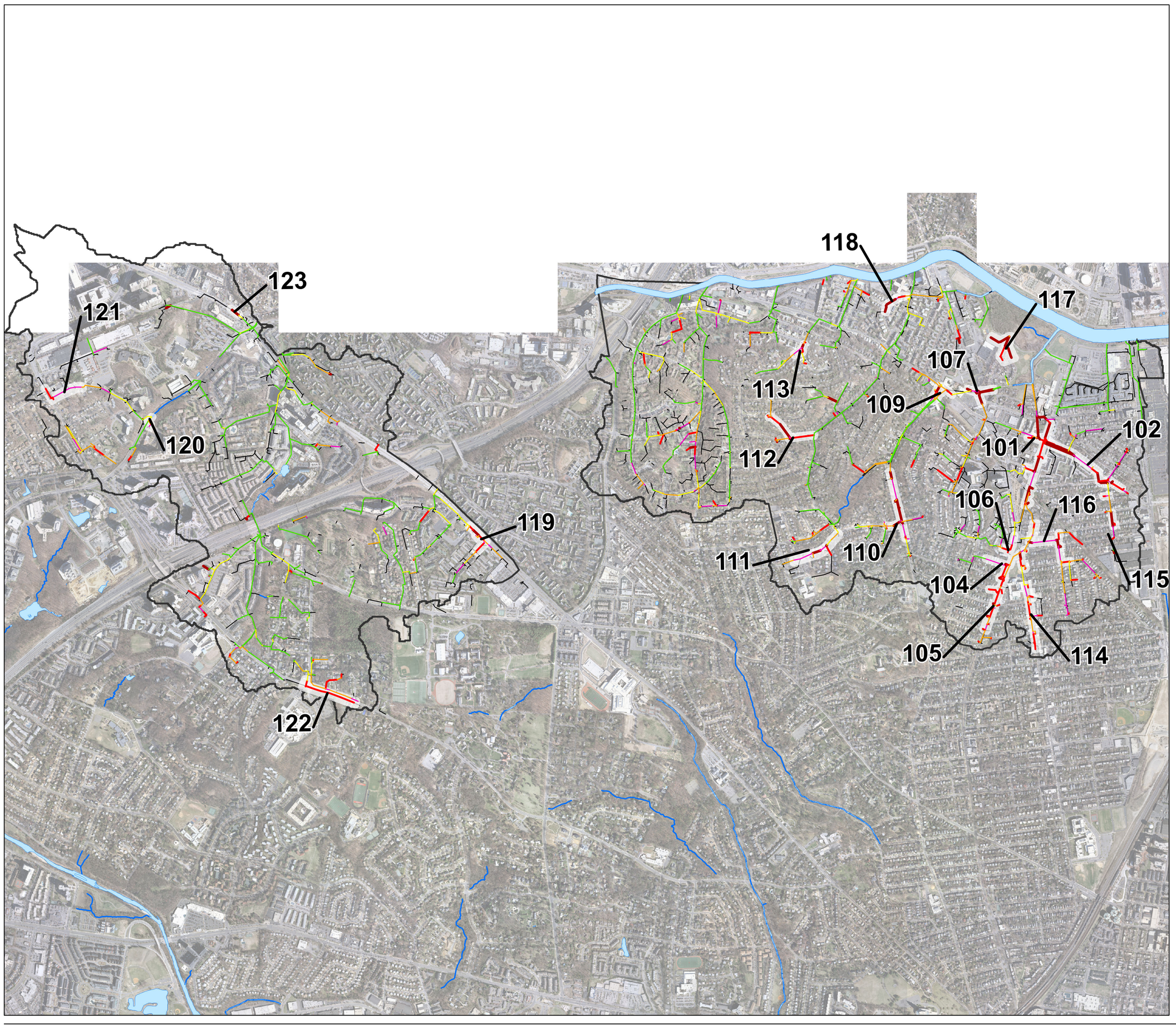

EXHIBIT 4A
Task 2 Existing Conditions Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Four Mile Run Watershed, Alexandria, Virginia

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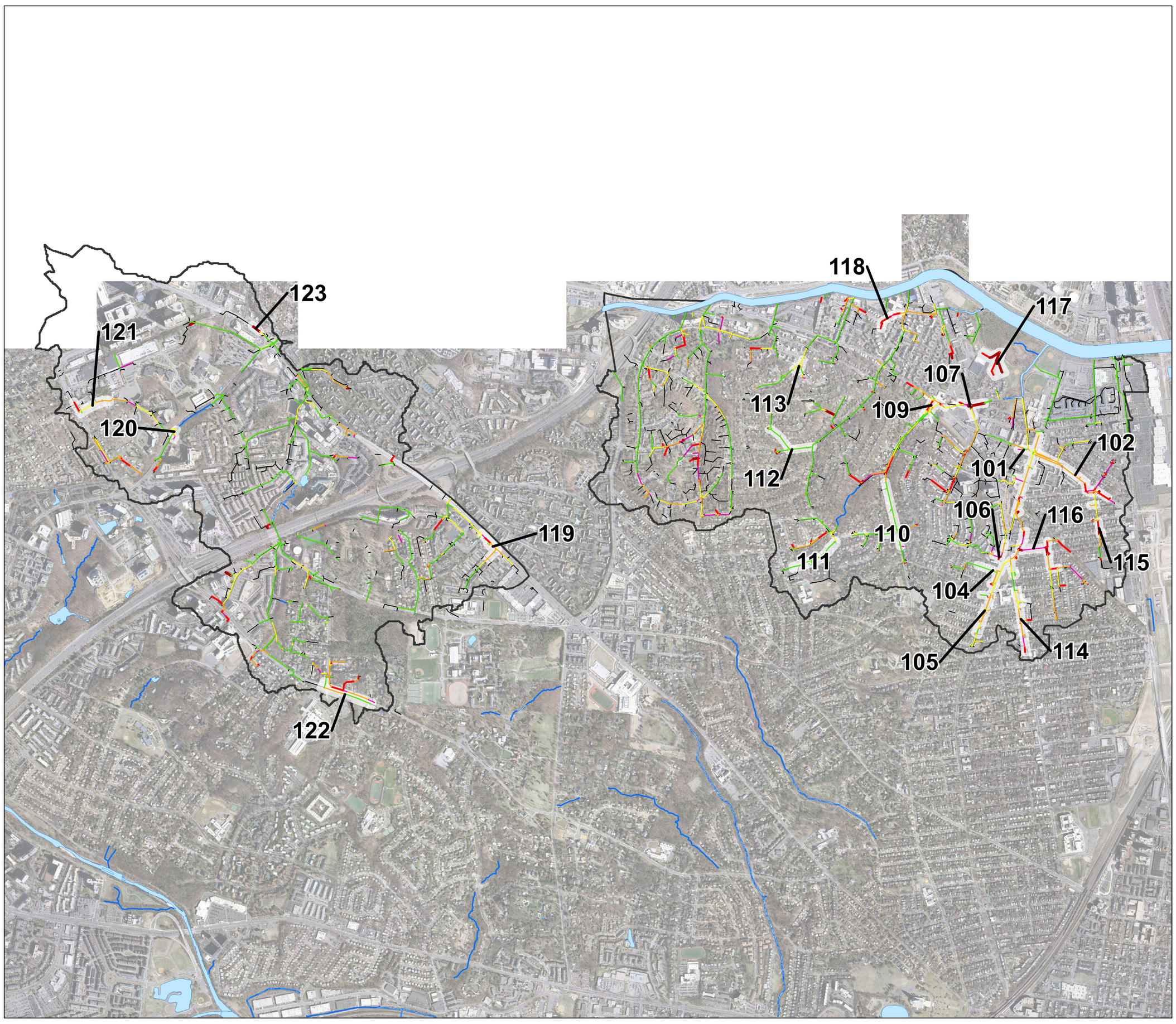
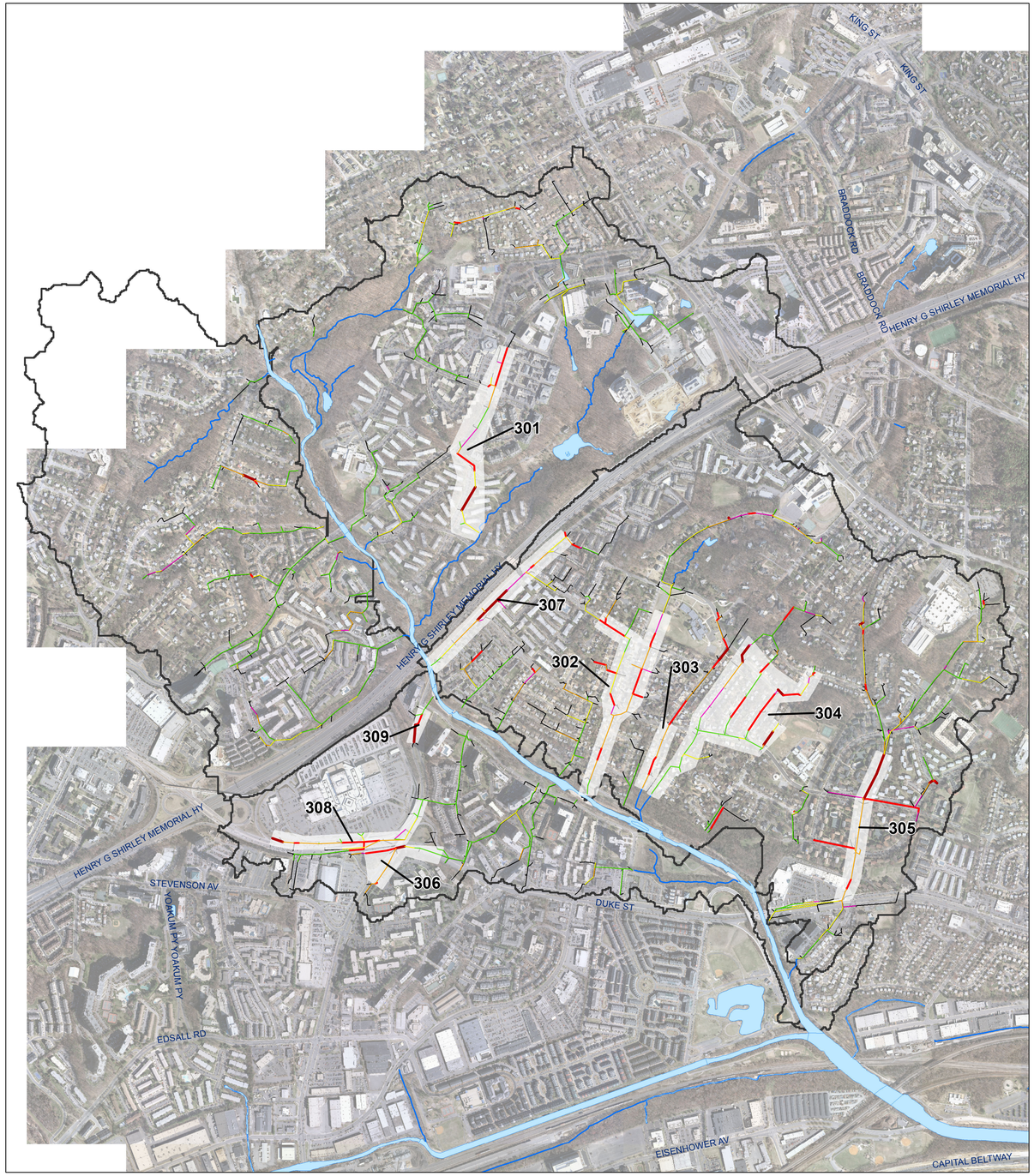


EXHIBIT 4B
Watershed-wide Alternative 3 Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Four Mile Run Watershed, Alexandria, Virginia

CH2MHILL



Legend

Model Results

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu.ft)

- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 200,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

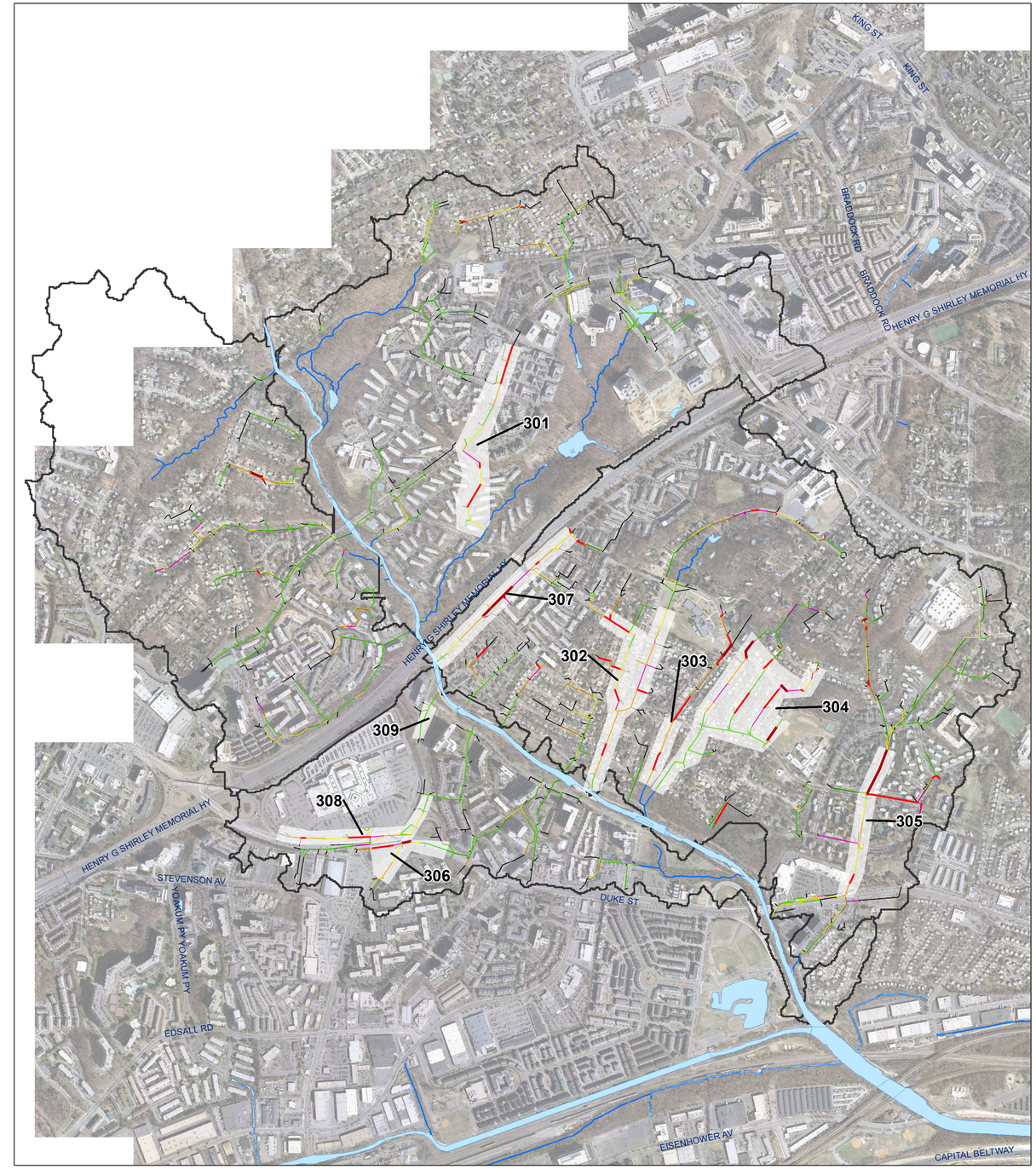
EXHIBIT 5A

Task 2 Existing Conditions Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Holmes Run Watershed, Alexandria, Virginia

0 1,000 2,000 4,000 Feet

CH2MHILL



Legend

Model Results

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu.ft)

- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 200,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

EXHIBIT 5B

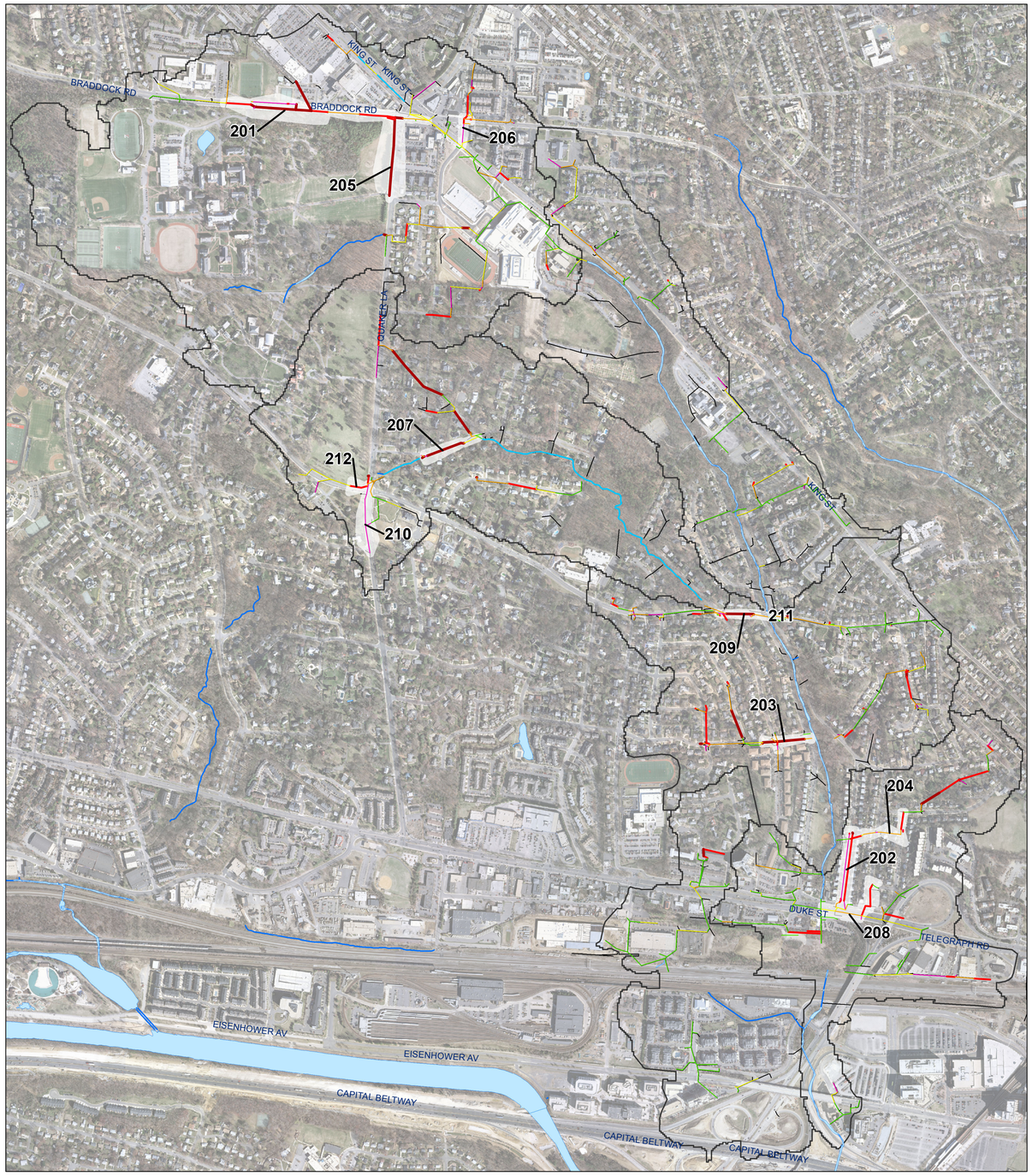
Watershed-wide Alternative 2

Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Holmes Run Watershed, Alexandria, Virginia

0 1,050 2,100 4,200 Feet

CH2MHILL



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

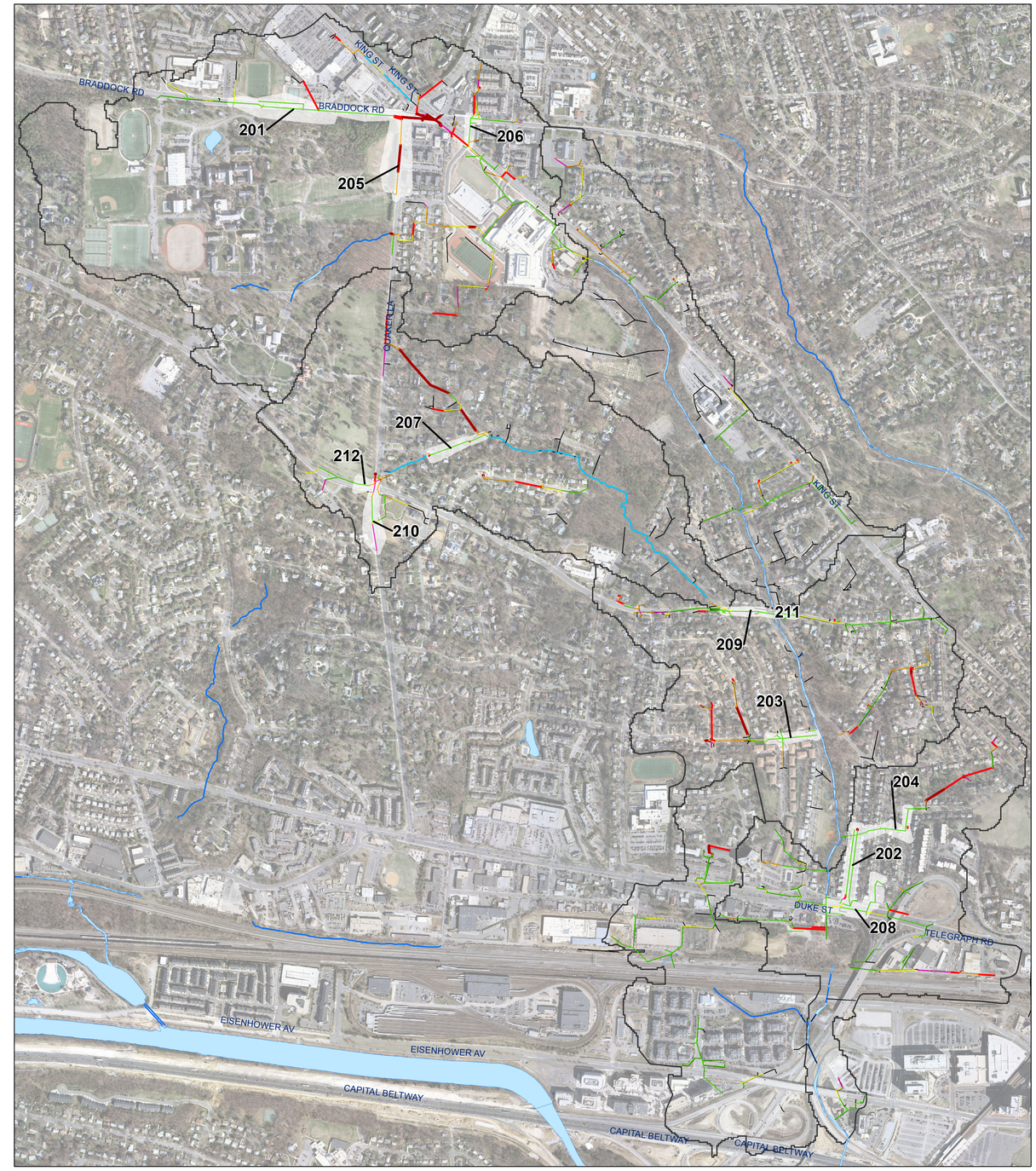
Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 140,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

EXHIBIT 6A
Task 2 Existing Conditions Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Taylor Run Watershed, Alexandria, Virginia

0 750 1,500 3,000
Feet

CH2MHILL



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

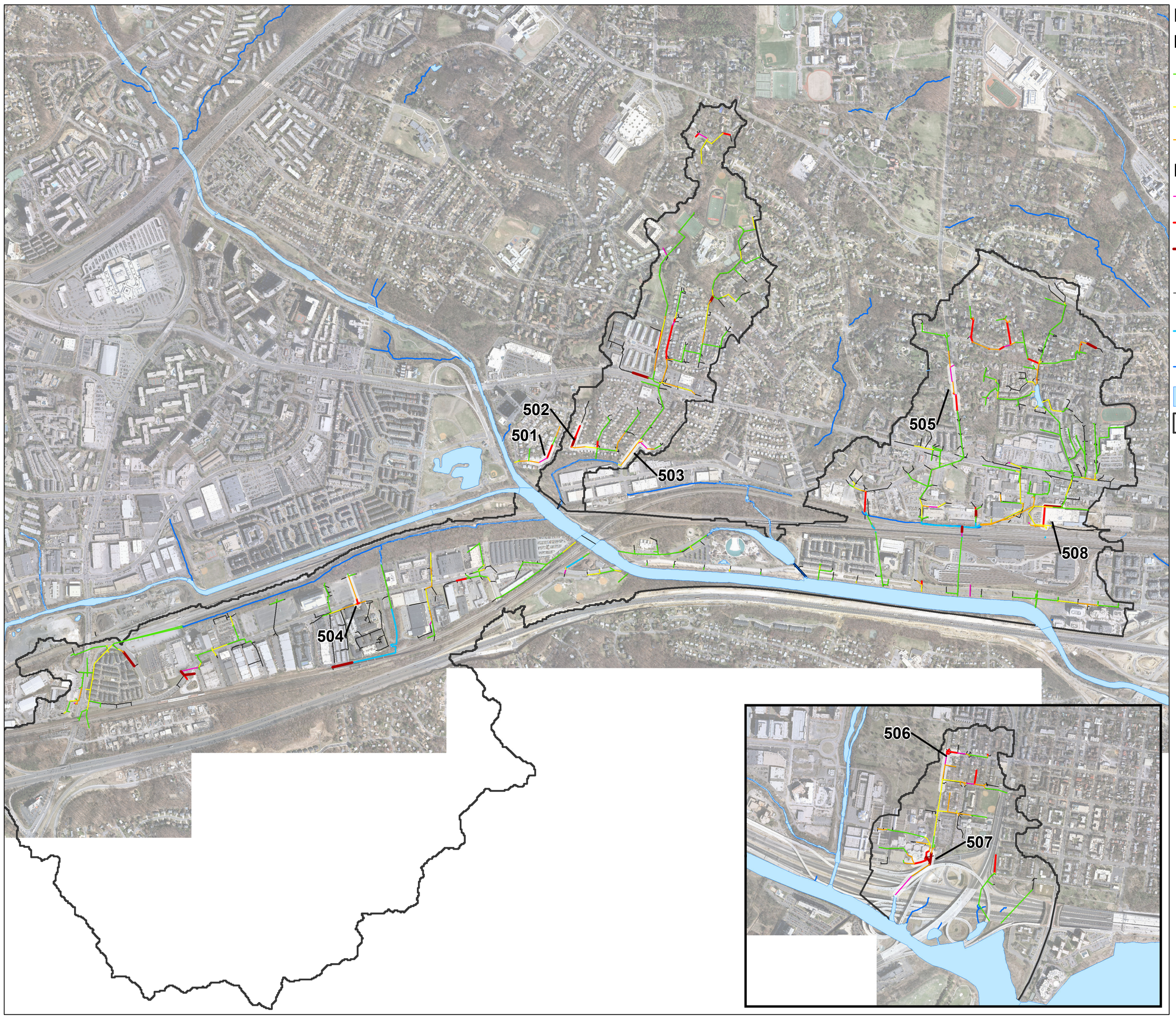
Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 140,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

EXHIBIT 6B
Watershed-wide Alternative 2
Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Taylor Run Watershed, Alexandria, Virginia

0 750 1,500 3,000
Feet

CH2MHILL



Legend

Model Results

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)

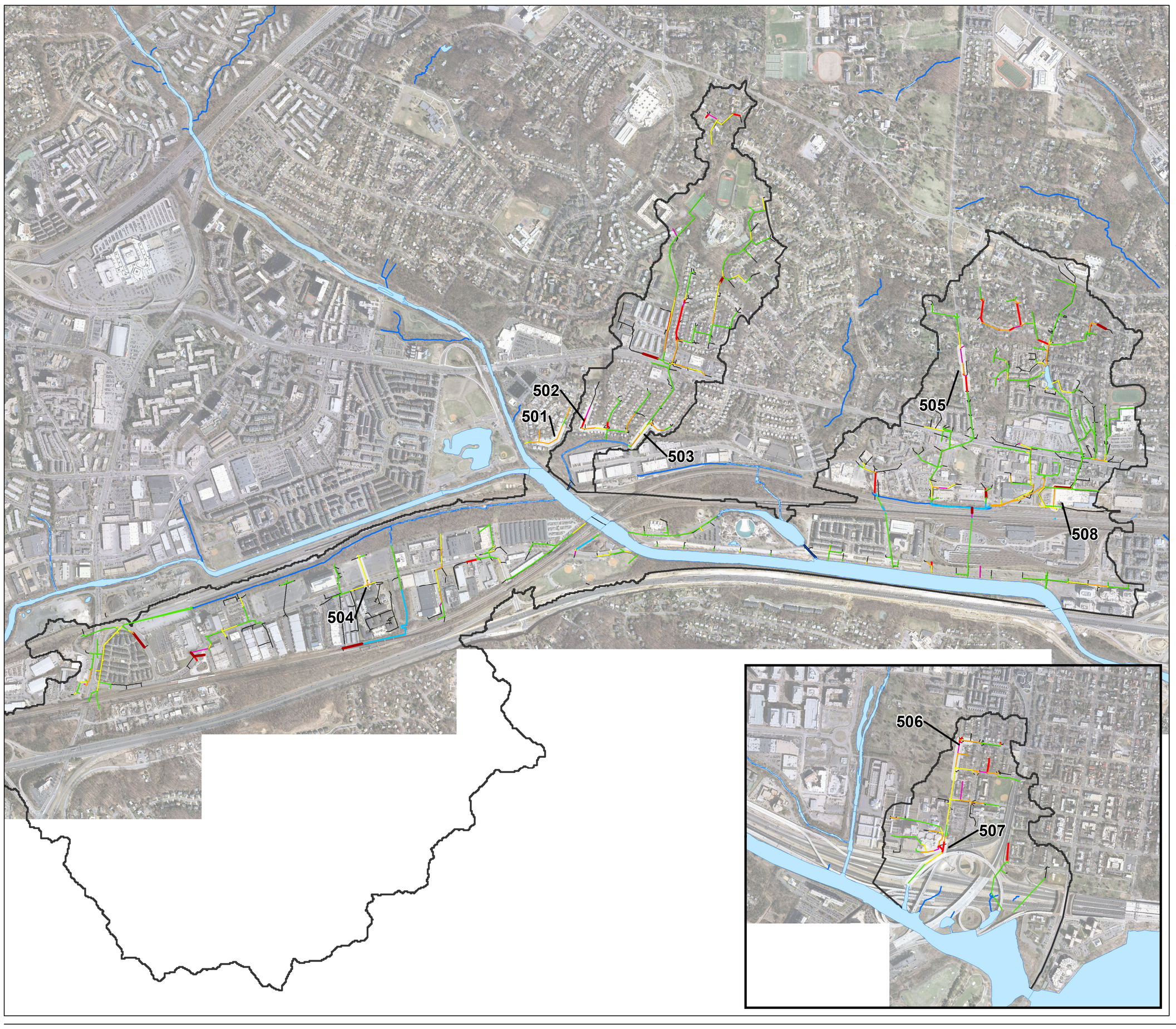
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 1,020,000
- Not Analyzed (Private, disconnected, upstream of runoff input)
- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

N

0 750 1,500 3,000
Feet

EXHIBIT 7A
Task 2 Existing Conditions Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Cameron Run Watershed, Alexandria, Virginia

CH2MHILL



Legend

Model Results

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)

- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 1,020,000
- Not Analyzed (Private, disconnected, upstream of runoff input)
- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

N

0 750 1,500 3,000
Feet

EXHIBIT 7B
Watershed-wide Alternative 1 Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Cameron Run Watershed, Alexandria, Virginia

CH2MHILL

Legend

Model Results

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)

- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 15,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

EXHIBIT 8A

Task 2 Existing Conditions Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Strawberry Run Watershed, Alexandria, Virginia

0 500 1,000 2,000 Feet

CH2MHILL

Legend

Model Results

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)

- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 15,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

EXHIBIT 8B

Watershed-wide Alternative 3

Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Strawberry Run Watershed, Alexandria, Virginia

0 500 1,000 2,000 Feet

CH2MHILL

EXHIBIT 9A
Task 2 Existing Conditions Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Backlick Run Watershed, Alexandria, Virginia

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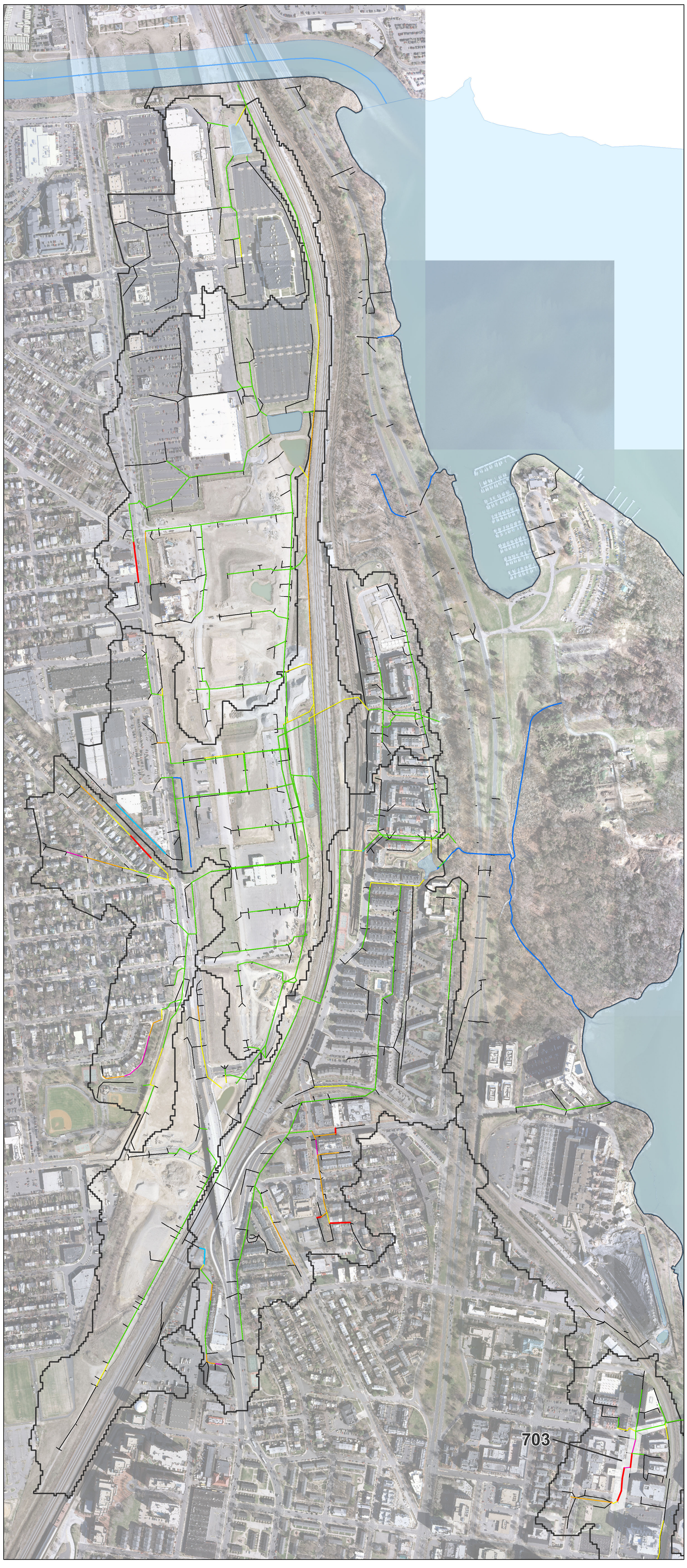
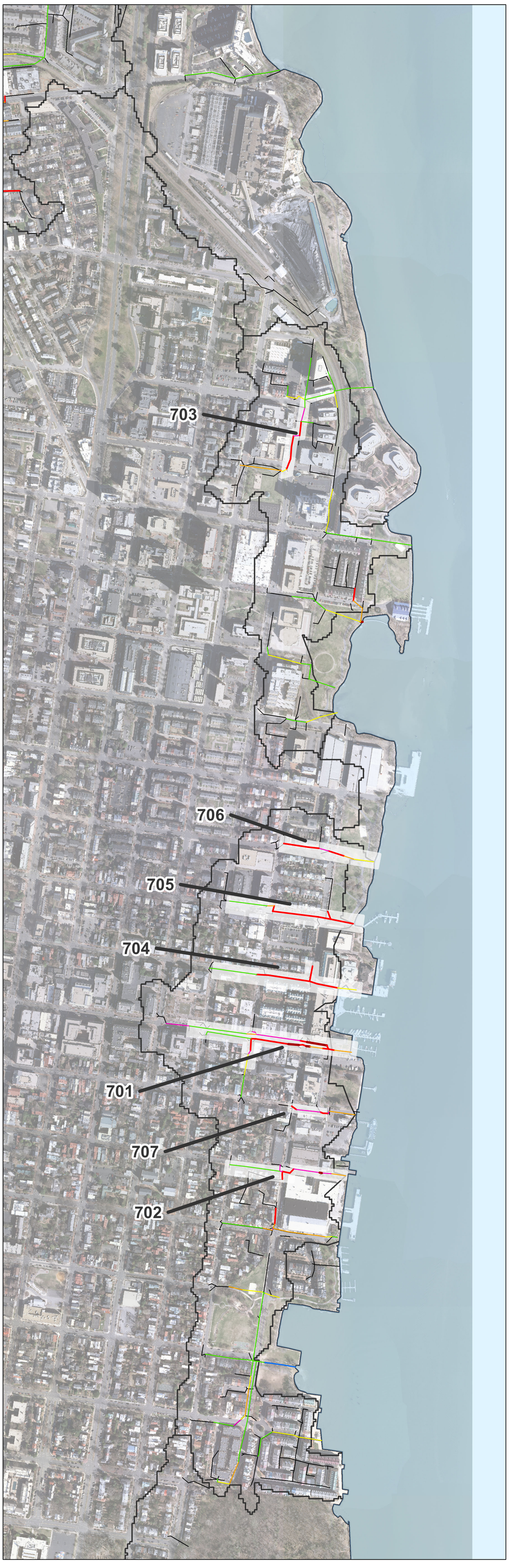
EXHIBIT 9B
Watershed-wide Alternative 3 Model Results and High Priority Problem Areas
Stormwater Capacity Analysis for Backlick Run Watershed, Alexandria, Virginia

CH2MHILL





Legend

Capacity

- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flood Volume (cu. ft.)

- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 38,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Watershed

EXHIBIT 10

Task 2 Existing Conditions Model Results and High Priority Problem Areas

Stormwater Capacity Analysis for Potomac River Watershed, Alexandria, Virginia

0 500 1,000 2,000

Feet

N

CH2MHILL