ARLINGTON
VIRGINIA

# FLOOD RISK ASSESSMENT AND MANAGEMENT PLAN

VOLUME 2 - SUMMARY REPORT

April 2024


Jacobs

Jacobs Engineering Group Inc.
1100 N Glebe Road, Suite 500
Arlington, VA 22201

## Flood Risk Assessment and Management Plan (RAMP) – Final Report

| | | | |
|---|---|---|---|
| **Client name:** | Arlington County, Virginia | | |
| **Project Directors** | Demetra J McBride and Rich Dooley. | | |
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### County Agencies

- County Manager's Office (CMO)
- County Attorney (CAO)
- Arlington Economic Development (AED)
- Community Planning, Housing & Development (CPHD)
- Environmental Services (DES)
- Human Resources (HRD)
- Human Services (DHS)
- Management & Finance (DMF)
- Parks & Recreation (DPR)
- Public Safety Communications and Emergency Management (PSCEM)
- Technology Services (DTS)

### External Stakeholders

- Arlington Public Schools
- Cherrydale Health and Rehabilitation Center
- Virginia Hospital Center

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## Acronyms and Abbreviations

| | |
|---|---|
| 1D | one-dimensional |
| 2D | two-dimensional |
| AACE International | Association for the Advancement of Cost Engineering International |
| ART | Arlington Transit |
| ASCE | American Society of Civil Engineers |
| ASTM | ASTM International |
| BCA | Benefit-cost analysis |
| BCR | benefit-cost ratio |
| Cherrydale Center | Cherrydale Health and Rehabilitation |
| DPR | Department of Parks and Recreation |
| FEMA | Federal Emergency Management Agency |
| GSI | green stormwater infrastructure |
| LOS | level of service |
| MG | million gallon(s) |
| NFIP | National Flood Insurance Program |
| NOCII | Network Operations Center II |
| NPV | net present value |
| O&M | operations and maintenance |
| PA | problem area |
| RAMP | Risk Assessment and Management Plan |
| RPA | Resource Protection Area |
| SVI | Social Vulnerability Index |
| USACE | U.S. Army Corps of Engineers |
| WPCP | Water Pollution Control Plant |

# 1. Introduction

For more than a decade, Arlington County (the County) has experienced significant and repetitive flooding and flash-flooding, which has produced increasing social and economic impacts. To better predict and plan for flooding, the County has developed a flood Risk Assessment and Management Plan (RAMP). The RAMP is documented in three separate volumes—Volume 1, Executive Summary; Volume 2, Final Report, consisting of an overall summary of the detailed technical memoranda; and Volume 3, Appendices, consisting of updated technical memoranda that were prepared at the end of each Subject Area Task during the RAMP. Importantly, the data and deliverables produced throughout the RAMP process have, over the past 3 years, influenced and crafted engineering action, benefit analyses, and public engagement under the County's stormwater program.

## 1.1 Purpose

The RAMP was designed and developed to:

- Inform, quantify, qualify, and assess the County's long-term vulnerability to flooding generated by a combination of marginally regulated development and density (1940-1970) and dramatic, climate-driven changes in the intensity, frequency and duration of storms;
- Identify and suppress direct and cascading impacts that would otherwise produce adverse property, civic, economic, and social impacts, and to quantify those risks;
- Provide an action pathway for programs, projects, and policies that will mitigate and manage future flooding; and
- Demonstrate the County's pivot from a conventional program based on past and current data, to a climate-facing program focused on long-term adaptation and resilience.

Previously, the County—like most jurisdictions—based its flood *mitigation* planning and execution on the Atlas 14 Tool and its principles, including the fundamental premise that assessments of flood risk are grounded in the study of historical data, rather than future projections. The RAMP project represents a future-facing strategy for impacts the world is already experiencing today; it includes flood modeling and risk assessment for current and projected future conditions that considers *adaptation and resilience* to climate change impacts on urban interior flooding, riverine flooding, and coastal flooding. Thus, the RAMP is able to project and quantify risk (the cost of inaction) over the climate horizons of 2040 and 2070.

The importance of this expansion beyond present-day mitigation to future, long-term adaptation and resilience cannot be overstated. It corrects the misunderstanding that the impacts of flooding are limited to only those property owners who experience direct flood damage by demonstrating how extreme and repetitive flooding exacts community-wide economic, operational, civic, and social impacts. The RAMP examines community-wide impacts and consequences in a supplemental Market Trends Report (Appendix H).

Also included in the RAMP are flood management strategies to inform and prioritize strategic investments for mitigating risk based on economic, environmental, and social equity criteria, as well as quantified project benefits and co-benefits, using a benefit-cost analysis methodology. This proactive method also considers that the opportunity and physical ability to implement flood mitigation diminishes with time while, conversely, the costs of mitigation will dramatically increase.

## 1.2 History of Flooding in Arlington County

Flooding and extreme heat are considered the two primary climate vulnerabilities in Arlington County. The RAMP project was precipitated by a series of flood events going back to June 2006, culminating in a series of localized, high-intensity storms in 2016, 2018, and 2019 that caused significant damage to property and civil infrastructure, and hindered County operations, economic activity, and delivery of emergency services. In particular, the July 8, 2019, storm was a catalyst for the RAMP project. During that historic storm, flooding was the most severe in the northern part of Arlington County, where rainfall totals were 3.1 inches in 2 hours, with peak intensities of 2.5 inches in 15 minutes.[1]

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[1] 2.5 inches in 15 minutes corresponds to more than a 1,000-year storm for the 15-minute duration based on rainfall statistics compiled in National Oceanic and Atmospheric Administration Atlas 14 data (Bonnin et al. 2006).

Figure 1-1 shows where most flood complaints have occurred in the County since 2006. The damage estimates from these events vary widely.

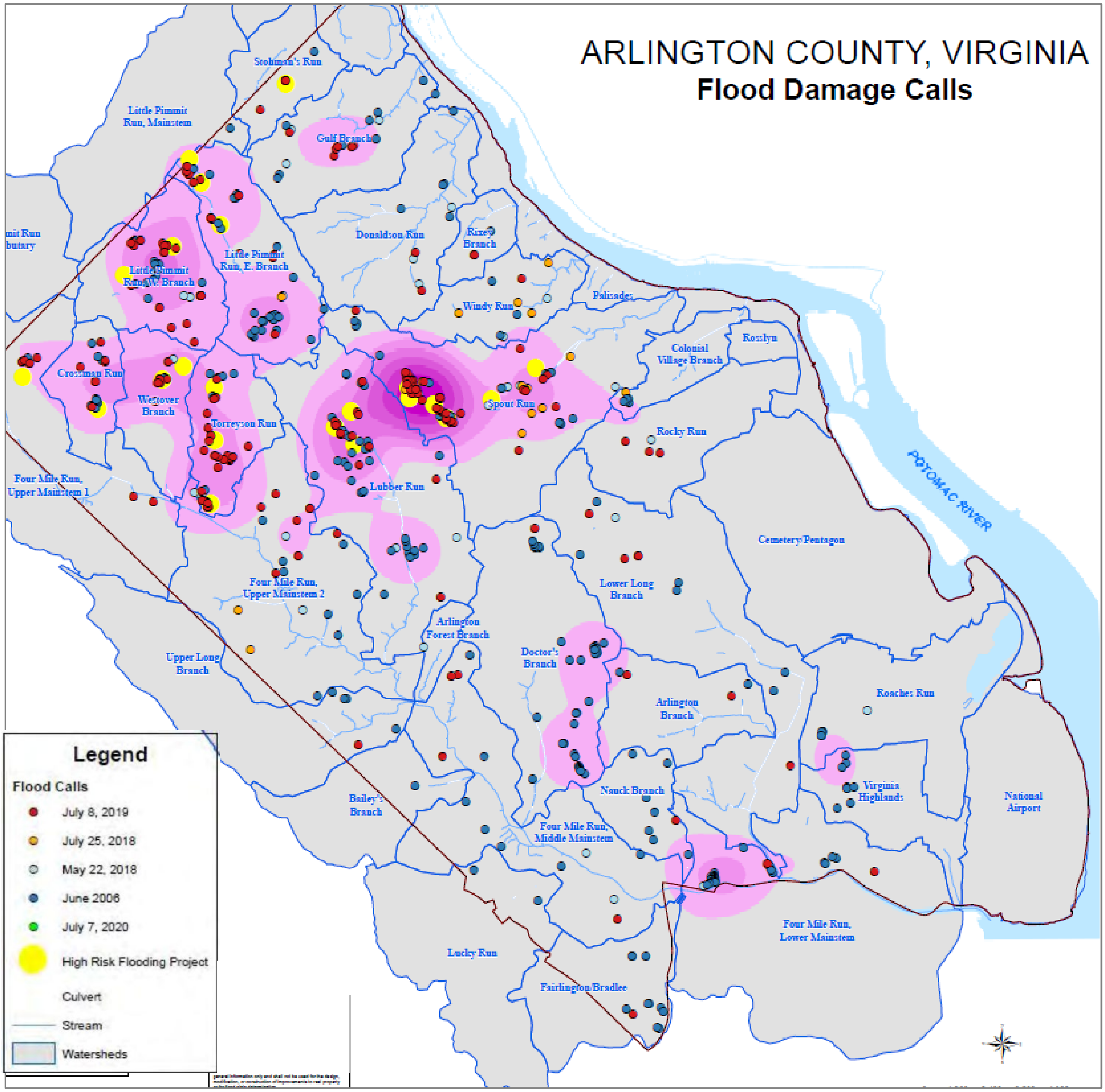



**Figure 1-1. Arlington County Flooding Complaint Calls**

Although the RAMP project did not involve evaluating extreme heat, the County recognizes that resilience solutions for flooding should integrate aspects to mitigate heat island effects. As Figure 1-2 shows, the projected number of days hotter than 35 degrees Celsius (95 degrees Fahrenheit) are expected to increase from 8 days per year in 2005 to between 20 and 26 days per year in 2050, and from 31 to 83 days per year in 2100.

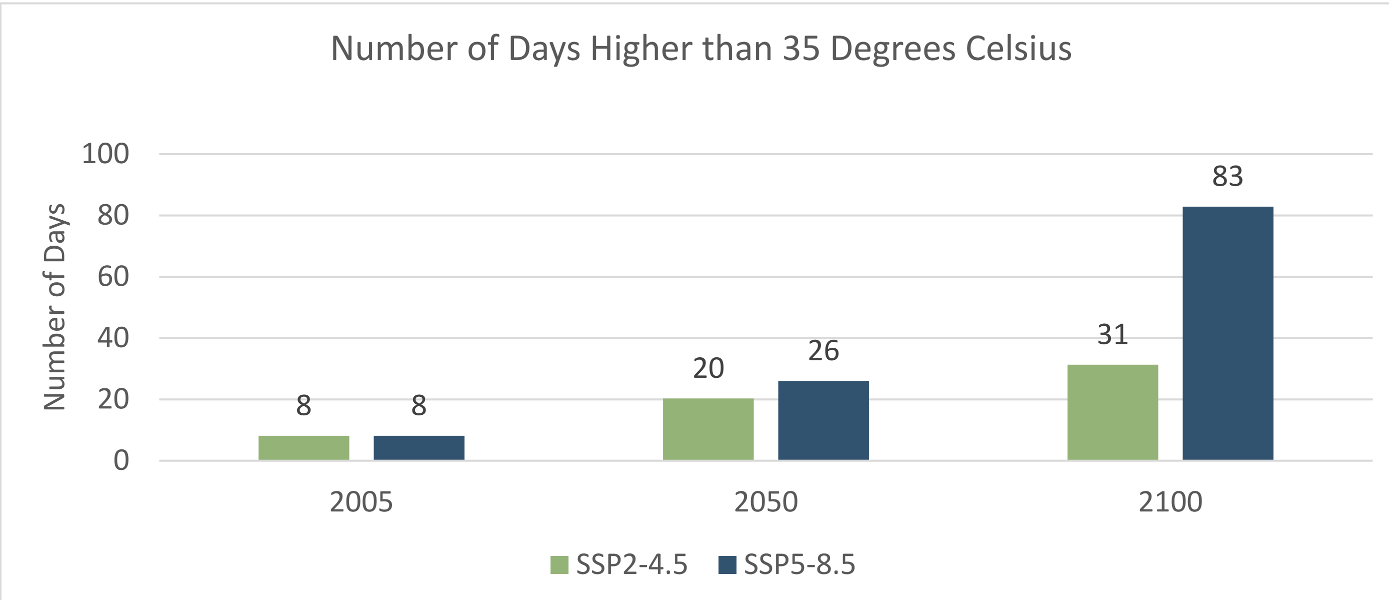
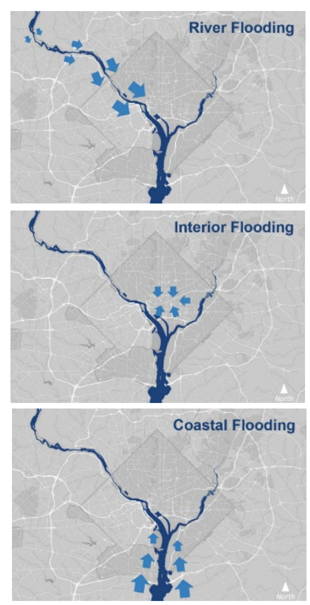



**Figure 1-2. Projected Days per Year of Over 35 Degrees Celsius (95 Degrees Fahrenheit) in Arlington County**

Source: Analysis conducted by Jacobs using Climate Insights modeling platform; for more information, visit the Climate Insights website (CLIMsystems Ltd. n.d.).

SSP = Shared Socioeconomic Pathway. SSP2-4.5 represents a future with climate change and SSP5-8.5 represents higher degree of warming compared to SSP2-4.5.

## 1.3 Types of Flooding and the Role of Interior Flooding Outside of FEMA Floodplains




Flood risk management has historically been regulated by the U.S. Federal Emergency Management Agency (FEMA) and local governments through mapping of FEMA floodplains and the National Flood Insurance Program. FEMA floodplains are used to map areas of riverine or coastal flood risk, which are two of the three types of flooding that occurs in Arlington County, depending on location:[2]

- **Riverine flooding** occurs when a stream or river overtops its banks because of an inability to contain water in the channel from rain collected upstream in the watershed. Riverine flooding is also referred to as fluvial flooding. In Arlington County, riverine flooding is generally found along Four Mile Run, the Potomac River, and their tributaries.
- **Interior flooding** occurs when direct rainfall overwhelms the capacity of soil and local drainage systems. Interior flooding is often referred to as pluvial flooding, urban flooding, or cloudburst flooding. **Interior flooding is a primary concern of the RAMP**.
- **Coastal flooding** occurs when overbank flooding occurs in areas that are subject to high tides or tropical storm surge (or both). Coastal flooding because of high tides is sometimes referred to as king tides, tidal flooding, or sunny day flooding. Coastal flooding is a concern only in Lower Four Mile Run and along the Potomac River waterfront.

[2] Flooding graphics source: NCPC and Silver Jackets, 2018.

All three types of flooding can occur in different parts of Arlington County, and all three types are projected to become more frequent and severe because of climate change, with more intense rainfall, sea level rise, and more severe tropical storms with increased storm surge. The County's early (1975-1985) bond-funded projects included purchase of floodplain areas for open space, green space, and parks in order to curtail development in FEMA-designated areas vulnerable to riverine or coastal flooding.

However, **damage from recent flood events in Arlington County has largely been caused by interior flooding outside and often** far from FEMA-designated floodplains. As a result, many residents and businesses impacted by interior flooding events did not realize they are in areas at risk of flooding. Figure 1-3 shows an example of areas subject to interior flooding, as well as the nearest FEMA floodplain in the Lubber Run watershed.

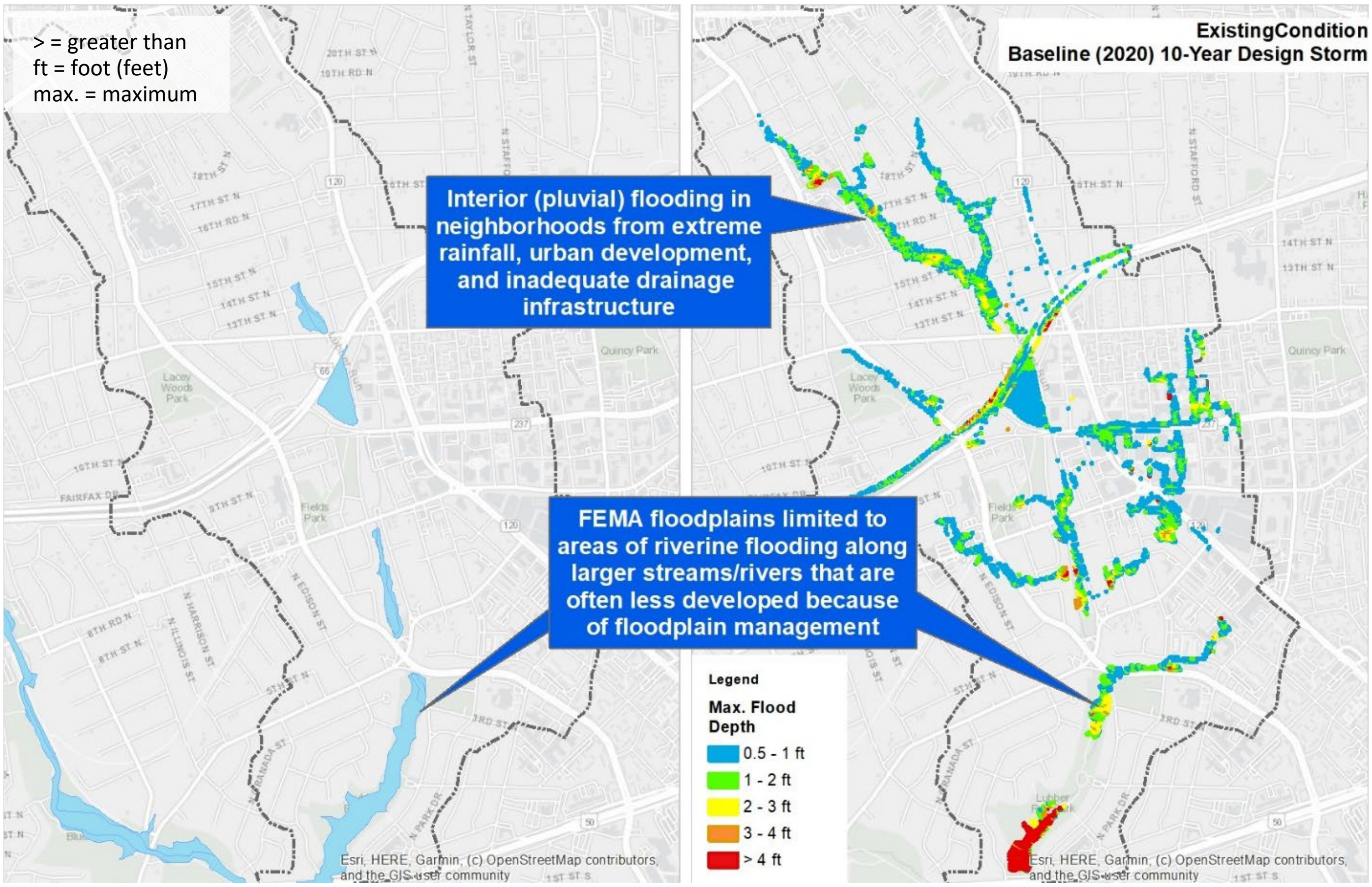



**Figure 1-3. FEMA Floodplains are Distinct from Areas of Interior Flooding and Do Not Adequately Characterize Risk from Extreme Rainfall and Urban Development**

## 1.4 Arlington County's Development History and Evolution of Drainage Design Standards

In the early decades of Arlington County's most prolific expansion (1930 to 1960s), there was limited regulation for development. The natural stream network of more than 92 miles had previously served as the stormwater management system. But as swift development caused stream erosion and gullies, streams and floodplains were filled in or paved over, and 66% of streams were encased in stormwater pipes because there were no regulations protecting streams or floodplains at this time, e.g., mandating lateral systems, or setting overland relief baselines.

Figure 1-4 shows Arlington County's remaining streams compared to the original network. The watersheds are distinguished by different colors.

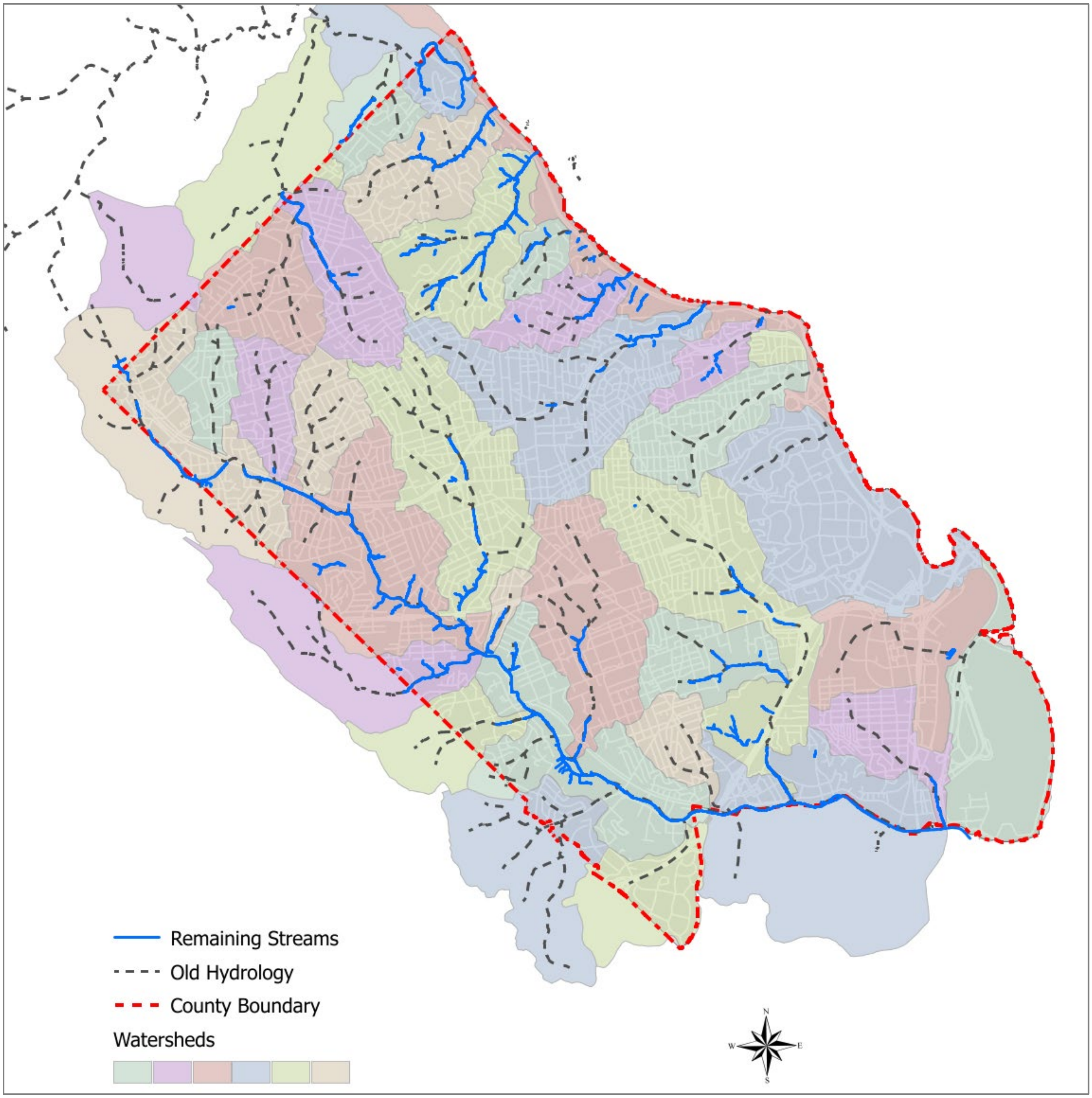



**Figure 1-4. The Legacy of Development in Arlington County Has Encased About 66% of Streams in Stormwater Pipes**

Source: The County, n.d.

As streams were put in underground pipes, the land above was subdivided, and new homes and structures were built on top. Figure 1-5 shows the Waverly Hills neighborhood in the Spout Run watershed, which was largely undeveloped in 1934 and is heavily developed today. Figure 1-6 shows the alignment of the storm drain pipe that encased the stream that previously followed the same alignment.

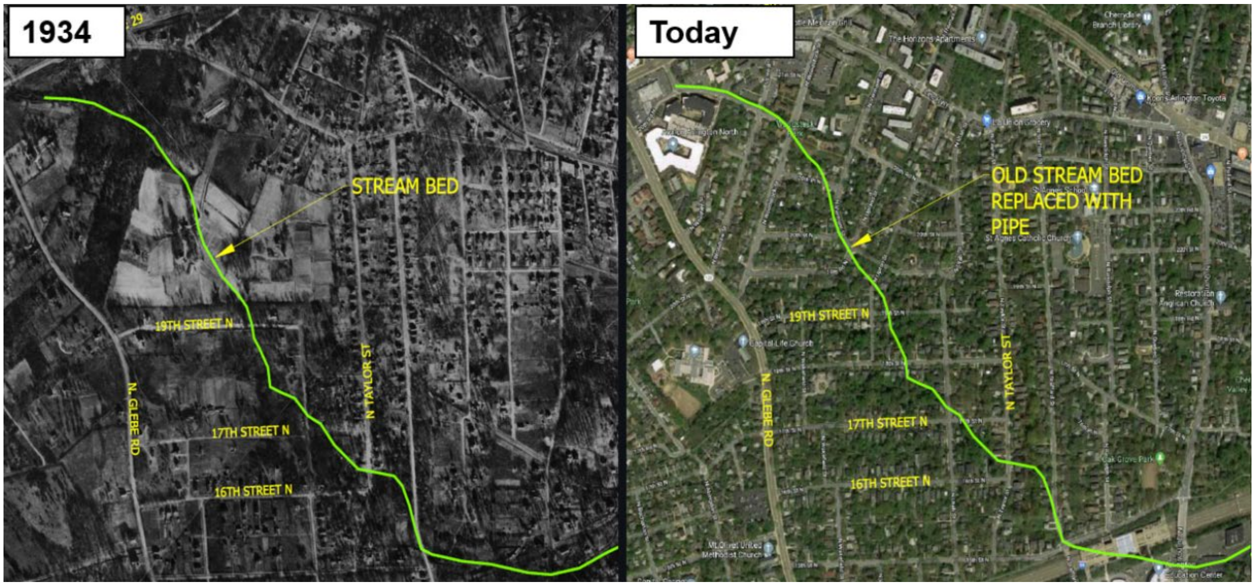



**Figure 1-5. Stream Alignment in Waverly Neighborhood, with Predevelopment Alignment (left) and with Fully Developed Single Family Residential and Commercial Properties (right)**

In the 1940s and 1950s, when most development occurred, stormwater system design standards were different than today. The system was not designed for the amount of impervious area that is currently located within the watersheds. In addition, storm sewers were constructed without considering the hydraulic grade line within the system, did not account for losses, and were often built at more shallow depths. Arlington County adopted its first Stormwater Master Plan in 1957. The pipe capacity was designed for about a 12 to 15-year storm (roughly 5 inches of rain in 24 hours). Overland relief was not required to direct where excess flood waters from stormwater runoff would go, and easements were not always required from development, so piping systems could run under or immediately next to buildings, making future construction access challenging. Figure 1-6 shows the extent of overland flooding in the Waverly neighborhood based on flood modeling conducted for the RAMP project, which not surprisingly, runs along the alignment of the existing storm drains and the original mainstem stream.

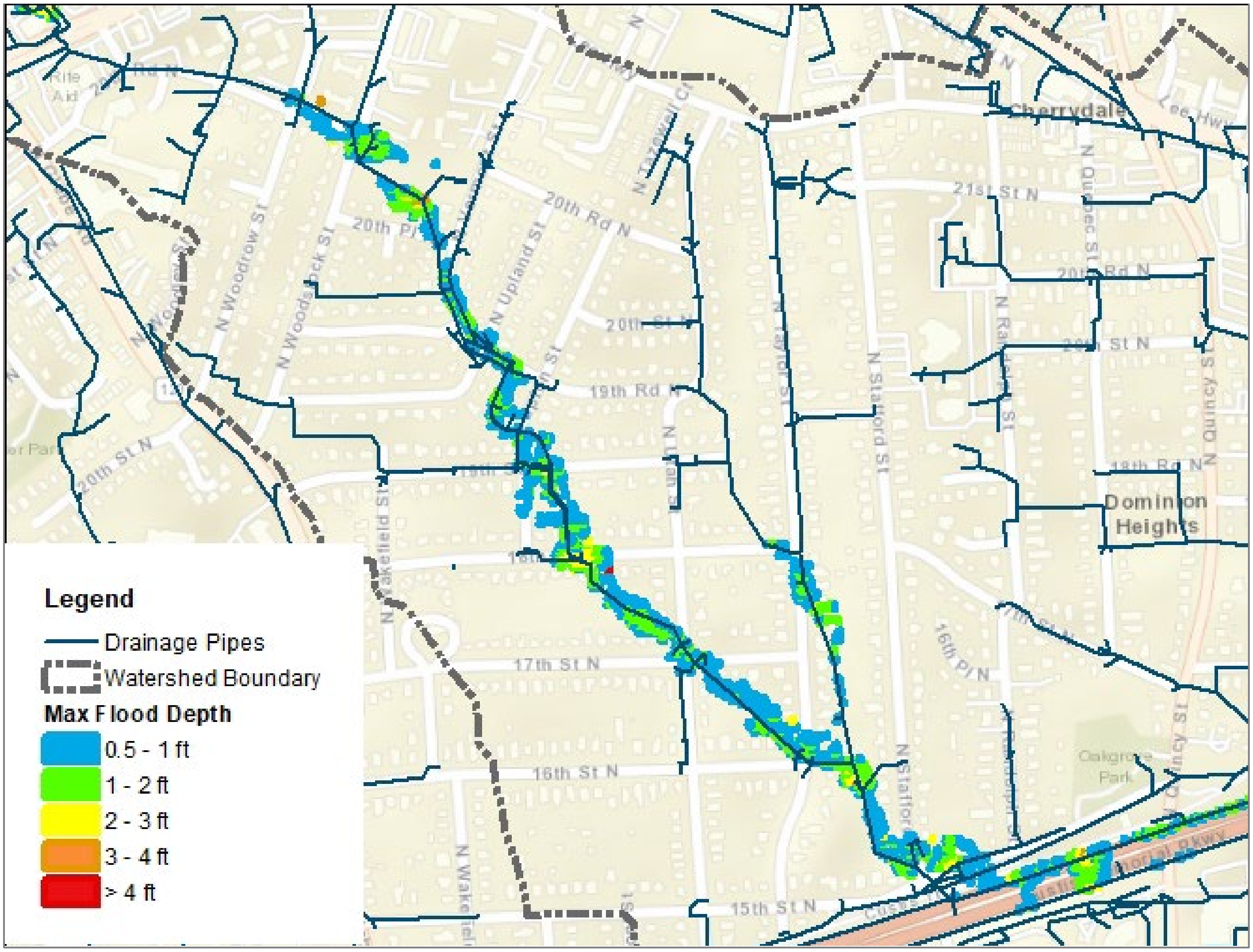



**Figure 1-6. Overland Flooding From 100-year Storm in Waverly Neighborhood Shows Potential Extent of Flooding for Flows That Exceed Capacity of Underground Pipes Placed in Old Streambed**

Today, regulations would require overland relief for a 100-year storm. Remaining streams are protected. Buildings, fences, or other obstructions would not be allowed in the path of flood waters. Wide easements would be required. To manage development legacies and mitigate future flooding, the County is undertaking a number of stormwater and flood management measures (described in Section 5), and other strategies such as changes to the Floodplain Ordinance and development of flood-resilient design and construction guidelines for (re)development in flood-vulnerable areas.

# 2. Risk Calculation and Management as a Flood Mitigation Strategy

Adaptation and resilience call for significant investments, phased over time. The RAMP was designed to model current and projected flooding from increased rainfall, sea level rise, and storm surge over 2040 and 2070 time horizons; to assess capacity limitations in the stormwater infrastructure system; and to identify programs, projects, and policies that amplify the County's ability to mitigate interior flooding and the impacts of severe storms. Importantly, the RAMP demonstrates the *cost of inaction*, which informs investment decisions and benefit-cost analyses (BCAs) and provides the public a means to engage the government on public and private action to adapt to, and gain resilience from, the threat of flooding caused by the acceleration of climate extremes.

## 2.1 Overview of Approach and Organization of this Report

This section provides a broad overview of how the RAMP can help address the likelihood and impacts of flooding.

The RAMP project includes the following key tasks:

- Data collection
- Climate projections and scenario development
- Interior and riverine flood modeling
- Coastal storm surge modeling with future sea level rise
- Vulnerability assessments
- Risk assessments
- Gaps analysis
- Conceptual alternatives development and benefit-cost analysis
- Support for public outreach and grant writing

Risk assessments use a combination of tools to assess direct damage and indirect economic impacts from lost wages and income, as well as assessment of flood impacts on socially vulnerable groups. In addition, site-specific flood risk assessments were conducted at 10 critical facilities, mostly County-owned utilities, schools, transportation facilities, and private healthcare facilities.

The RAMP Final Report is composed of three volumes. This Summary Report represents Volume 2, comprising the following sections:

1. Introduction
2. Risk Calculation and Management as a Flood Mitigation Strategy
3. Flood Vulnerability and Risk Assessment Results
4. Programmatic and Policy Strategies and Financial Market and Economic Trends
5. Flood Mitigation Strategies, Benefits, and Cost Effectiveness
6. Conclusions, Recommendations, and Next Steps

Volume 3 includes Appendices for each of the detailed technical memoranda for each of the RAMP tasks.

## 2.2 Description of Watersheds in the County and Selected Watersheds Included in RAMP

There are 36 separate watersheds within the 26-square-mile area of Arlington County that are either entirely within the County or partly in adjacent areas of Fairfax County. The watersheds range in size from 0.13 to 2.48 square miles and are almost entirely developed, except for parkland and stream corridors. An initial screening of watersheds was conducted to select those with greater likelihood of significant flooding, which were then subject to more detailed modeling, analysis, and alternatives assessment. A screening-level flood model was run Countywide to support the screening process, which included three main criteria: (1) number of flood complaints, (2) complaints per acre, and (3) the flooded area based on the screening model. Figure 2-1 shows all Arlington County watersheds and those selected for more detailed modeling. The final list of watersheds selected for more detailed analysis was vetted with County staff and adjusted based on multiple key factors, including (1) whether detailed studies have already been completed and solutions developed (Westover Branch); (2) whether there are critical facilities for which flood modeling results are needed to conduct risk assessments in watersheds not otherwise high priority (Four Mile Run and Middle Mainstem); (3) whether there are known locations of serious or repetitive impacts/losses to residents and businesses; and (4) equity considerations that account for disproportionate impacts from otherwise localized but severe flooding (Bailey's Branch). The screening process resulted in the watersheds shown on Figure 2-1 being selected for detailed flood modeling.

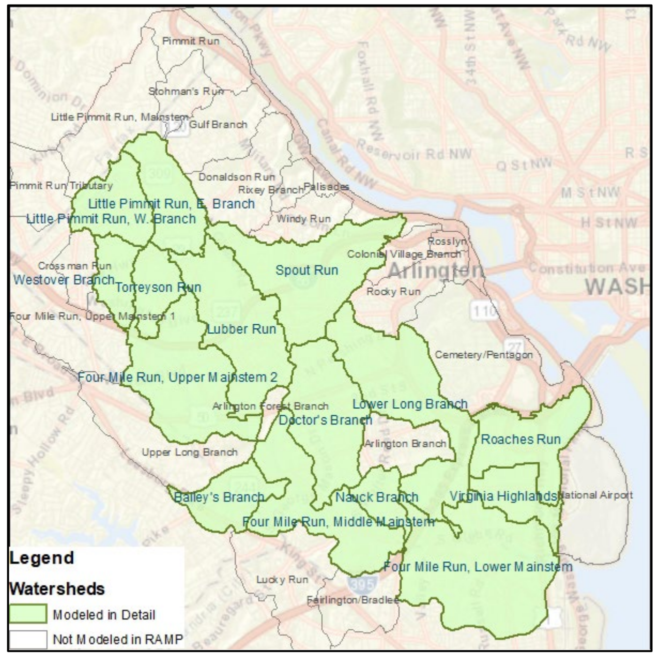



**Figure 2-1. Arlington County Watersheds and the Watersheds Selected for Detailed Analysis in RAMP Project**

## 2.3 Two-Dimensional Flood Inundation Maps for Current and Future Climate

For the selected watersheds, a critical output from the first task of the RAMP was a series of 2-dimensional (2D) flood inundation maps showing the extent and depth of flooding for different size storms, referred to as climate scenarios. The RAMP also expanded on the 2014 Stormwater Master Plan by looking at a range of current and projected future rainfall (including acute changes in storm patterns and intensities following adoption of the 2014 Stormwater Master Plan). Projections were completed for the 2-, 10-, 100-, and 500-year storm recurrence interval events. Ten future climate scenarios were selected to bracket the range of current and potential future risk. Appendix A provides details on how the climate projections were developed.

Three distinct time horizons were considered—baseline (2020), 2040, and 2070. The future time frames were selected based on typical useful life of different types of infrastructure, factored at 20 years for electrical and mechanical systems, like motors, and 50 years for systems made of concrete, like underground storm drains. For each of these time periods, a range of different size storms were selected that are based on different recurrence intervals or probability of occurrence, such as 10-year (10% chance annually) or 100-year (1% chance annually) storms. This range of storm probabilities is critical for calculations of risk in later tasks. Table 2-1 summarizes all the storms that were modeled. For example, Scenario 6 shows that the projected total rainfall in 2040 for a 100-year storm is 9.0 inches in 24 hours. By comparison, Scenario 3 shows the current total rainfall for a 100-year storm is 8.4 inches in 24 hours, and Scenario 9 shows that amount will increase by the year 2070 to 9.6 inches in 24 hours.

**Table 2-1. Rainfall Climate Scenarios for Interior and Riverine Flood Modeling**

| Scenario | Planning Horizon | Precipitation Return Interval (annual probability %) | 24-hour Precipitation (inches)[a] |
|---|---|---|---|
| 1. Observed event: July 8, 2019 | Current conditions | AG4JW Station in north Arlington County | 3.32 (in 2.5 hours) |
| 2 | Current conditions | 10-year (10%) | 5.2 |
| 3 | Current conditions | 100-year (1%) | 8.4 |
| 4 | Current conditions | 500-year (0.2%) | 11.4 |
| 5 | 2040 | 10-year (10%) | 5.4 |
| 6 | 2040 | 100-year (1%) | 9.0 |
| 7 | 2040 | 500-year (0.2%) | 12.2 |
| 8 | 2070 | 10-year (10%) | 5.8 |
| 9 | 2070 | 100-year (1%) | 9.6 |
| 10 | 2070 | 500-year (0.2%) | 12.9 |

[a] The values for rainfall totals in scenarios 2 through 10 represent statistical averages that may occur anywhere in the County. However, any given storm will vary across the County in total volume and intensity, which means that the return interval (annual probability percentage) of the storm varies from one location to another, as was experienced in the observed event on July 8, 2019, during which much higher rainfall intensities were experienced in northern Arlington County (see Appendix A).

The 2D flood inundation maps build on previously developed one-dimensional (1D) models for the County's 2014 Stormwater Master Plan. The 1D models analyzed capacity of storm drainpipes based on a rainfall event equal to the Virginia Department of Transportation Standard 10-year storm (4.84 inches in 24 hours), which is the current design standard for the County. For the RAMP 2D modeling work, the baseline 10-year storm was updated to reflect more recent statistical estimates of the 10-year storm (5.16 inches in 24 hours). The 1D models are referred to as "one-dimensional" because they analyze only water that is in the pipe. When capacity is exceeded and water is on the ground surface, the 1D model will not show where the flow goes over land. Figure 2-2 compares a watershed area modeled 1D previously (left panel), showing pipes at or over capacity, with the 2D model produced during the RAMP (right panel). Appendix B provides details of how the interior and riverine flood modeling was conducted. Appendix C provides details on how the coastal modeling was conducted.

Figure 2-3 shows an example of 1D/2D flood model results for two current (10- and 100-year) and one future scenario based on projected rainfall with climate change (100-year in 2070) for Lubber Run. Map exhibits are included at the end of Volume 2, showing flood extents and depths for current conditions (without mitigation alternatives) and with mitigation alternatives (presented later in this report).

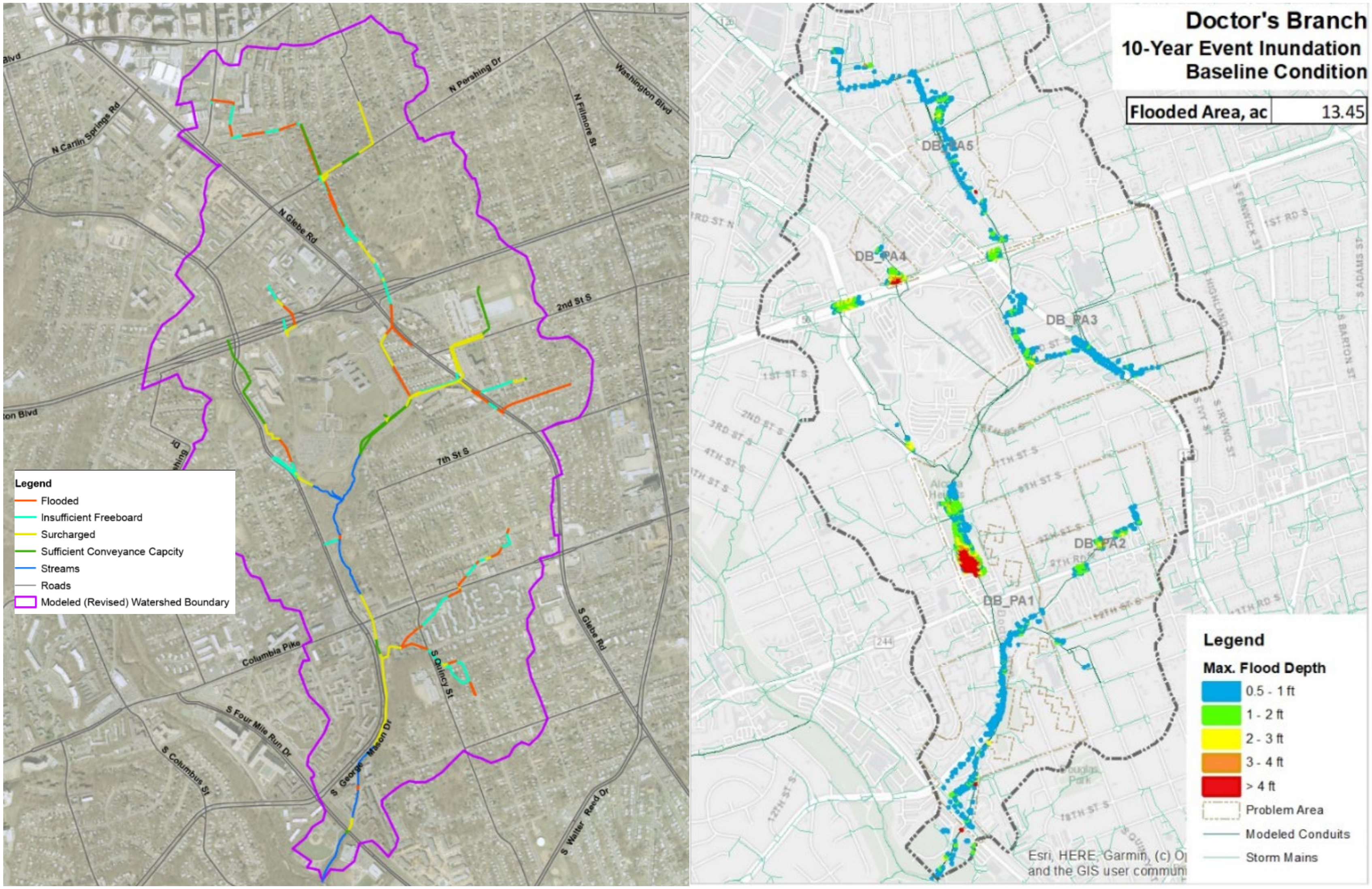



**Figure 2-2. Example of Previous 1D Modeling Results (Left), Showing Pipes at or Over Capacity, Versus 1D/2D Modeling Results (Right) Produced During the RAMP, Showing Surface Flooding**

ac = acre(s)

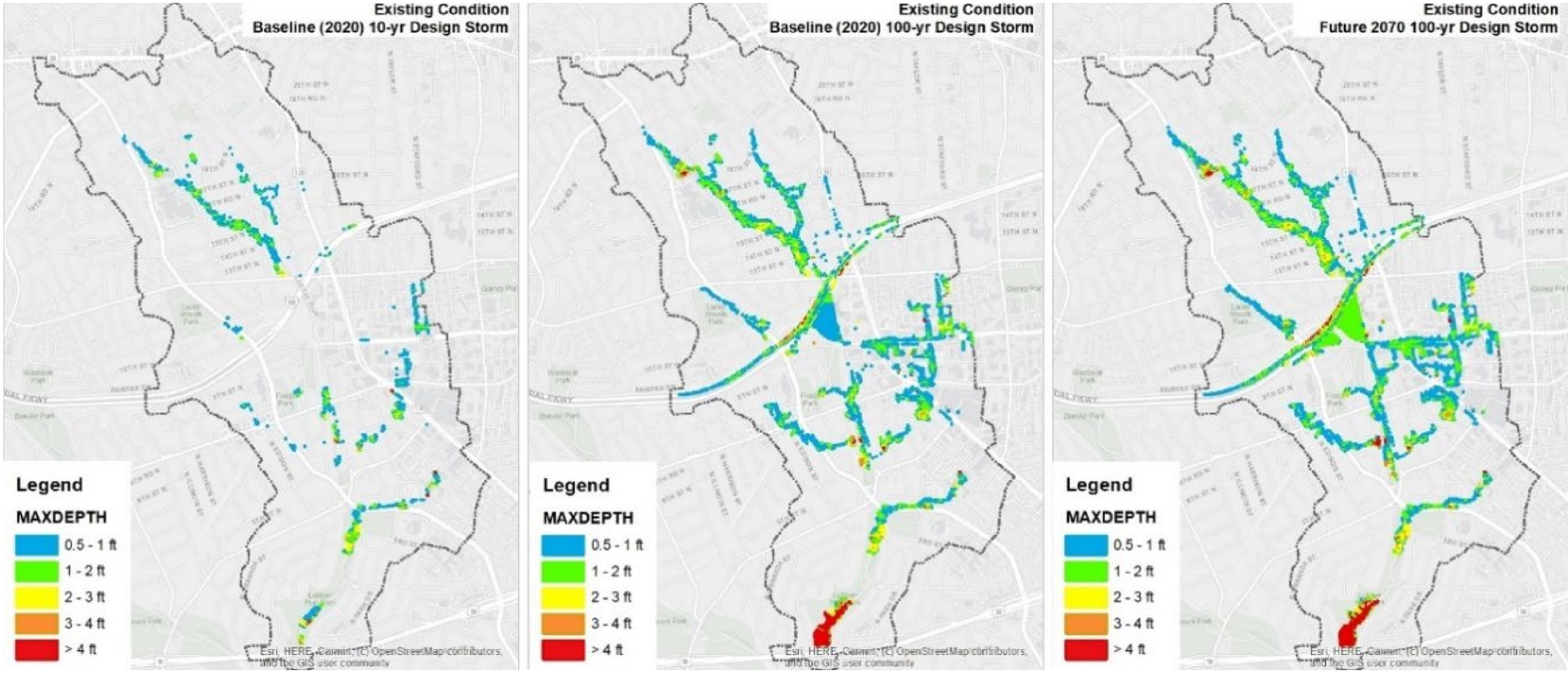



**Figure 2-3. Example 1D/2D Flood Model Results for Three Scenarios in Lubber Run Watershed: 10-year and 100-year Current Scenarios and 100-year Projected in 2070 Scenario**

yr = year

## 2.4 How the RAMP is Already Supporting County Flood Management Investments and Planning

Preliminary results from the RAMP are already contributing to increased, informed investment in flood mitigation and application in land use planning. The following are examples:

- The RAMP has already helped support significant increases in annual capital improvement program funding for flood mitigation infrastructure (fiscal years 2022–2031), and it will serve as a decision-support tool in developing future capital improvement plans.
- Staff are already using the data from the RAMP for private (re)development and plan review processes (for example, Plan Langston Boulevard, Transportation Strategic plan, and an innovative Green Infrastructure Plan).
- The RAMP is expected to be a key component for the County's first comprehensive resiliency strategy.
- The RAMP programmatic and policy recommendations are expected to advance and support future code changes to account for resilience, particularly in areas of interior flooding, where the County is planning to create a Flood Resilience Zoning Overlay District.
- Flood-resilient design and construction guidelines.
- Public engagement and communication on matters including, but not limited to, flood vulnerability, climate adaptation and resiliency, direct and cascading financial impacts, and consequences of repetitive flooding and loss.

# 3. Flood Vulnerability and Risk Assessment Results

## 3.1 Overall Approach to Flood Vulnerability and Risk Assessments

The flood modeling was a key input to assessing flood exposure, vulnerability, and risk of neighborhoods and critical infrastructure. **Flood exposure** is a measure of whether a neighborhood or facility is potentially flooded by different size storms and how much area is flooded. Broadly speaking, exposure is the presence of people or infrastructure, or economic and environmental assets in places that could be adversely impacted by flooding.

**Vulnerability assessment** combines exposure, with measures of whether a flooded area is sensitive to flooding or has an adaptive capacity. Sensitivity reflects the susceptibility to harm or damage. Vulnerability assessments are inherently qualitative metrics and provide a screening process to decide which areas and facilities should undergo more detailed risk assessments and evaluation of site-specific flood mitigation alternatives.

**Risk assessment** is a quantitative assessment of monetary impacts (the cost of no action) as well as impacts to vulnerable groups. Risk factors in both the likelihood of damage or impact and the consequence of damages and impacts.

Each of these assessments provide an increasing level of detailed information, with each successive step resulting in screening out areas or facilities that have less potential risk; and the final risk assessment step feeds into the assessment of site-specific flood mitigation alternatives for which BCAs are performed. The overall approach to assessing flood vulnerability and risk is summarized on Figure 3-1, which is applied both to spatial areas exposed to flooding and to individual critical facilities. The flood exposure was first determined based on the flood modeling results, which provided the total area flooded for different land use types.

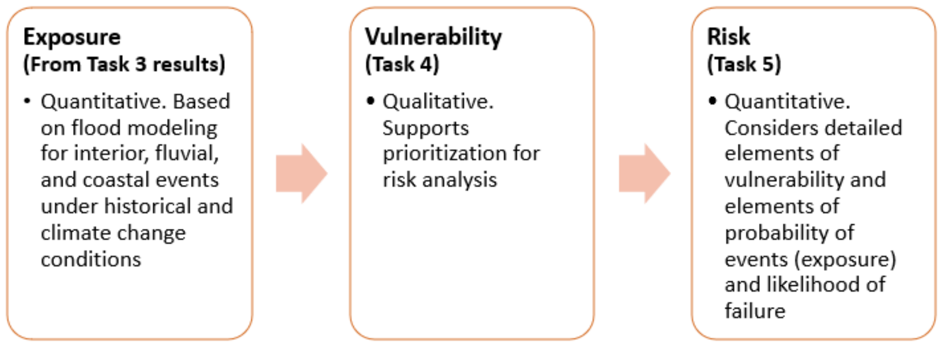



**Figure 3-1. Overview of Flood Exposure, Vulnerability, and Risk Assessment Process**

Vulnerability assessments were then conducted using data from the exposure analysis and a multi-criteria decision process to assign an overall vulnerability score to each watershed. The score combines three indices using weights developed with County stakeholders: (1) a vulnerability index, (2) a flooded area index, and (3) a high-criticality facility index. Each index is based on overlays of the flood modeling results and relevant parameters, such as areas with high social vulnerability, commercial areas, environmentally sensitive areas, and critical facilities.

Seven watersheds with the highest vulnerability (based on number of vulnerable areas, assets, and resources) were selected for detailed risk assessments using FEMA's Hazus tool, which estimates monetary losses associated with flooding. In addition, site-by-site risk assessments were conducted for selected critical facilities to assess individual assets at risk within those facilities based on projected depth of flooding.

Results are summarized below, and details of the vulnerability assessments and risk assessments are provided in Appendices D and E, respectively.

## 3.2 Watersheds with the Largest Flooded Area

Using the flood inundation maps, the total area flooded was calculated for each watershed, as was the percentage of the watershed flooded for different size storms. Figure 3-2 presents an overview of the flooded area (for inundation depths greater than 6 inches) for different scenarios. Watersheds impacted by coastal flooding include the flooded area under coastal flood scenarios, which include Four Mile Run Lower Mainstem and Roaches Run.

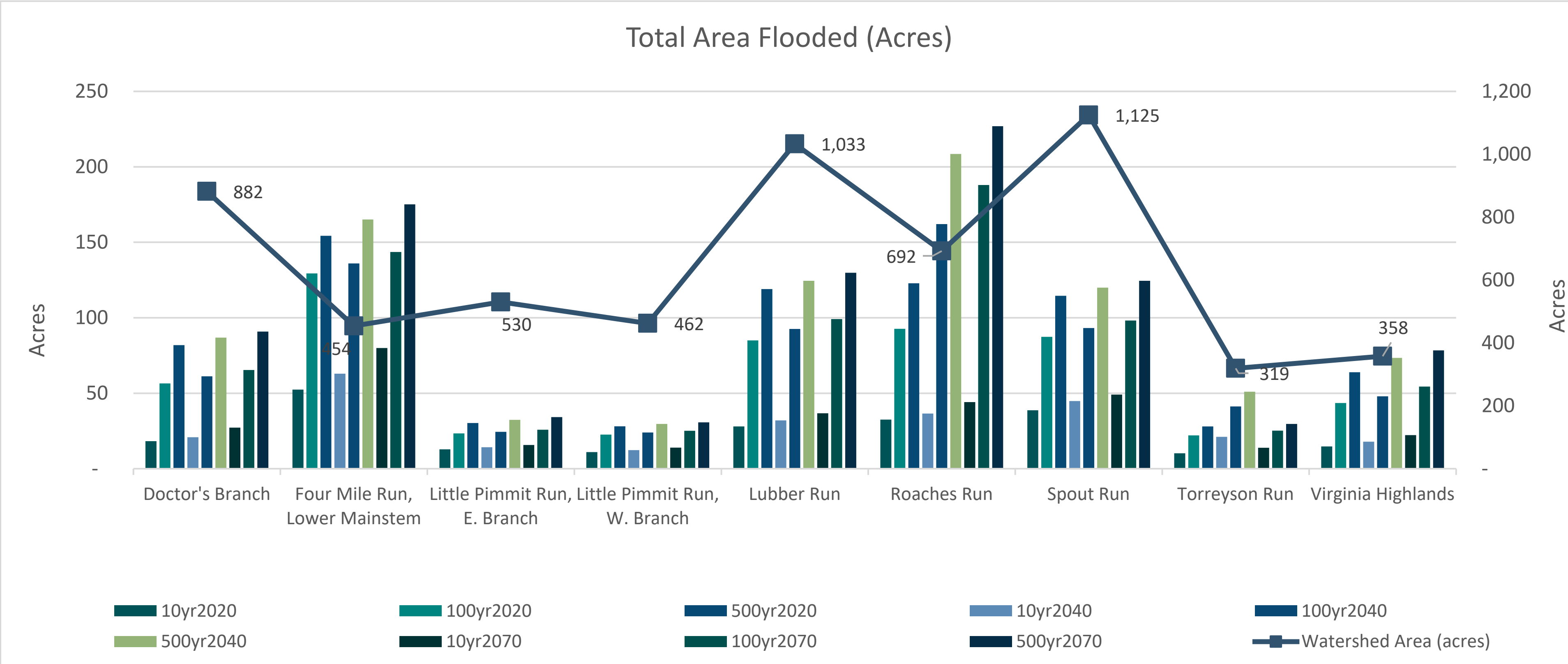



**Figure 3-2. Extent of Flooded Areas by Watershed Under Different Scenarios**

## 3.3 Watershed Vulnerability Scores

A composite vulnerability score was computed at a watershed level based on three indices:

**Watershed-level Vulnerability Index**: The Watershed-level Vulnerability Index is an aggregate measure of the vulnerability of receptors in the watershed, in which vulnerability is a measure of exposure across all storm events, sensitivity, and adaptive capacity.[3]

**Flooded Area Index**: The Flooded Area Index is a measure of the geographic extent of flooding in the watershed, with specific measures of flooding in high social vulnerability areas and commercial areas.

**High-criticality Receptor Index**: The High-criticality Receptor Index is a measure of how many highly critical receptors flood.

Assuming equal weights for the three indices, the resulting watershed prioritization is presented on Figure 3-3. The ranking shows Four Mile Run Lower Mainstem as the top watershed to prioritize, with Little Pimmit and Virginia Highlands as lower priority watersheds.

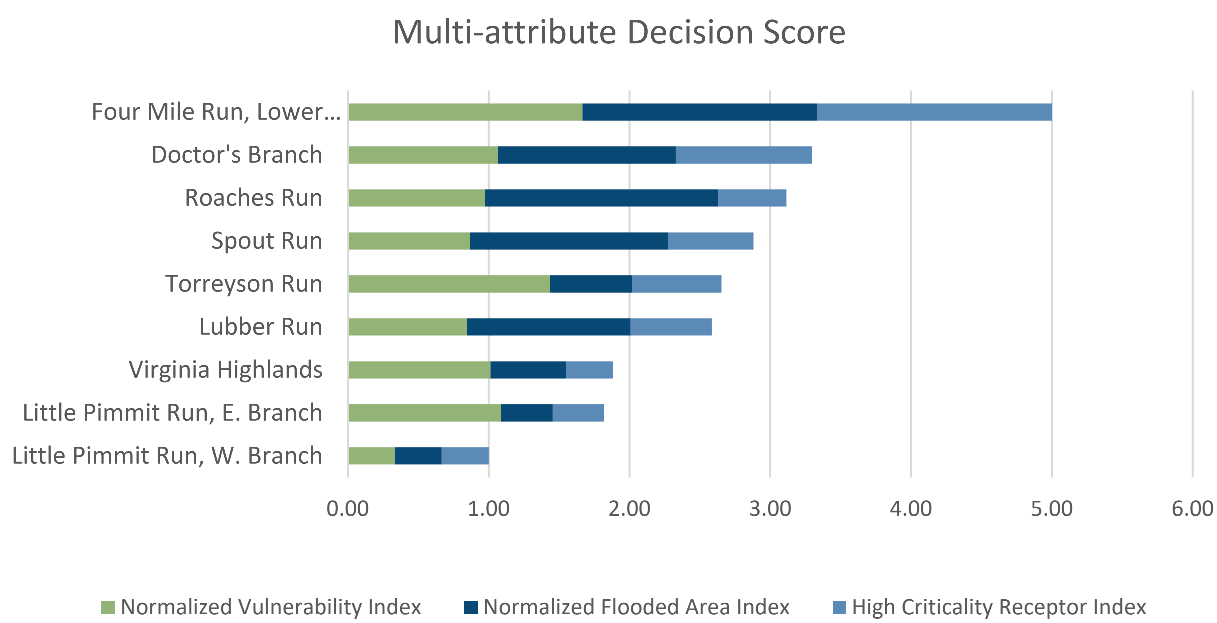



**Figure 3-3. Watershed Prioritization Based on Watershed-level Vulnerability Assessment Scores**

E. = East
W. = West

[3] A **receptor** is any entity of interest that can be exposed to flooding—examples include a facility, an asset, a public building providing critical services, or an environmental resource.

**Sensitivity** is a measure of the degree to which a receptor would be impaired by flood exposure. For example, roadways are generally less sensitive to temporary flooding because they are unlikely to be damaged (though may require removal of debris). In contrast, a non-submersible pump station is considered highly sensitive to flood events if exposed to water, as it may be damaged beyond repair.

**Adaptive capacity** represents the existing asset/facility/receptor's inherent ability to adjust to maintain its primary functions. Examples include the existence of back-up generators or the ability to raise a seawall protecting a receptor.

## 3.4 Vulnerability of Critical Facilities

A short list of critical facilities was prioritized for detailed risk analysis as a result of the vulnerability assessment, which factored in flooding exposure and considerations of criticality of the facilities, as well as feedback from County staff. Two main factors were considered in short-listing these facilities: (1) facility exposed to flood under more than one scenario evaluated and (2) facility previously identified as critical during earlier RAMP tasks. This criticality of facilities, in turn, was established by considering factors related to public health and safety, value of the facility during emergency response and the consequences to operations and services if the facility interrupts operations. The ranking of criticality of facilities followed a similar approach to the Northern Virginia Hazard Mitigation Plan from 2017, which included Arlington County as one of the participant communities. The RAMP did not include federal or state facilities or interstate transportation facilities as these are being addressed by other agencies. The list of prioritized facilities includes the following:

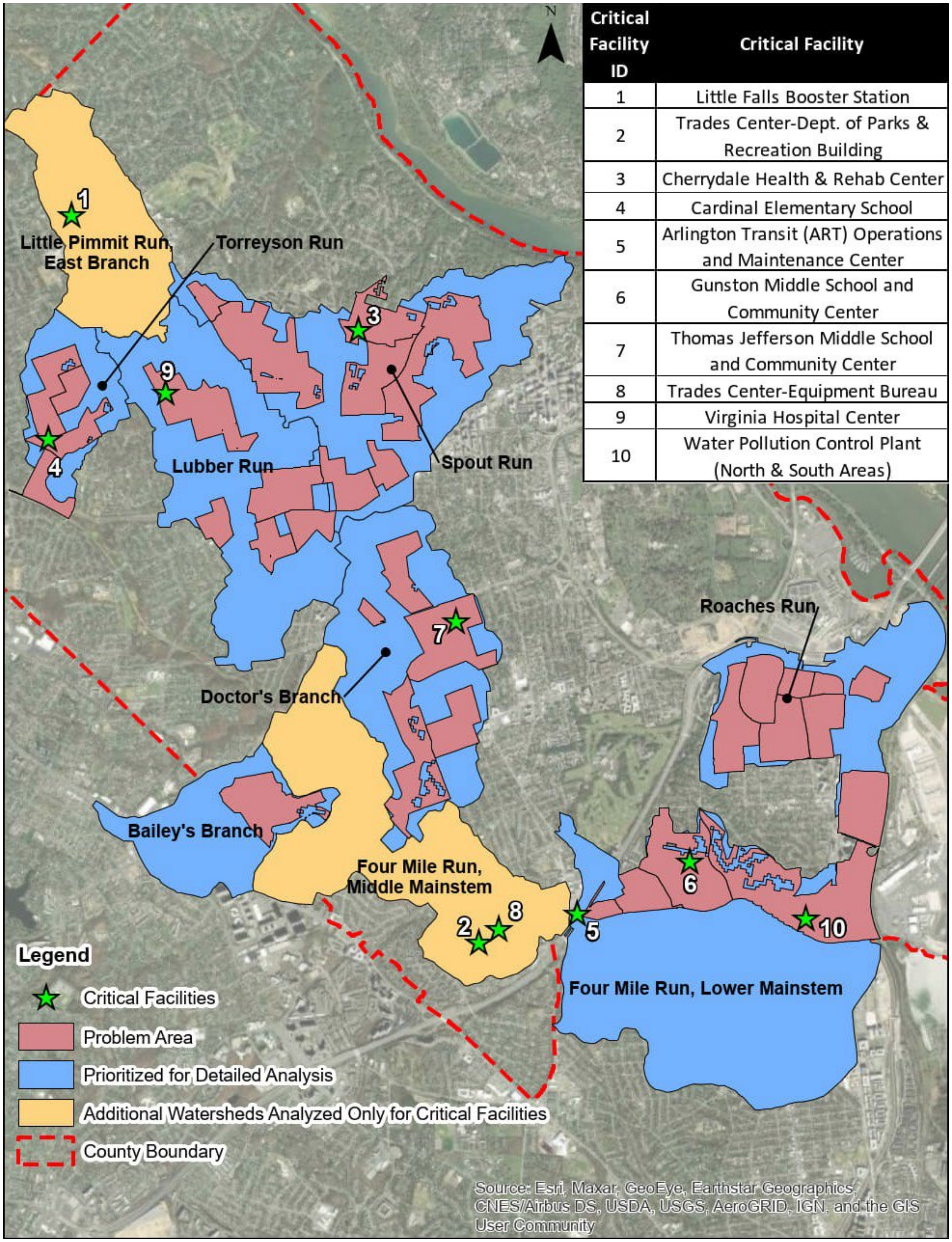
- Arlington Transit (ART) Operations and Maintenance (O&M) Facility, located in Four Mile Run Lower Mainstem (with a part of it in Nauck Branch watershed)
- Cardinal Elementary School, located in Torreyson Run
- Cherrydale Health and Rehabilitation Center (Cherrydale Center), located in Spout Run
- Gunston Middle School and Community Center, located in Four Mile Run Lower Mainstem
- Little Falls Booster Station, located in Little Pimmit Run East Branch
- Thomas Jefferson Middle School and Community Center, located in Doctor’s Branch
- Trades Center Department of Parks and Recreation (DPR) Building and Network Operations Hub, located in Four Mile Run Middle Mainstem
- Trades Center Equipment Bureau, located in Four Mile Run Middle Mainstem
- Virginia Hospital Center, located in Lubber Run
- Water Pollution Control Plant (WPCP), located in Four Mile Run Lower Mainstem

Please note that the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus, at their own cost, thereby saving the public considerable costs. The timing of that project and delivery of the associated plans and information was such that it could not be included in the RAMP modeling and vulnerability/risk assessments. The improvements made to the Virginia Hospital Center were designed to mitigate the flooding concerns on their campus and improve the overall conveyance system. The improvements did not impact downstream flooding or overland flow paths of flood waters, or downstream inundation areas. This section or report does not address the mitigation provided by the Virginia Hospital Center stormwater improvements.

## 3.5 Summary of Risk Assessment Results for Problem Areas

As previously noted, risk assessment was conducted to quantify both monetary impacts (the cost of no action) as well as impacts to vulnerable groups. Risk is a combination of both the likelihood of damages and the consequence of damages. Although the vulnerability assessment in the previous step was conducted at a watershed scale to select watersheds with vulnerable critical facilities and problem areas (PAs), the risk assessment was conducted at a sub-watershed scale using 34 PAs and at a facility scale for 10 critical facilities. This smaller scale allows for more site-specific definition and evaluation of alternatives, including conceptual flood mitigation projects for which BCAs were then performed. A PA was defined as the maximum contiguous area exposed to flooding within a watershed based on flood modeling, expanded to the nearest census block boundary. The 34 PAs considered in the risk assessment across all seven watersheds found to be the most vulnerable are presented on Figure 3-4. The watersheds are used here for reference to summarize benefit-cost information, which is calculated separately for each PA.

Risk principles based on probability of a flood event and resulting consequences of that event were used in the risk analysis for both PAs and critical facilities. The PAs and critical facilities, however, used different tools for the analysis, given the different scale (neighborhood scale versus parcel or property scale).




| Critical Facility ID | Critical Facility |
|---|---|
| 1 | Little Falls Booster Station |
| 2 | Trades Center-Dept. of Parks & Recreation Building |
| 3 | Cherrydale Health & Rehab Center |
| 4 | Cardinal Elementary School |
| 5 | Arlington Transit (ART) Operations and Maintenance Center |
| 6 | Gunston Middle School and Community Center |
| 7 | Thomas Jefferson Middle School and Community Center |
| 8 | Trades Center-Equipment Bureau |
| 9 | Virginia Hospital Center |
| 10 | Water Pollution Control Plant (North & South Areas) |

**Figure 3-4. Arlington County Problem Areas Selected for Risk Analysis**

ID = identification

### 3.5.1 Economic Risk Results for Problem Areas

The economic risk analysis is calculated using FEMA's Hazus tool, which uses an economic property valuation and economic losses database. Direct and indirect losses associated with building and vehicle stock are combined into an overall monetized risk value. Table 3-1 presents the annualized risk results by watershed, rolled up from the PA level results. Table 3-1 also shows how, from 2020 to 2070, potential losses increase for the 100-year storm as a result of rainfall increases from climate change, which increases the area and depth of flooding for the 100-year storm.
The annualized risk of losses in Table 3-1 is the aggregate risk from different intensity storms that might occur in a given year.[4] The losses for 100-year storms listed in Table 3-1 are the losses from just one large, low-probability event (1% probability for a 100-year storm). [5]

The data in Table 3-1 are also presented on Figures 3-5 and 3-6. Figure 3-5 presents the annualized risk results for each watershed. Figure 3-6 shows a comparison by watershed of the damages from baseline and projected 2070 100-year storms. Figure 3-7 presents a map of the annualized risk result for each PA.

**Table 3-1. Economic Risk by Watershed**

| Watershed | Annualized Risk of Losses (millions $)[a,b] | Potential Losses for 100-year Storm (millions $)[a] | |
|---|---|---|---|
| | | 100-year Storm in 2020: 8.5 Inches in 24 Hours | 100-year Storm in 2070: 9.6 Inches in 24 Hours |
| Roaches Run | 112.8 | 718.9 | 803.5 |
| Spout Run | 41.0 | 234.4 | 263.4 |
| Lubber Run | 32.4 | 297.1 | 344.2 |
| Four Mile Run Lower Mainstem | 14.7 | 109.2 | 136.8 |
| Doctor's Branch | 6.4 | 39.0 | 46.1 |
| Torreyson Run (c) | 2.6 | 17.9 | 19.7 |
| Bailey's Branch | 1.0 | 7.5 | Not available[d] |

[a] Hazus uses loss and economic property valuation data sets that were last updated in 2018.
[b] Risk of losses accounts for the probability associated with different storm events generating losses.
[c] The County recently completed construction of 4 MG Cardinal School Vault, which was assumed to be included in baseline scenario. The values for annualized risk and potential losses for Torreyson Run represent remaining risk, after that storage vault is in place.
(d) This watershed was not modeled under 2070 conditions.

4 The annualized risk of total losses is equal to damage losses from a given-size storm times the probability for each storm size, summed for all storm probabilities, such as 20%, 10%, 4%, 1% and 0.2% chance storms (also known as 5-year, 10-year, 25-year, 100-year, and 500-year storms, respectively).

5 A 100-year storm is one that has a 1% chance of occurring in any given year, based on historical records. However, that equates to 30% chance in 30 years. With climate change, that probability is expected to increase with large storms happening more frequently.

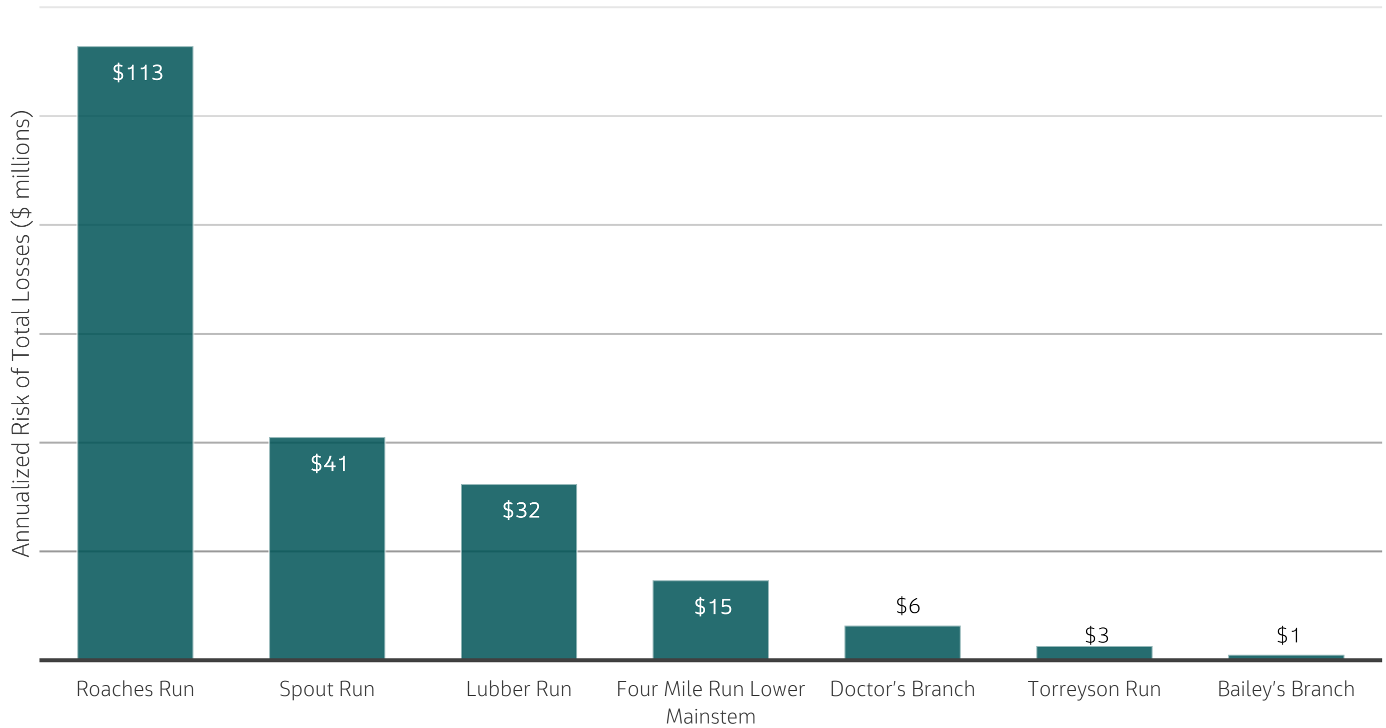



**Figure 3-5. Annualized Risk of Total Losses ($ millions)**

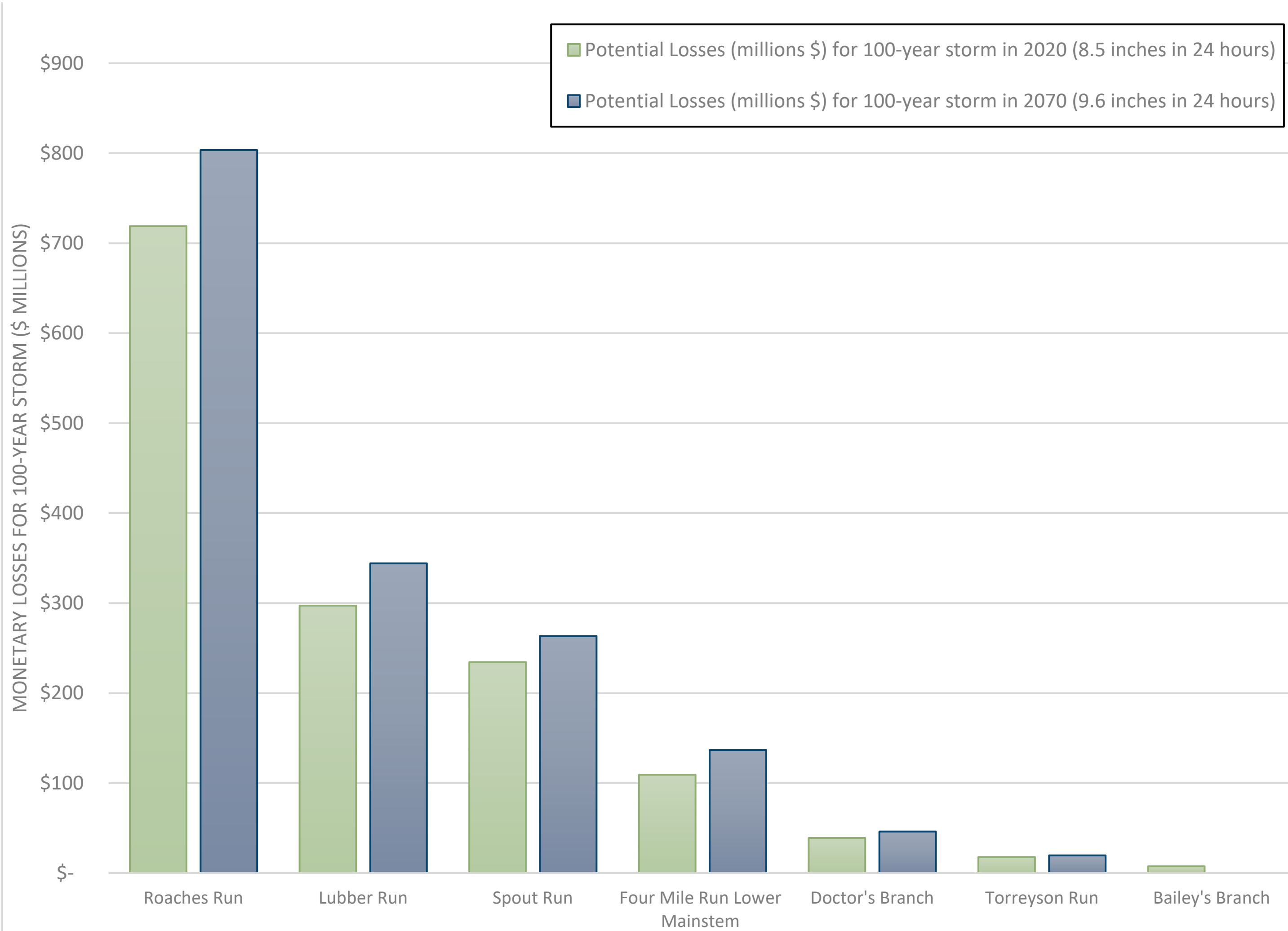



**Figure 3-6. Potential Monetary Losses from 100-year Storm (2020 Baseline Versus Projected 2070) by Watershed**

Loss estimates presented in Figures 3-5 and 3-6 assume that the now-built storage tank at Cardinal Elementary School is present; in other words the losses are those losses remaining in the Torreyson Run watershed assuming the 4 MG tank is in place. Flood models were not run for the projected 2070 rain conditions in Bailey's Branch.

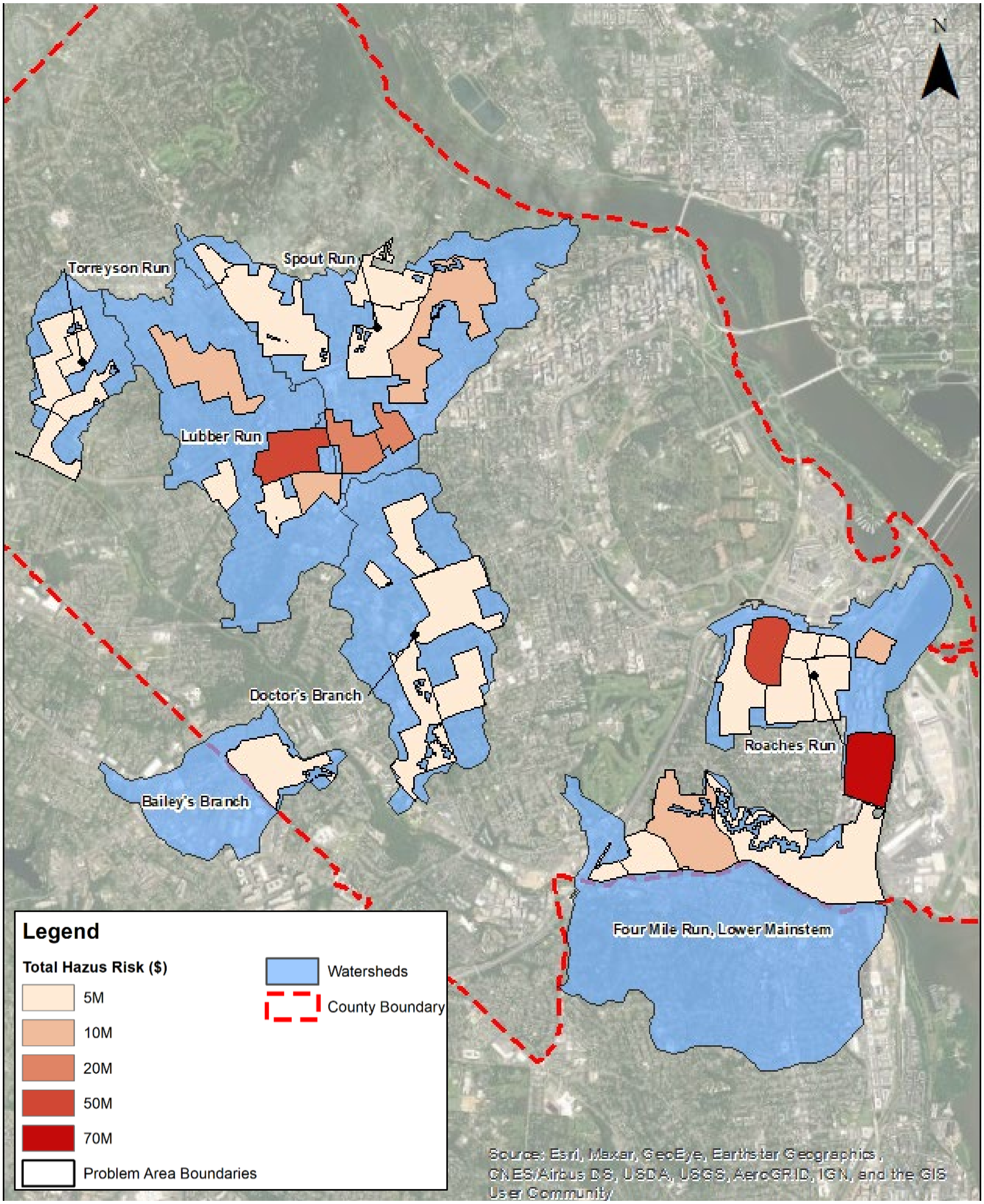



**Figure 3-7. Annualized Economic Risk for Problem Areas in Vulnerable Watersheds**

The summary of economic risk by watershed illustrates that the most significant risk is generally associated with areas with higher property values and more economic activity. The most significant economic risk was found to be in PAs in Roaches Run, Lubber Run, and Spout Run that coincide with areas that have commercial activity.

### 3.5.2 Social and Environmental Risk

Table 3-2 presents the risk results for socially vulnerable areas and environmental areas by watershed. Socially vulnerable groups were based on areas where the Centers for Disease Control and Prevention Social Vulnerability Index (SVI) is greater than 0.5. Environmental areas were based on County Resource Protection Areas (RPAs). PAs within Four Mile Run Lower Mainstem appear to show the most consistent flooding within their RPAs across all flood event scenarios. Four Mile Run Lower Mainstem watershed sits directly adjacent to the mouth of Four Mile Run as it exits into the Potomac River; as such, the consistent flooding of its RPAs is understandable. Although RPAs are areas of significant environmental value, a significant extent of the total RPA area in the County is in the designated floodplain for runs and creeks.

The results clearly show Doctor’s Branch is the watershed with the greatest flood risk to socially vulnerable communities. Results of the social vulnerability flooded areas illustrate the importance of using more than economic parameters for risk prioritization. The Hazus results (economic risk) rank Doctor’s Branch as the fifth most vulnerable watershed out of the seven watersheds with regards to economic risk.

**Table 3-2. Socially and Environmentally Vulnerable Area Risk by Watershed**

| Watershed | RPA Expected[a] Flooded Area (square feet) | High SVI Expected[a] Flooded Area (square feet) |
|---|---|---|
| Bailey’s Branch | 9,864 | 26,342 |
| Doctor’s Branch | 352,243 | 511,763 |
| Four Mile Run Lower Mainstem | 860,826 | — |
| Lubber Run | 196,776 | — |
| Roaches Run | — | — |
| Spout Run | 107,988 | — |
| Torreyson Run | 2,172 | — |

[a] Areas estimated for each flood scenario and adjusted by probability, consistent with Hazus methodology for annualized economic risk

— = no areas with high SVI are within expected flood areas

### 3.5.3 Summary of Risk for Problem Areas

An aggregate risk score was calculated to account for combined economic, social, and environmental risk. The total risk scores for all PAs are presented on Figure 3-8.

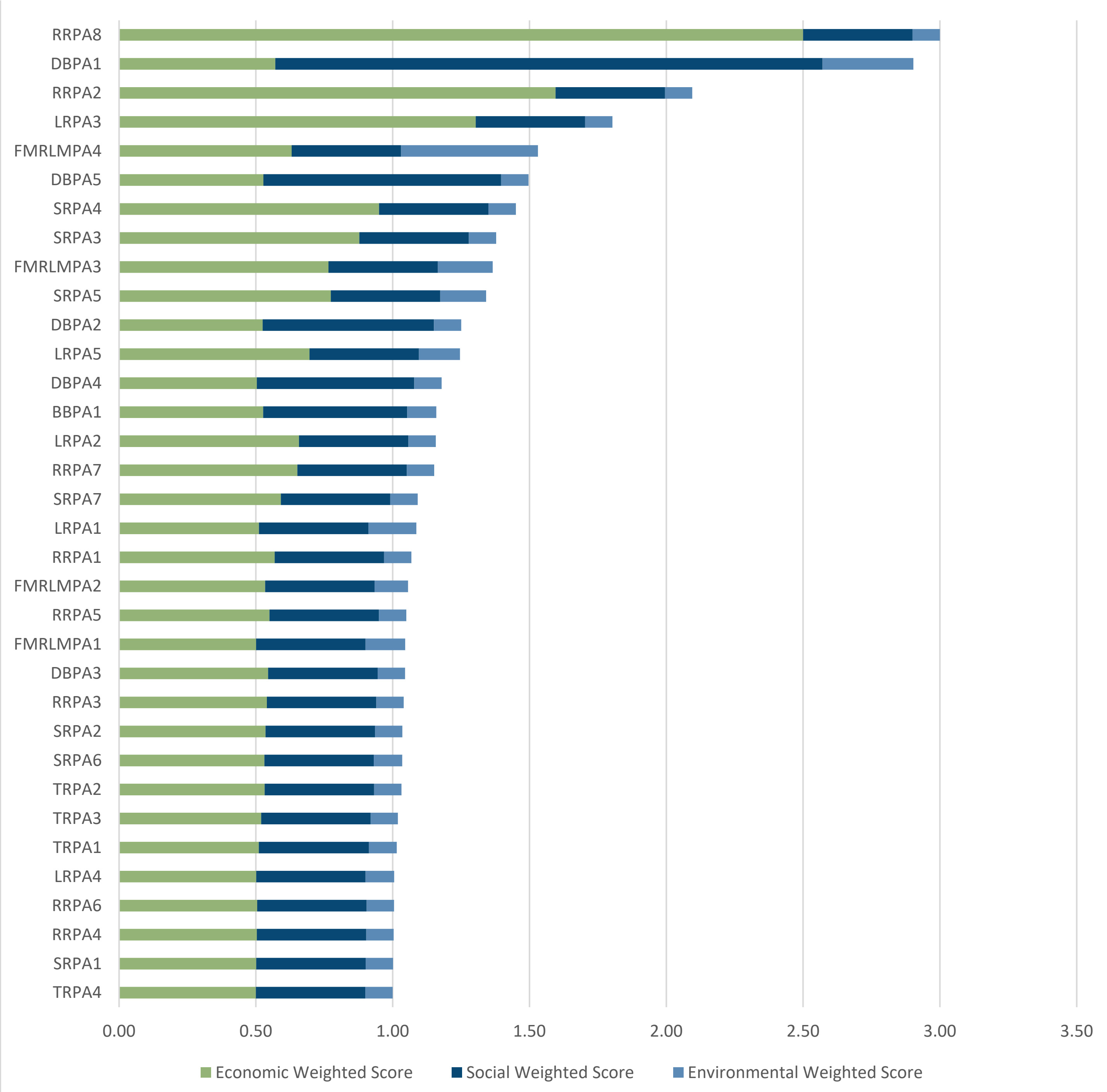



**Figure 3-8. Problem Areas Aggregate Risk Scores, Including Economic, Social, and Environmental Criteria**

Analyzing the contribution of individual criteria to the total score shows that PAs can be high ranking because of high economic risk or high social risk. The environmental criterion is a significant contributor to FMRLPA4 (in Four Mile Run Lower Branch) and DBPA1 (in Doctor's Branch).

A sensitivity analysis of different weighted values for each of the economic, social, and environmental criteria was tested. The sensitivity analysis generally showed low sensitivity in the top-ranking PAs, with Roaches Run and Doctor's Branch PAs reaching the top spots as the economic criterion weight and social criterion weight increase, respectively.

### 3.5.4 How Climate Change Increases Risk

The results from the future scenarios assessment can be used to evaluate the impact of future climate change on flood risk. Figure 3-9 shows how the economic risk increases for PAs with high economic risk from historical conditions (2020) to the year 2070. The figure also illustrates the social vulnerability area increase for a different area with high social vulnerability risk. The figure shows that the impacts of a 100-year storm under existing conditions will be similar to the impacts of a future (2070) 10-year storm as climate change continues to unfold.

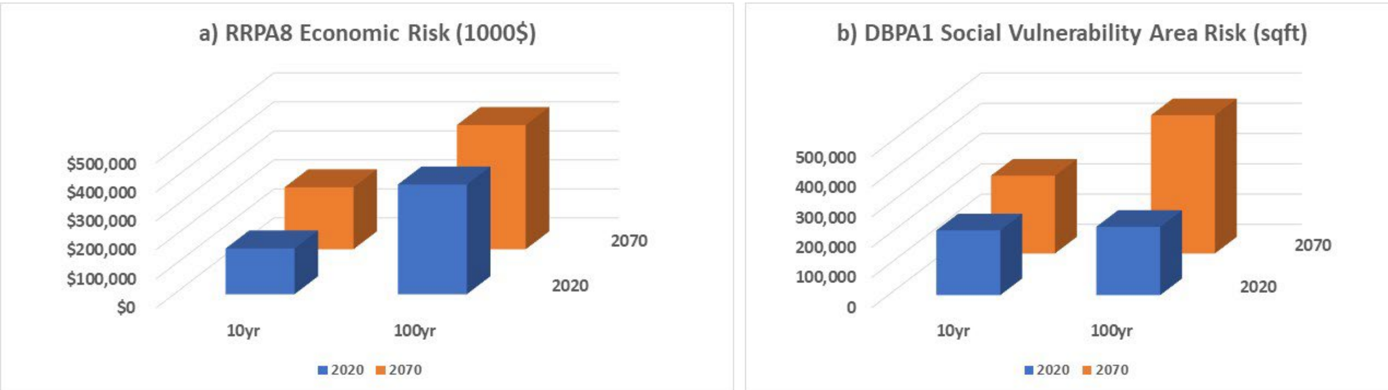



**Figure 3-9. Example of Risk Evolution in Problem Areas As a Result of Climate Change, for Two Representative Areas**

sqft = square foot (feet)

## 3.6 Summary of Risk Assessment Results for Critical Facilities

Differences between the results of the critical facilities risk analysis compared to the PAs analysis are summarized as follows:

- The critical facilities risk analysis includes only the economic criterion (no social or environmental criteria are needed).
- The loss estimates for the critical facilities risk analysis are based on asset replacement values specifically for the assets identified in the field visit of each critical facility. The cost estimates are in year 2022 dollars (compared to the 2018 Hazus loss and valuation data sets used for PAs).
- Results of the critical facilities risk analysis account for cumulative risk over 20 years, with changing probability of flooding due to climate change.

The summary of risk by facility is presented in Table 3-3. The table also shows the number of assets that were identified as potentially vulnerable and the total replacement costs for those assets.

**Table 3-3. Summary of Economic Risk Cumulative Over a 20-year Period for Critical Facilities[a]**

| Critical Facility | Number of Assets | Asset Replacement Cost (thousands $)[a] | Total Cumulative Risk (thousands $)[b] |
|---|---|---|---|
| Water Pollution Control Plant South | 836 | 97,223 | 32,270 |
| Water Pollution Control Plant North | 282 | 26,240 | 10,137 |
| Virginia Hospital Center [c] | 68 | 19,822 | 5,659 |
| Thomas Jefferson Middle School | 92 | 8,724 | 1,798 |
| Little Falls Pump Station | 30 | 3,533 | 100 |
| Gunston Middle School | 129 | 3,420 | 60 |
| Cherrydale Center | 68 | 3,343 | 1 |
| Cardinal Elementary School | 94 | 3,156 | <1[d] |
| ART O&M Center | 87 | 40,240 | <1[e] |

[a] In year 2022 basis. This represents the value of all assets in the facility that could be sensitive to flood, not only the assets that are predicted to be exposed. The Trades Center Network Operations Center II (NOCII) and Equipment Bureau facilities are excluded from this table because no asset damage was predicted. These facilities do undergo flooding in access roads, which could represent indirect losses that are not accounted for in this analysis, which is based on direct damages.

[b] Over a 20-year period, using a discount rate of 4%.

[c] This does not reflect the mitigation provided by the Virginia Hospital Center stormwater improvements, as described in Section 3.4.

[d] Significant flooding observed in the vicinity and access roads.

[e] Significant flooding can occur in the vicinity and parking lots.

Results include a large range of cumulative risk, from minimal risk to the assets within the facilities to tens of millions of dollars. All facilities are in areas expected to flood based on historical information and model results. Some facilities, however, show limited monetary impact based on the approach used in this RAMP, which looks at monetary impact from physical losses “inside the fence” (within the facility). For most facilities, failure would also have indirect impacts on the population served by that facility, thus potentially creating cascading economic impacts. For example, if the WPCP were to fail for a few hours, some upstream customers would be impacted by lost wages or business income. To illustrate how including the indirect economic impacts outside the fence could increase total cost of no action, an analysis was conducted for the WPCP and is contained Appendix F. The risk and benefits were also calculated to include indirect economic impacts associated with closing the WPCP. The results indicate that by accounting for avoided losses from both direct equipment damage and indirect economic losses, the estimated benefits could increase by 19%, from $27.4 million to $32.6 million, with a corresponding increase in the benefit-cost ratio (BCR).

The critical facilities analysis also shows that climate change exacerbation of the intensity of rainfall has an impact on risk, increasing risk over time for a given facility. Figure 3-10 shows the comparison of risk for three planning horizons (2020, 2040, and 2070) for one of the flood-vulnerable locations visited at the WPCP (activated sludge effluent pump station, used as an example). The risk evolution shown on Figure 3-10 reflects the change in intensity of rainfall during the 10-year, 100-year, and 500-year storms, and the resulting flood exposure.

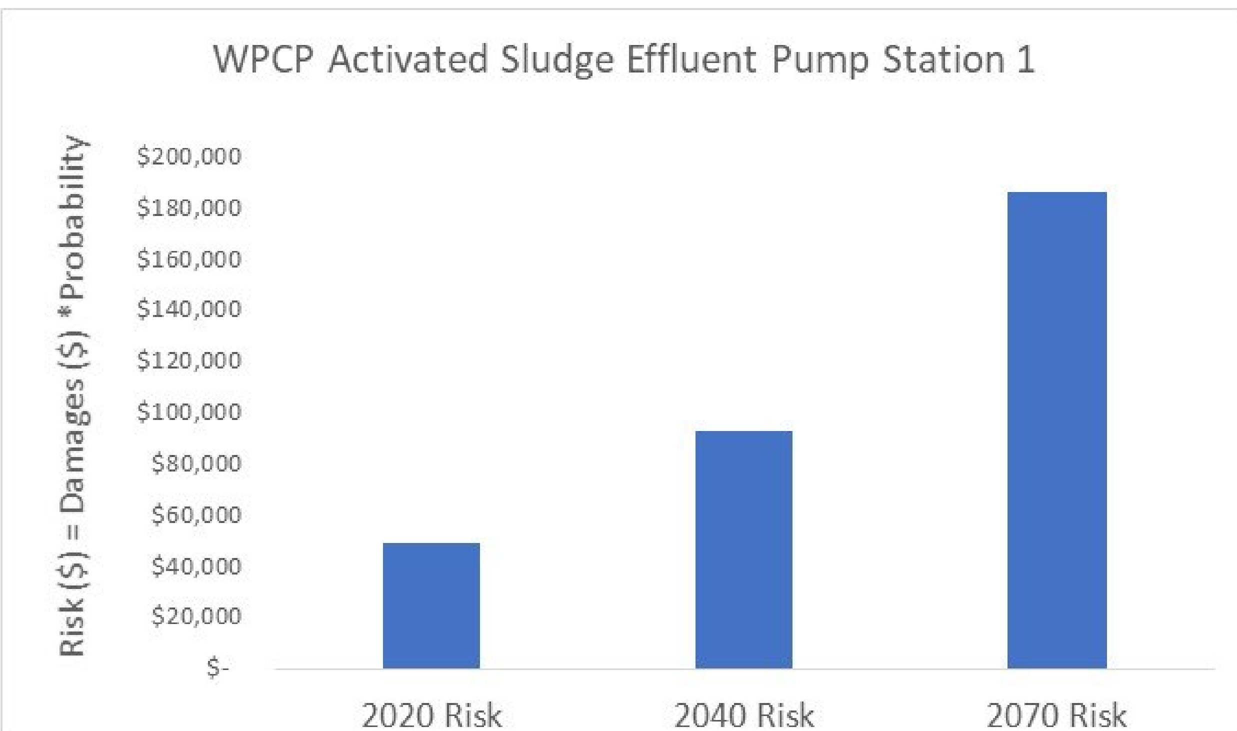



**Figure 3-10. Facility Flood Risk Increase Over Time as a Result of Climate Change**

# 4. Programmatic and Policy Strategies and Financial Market and Economic Trends

## 4.1 Programmatic and Policy Strategies

Programmatic and policy strategies constitute a valuable approach for flood management in Arlington County. In addition to structural flood mitigation concepts for PAs and critical facilities, a review of strategies was conducted to provide initial recommendations to enhance the County's administrative, policy, and strategic toolbox related to flooding. Two primary methods were used to understand the ways other jurisdictions have addressed flood management in their localities: (1) a desktop study including a literature review and (2) an informal interview with representatives from select jurisdictions. Interviews were conducted virtually using a prepared questionnaire.

A multitude of policy and program offerings used by jurisdictions nationally should be considered for management of flood risk on a Countywide scale and potentially applied on a site-specific basis in Arlington County. Appendix G summarizes ongoing strategies as well as existing regulations in the County but also describes novel policy or program approaches to flood management implemented in other jurisdictions. A matrix was generated to classify relevant policies and programs (for example, freeboard, public flood risk information tools, and flood overlay zoning) and to identify jurisdictions that may have experience with these policies and programs.

A discussion of strategies is included in the Programmatic Strategies Technical Memorandum (Appendix G). Because strategies cover a wide range of activities, they have been summarized according to the following categories:

- Governance considerations
- Public information
- Information supporting County flood risk activities
- Equity considerations
- Flood risk mitigation
- Integrating flood risk information into land use planning
- Updating regulations based on flood risk information
- Flood management financing and funding
- Storm drainage asset management

Table 6-1 in Section 6 presents a summary of programmatic and policy recommendations in each of these categories. Appendix G presents in more detail the strategies that may be considered by Arlington County to improve flood management. The projects that may result from the engineering concepts discussed in the next section will be implemented in the context of programmatic and policy solutions both new and currently in place in the County.

## 4.2 Financial Market and Economic Trends Related to Climate Change

In addition to developing policy and programmatic recommendations, the RAMP includes an overview of emerging issues around the consequences of climate change and its associated social and economic risks, as well as opportunities for comprehensive investment in resilience planning and infrastructure to encourage sustainable growth. Appendix H includes a white paper that discusses relevant financial markets and economic trends related to climate change that can have a direct impact on future investment decisions. The following key developments are addressed:

- Climate change considerations are beginning to impact policy and regulations within financial markets.
- New regulations are designed to aid investment decisions to take into consideration the opportunities and threats through additional climate change disclosures and assess the detrimental impacts of recurring and acute climate events. The new disclosures are anticipated to create increased investor awareness and inform business decisions related to climate impact and sustainability and instill new risk considerations when borrowing funds or acquiring property insurance.

- Bond ratings agencies are beginning to evaluate the additional risks from climate-related impacts and will increasingly evaluate those risks in bond ratings. The lowering of bond ratings because of the disruption to revenue generation from the uncertainty around climate risk can have a detrimental effect on communities' cost of capital and ability to borrow funds.
- Insurance premiums are projected to grow because of increased availability of information about climate vulnerabilities. These premium increases may be mitigated with resilience investments that will address climate-related risks.
- New pathways to financing resilience investments are under development, such as local revenue generation through taxes or stormwater fees; climate or resilience bonds; public-private partnerships, including partnerships with businesses or land trusts and landowner engagement; and competitive grants at both the federal and state levels.
- Investment in resilience can further spark local economic development through supporting a diverse economy, fostering environmental justice, building local supply chains, and improving the health of local communities.

# 5. Flood Mitigation Strategies, Benefits, and Cost Effectiveness

This section summarizes the flood mitigation strategies, benefits, and BCA that was conducted for both neighborhood PAs and critical facilities.

## 5.1 Strategies for Neighborhood Problem Areas

For PAs in the County that were identified and prioritized during the vulnerability and risk assessments, the RAMP focused on developing conceptual alternatives and costs for two types of mitigation solutions—one that uses only storage opportunities to reduce peak flows downstream and another that uses only conveyance improvements to increase the capacity of existing stormwater systems, thereby reducing surface flooding.

Refer to Appendix F for more detailed concept information for storage and conveyance solutions per each watershed analyzed, including details on size, location, and costs of these conceptual solutions. Figure 5-1 presents example storm drain capacity improvement concepts (also referred to as the conveyance solution) for flood mitigation projects in the Doctor's Branch watershed.

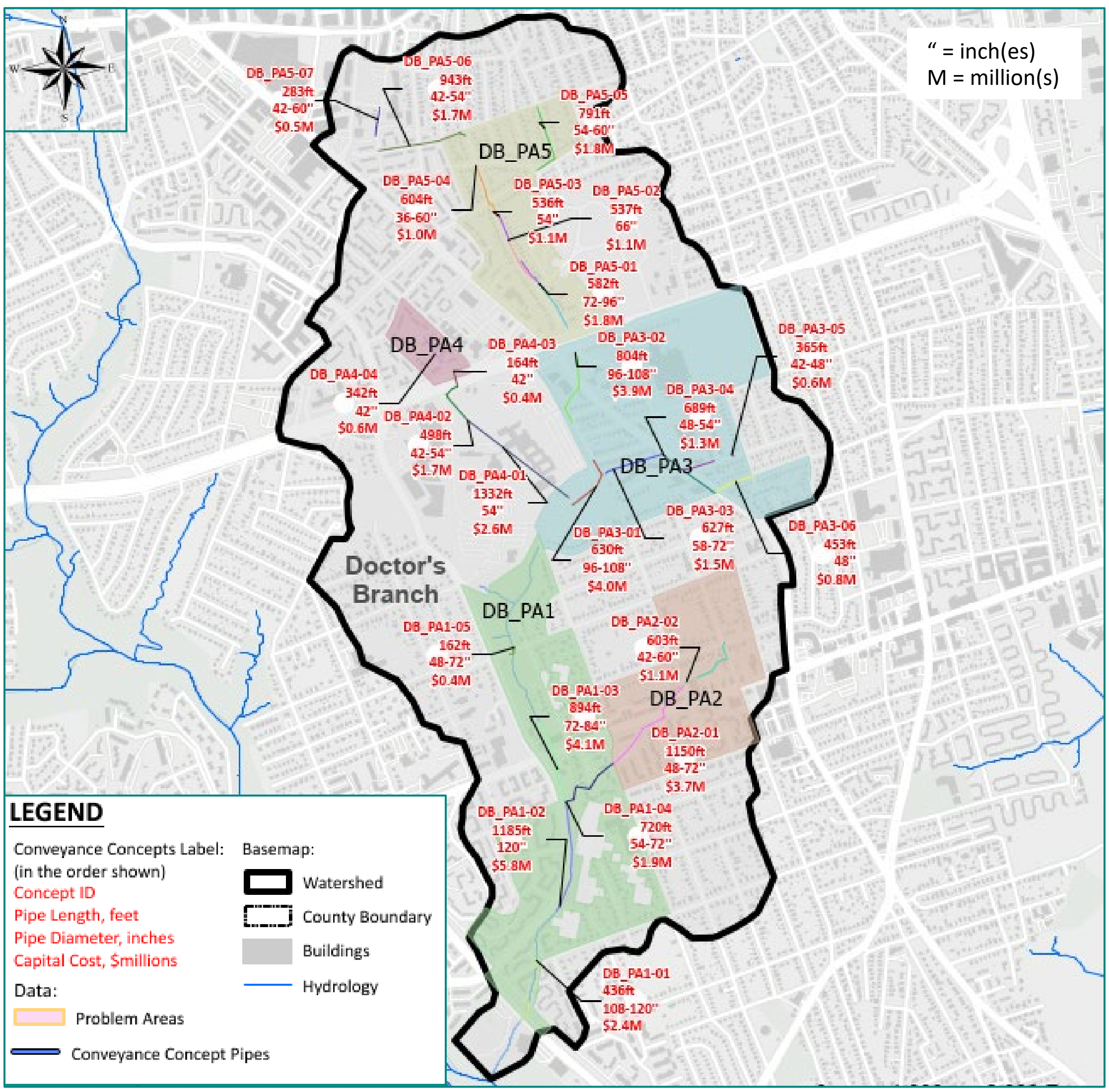



**Figure 5-1. Example Conveyance Concept Map Showing Potential Storm Drain Capacity Improvements in the Doctor's Branch Watershed**

### 5.1.1 Storage Solutions

Storage solutions were developed based on the presence of public or privately owned open space to site an underground storage facility. Diversions at stormwater manholes would divert peak flows to and from storage to the extent feasible by gravity flow. Pumping out of storage was considered as a viable option only where open space was limited and storage depth that would allow for gravity dewatering was constrained by downstream pipe elevations.

### 5.1.2 Storm Drain Capacity Improvement Solutions

Storm drain capacity improvements, referred to as conveyance solutions, were defined by identifying limitations in the storm systems causing backups and flooding in the identified PAs. The extent and size of each solution were determined through an iterative process of replacing the restricted sewers with larger pipes that could pass the predicted peak flows of the design storm event, further increasing pipe sizes and extending the projects as needed until flooding was eliminated.

### 5.1.3 Overland Relief Including Property Acquisition

Conveyance concepts assume replacement of existing infrastructure within an existing drainage easement, and this is an adequate assumption for most PAs. However, County staff provided information on areas where they have not been successful in implementing conveyance relief because of implementation constraints. In a parallel effort, the County has begun considering property acquisition to allow for overland relief of flood waters in two areas where the feasibility of conveyance and storage alternatives have been evaluated and found to be essentially infeasible. Overland relief pathways are clearly apparent when viewing flood maps. Even when conveyance and storage options are considered at current design standards (10-year storm) or, ideally, a larger storm to account for climate change, there will be residual risk associated with larger storms that exceed the capacity of those higher-capacity systems. This residual risk could be mitigated by some combination of overland flow relief and more stringent building codes and flood design criteria in areas of higher flood risk, particularly areas of interior flood risk not part of FEMA flood zones. Many such areas are in Arlington County.

## 5.2 Considerations and Limitations of Desktop Analysis

The RAMP is a high-level planning study. This section articulates the need for more detailed site-specific feasibility studies and integration of holistic solutions as part of further planning and design.

### 5.2.1 Need for Site-specific Feasibility Studies

The RAMP does not include detailed project development based on site-specific data collection and stakeholder engagement. The flood mitigation concepts for PAs and critical facilities will require additional analysis, including detailed feasibility analyses, before design activities and project implementation can proceed. Additionally, in almost every case, flood mitigation solutions for a PA or building within a critical facility result from the implementation of more than one individual project. The programmatic strategies described previously will also contribute to flood management solutions.

The conveyance and storage elements presented in the RAMP are based on desktop analysis with the hydraulic model developed for the RAMP. No detailed analysis has been conducted assessing rights-of-way, utility conflicts, other space constraints such as tree canopy, structures in the area not visible from aerial imagery (homes and other buildings and facilities), known public opposition, or other factors. These factors are typically addressed during a project’s feasibility study phase, which, in this case, would be conducted after the RAMP.

### 5.2.2 Blended Solutions and Green Stormwater Infrastructure

A further consideration in the analysis of these mitigation concepts is that specific projects for each PA may be more cost-effective or provide greater flood mitigation benefits when conveyance and storage options are combined into a single project.

In addition, the integration of green stormwater infrastructure (GSI) solutions, such as rain gardens, infiltration systems, and pervious pavement, was not considered as part of the RAMP because GSI is generally used to mitigate the effects of smaller, more frequent storms than the much larger storms that are associated with flooding events. However, it is recognized that the County has goals to include GSI in all projects with feasibility to address water quality, heat island impacts, and other co-benefits, and the County will consider such additional project goals during site-specific concept development and design.

The RAMP planning-level analysis did not explore blended solution concepts that would integrate combinations of storage, conveyance, GSI, and overland relief.

## 5.3 Strategies for Critical Facilities

Numerous strategies were evaluated for flood risk mitigation in the buildings with vulnerable assets in each critical facility. Selecting a strategy for specific buildings or assets was based on the information collected during site visits and the flood depth data for different scenarios.

The selection of flood mitigation strategies included the following two general categories:

- Elevating involves raising a specific asset using different strategies.
- Hardening includes watertight sealing to change the flood path elevation of an asset. Hardening strategies are described in Section 5.5 and Appendix F.

The flood scenario used to establish the design flood elevation corresponds to the 100-year event. One foot of freeboard was also assumed as part of the conceptual dimensioning of the concepts. The 100-year flood event and 1 foot of freeboard correspond to American Society of Civil Engineers (ASCE) guidelines for utilities (ASCE 24-14, Flood Resistant Design and Construction). It is worth noting the new flood plain ordinance for Arlington County requires 18 inches of freeboard and 2 feet for floodproofing (Arlington Co. Code § 48-51, 2023).

## 5.4 Costs and Benefits of Flood Mitigation Concepts for Problem Areas

A **benefit-cost analysis (BCA)** was conducted to determine the relative merits of the proposed flood mitigation concepts. Details of the methodology and results are presented in Appendix F. The purpose of the BCA is to compare the advantages (benefits) of the concepts to the costs for each flood mitigation concept. The BCA included calculating a **benefit-cost ratio (BCR)**, which is a measure of the relative monetary value of investing in each project or group of projects. In the absence of other non-monetary criteria, a BCR greater than 1.0 is generally needed to justify obtaining a grant or proceeding with the investment. The higher the BCR, the greater the benefit per dollar invested. So, in the absence of other criteria, the value of the BCR can be used to prioritize flood mitigation investments. The benefits, costs, and BCRs are summarized in the following paragraphs.

In addition to the BCR analysis, the BCA also considered the reduction of impacts to vulnerable communities, as measured by the change in flood area with medium and high SVI. Areas with higher flood exposure for vulnerable communities are primarily in the Bailey’s Branch and Doctor’s Branch watersheds. The conveyance solutions resulted in reductions of 88% and 32% in each of these watersheds, respectively. The storage solutions resulted in reductions of 78% and 66% in each of these watersheds, respectively.

Benefits of flood mitigation concepts for PAs were estimated, based on the flood modeling results and the estimates of flood-related losses, as the difference between the losses before and after the implementation of concepts. The analysis of flood reduction and associated reduction of losses was conducted for each PA and can be aggregated at the watershed scale. Figure 5-2 presents the summary of benefits of conveyance and storage concepts at the watershed level, expressed in terms of total annualized risk from Hazus losses, before and after each solution is applied.

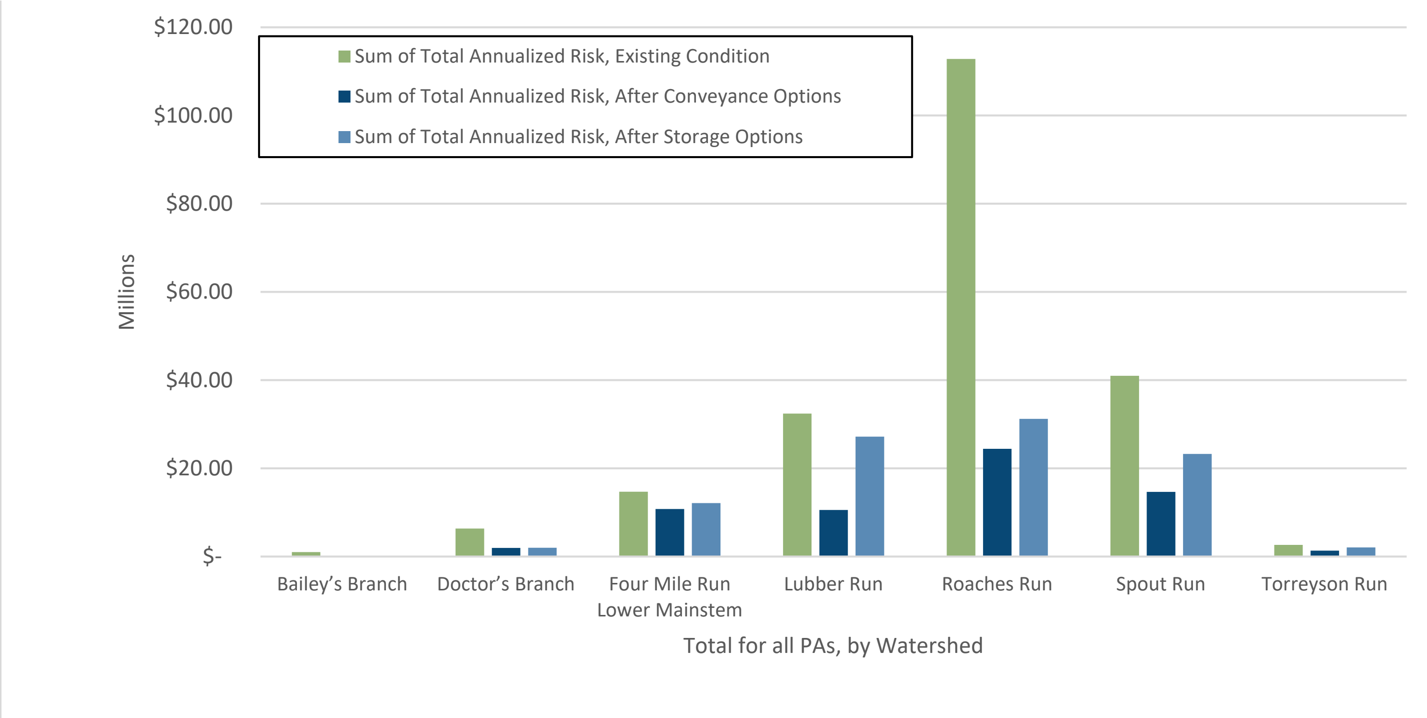



**Figure 5-2. Risk Mitigation (Benefits) from Conveyance and Storage Concepts per Watershed Based on Total Annualized Risk from Hazus Loss Analysis, Before and After Each Solution is Applied**

Table 5-1 presents the capital cost summaries per watershed; each capital cost value is presented along with a range to represent Class 5 cost estimates. Class 5 estimates relate to a range of -50% to +100% and are presented as defined by the Association for the Advancement of Cost Engineering International (AACE International) Recommended Practice No. 18R-97 (AACE International 2020) and as designated in ASTM International (ASTM) E2516-06. Overall totals for each solution type on a Countywide basis also have been provided in Table 5-1 with a respective Class 5 range.

**Table 5-1. Planning-level Capital Costs of Structural Solutions to Flooding (Conveyance and Storage Projects)**

| Watershed | Total Length of Conveyance Projects (linear feet) | Total Capital Cost of Conveyance Solution (millions $)[a] | Total Estimate Storage Volume Provided (MG) | Total Capital Cost of Storage Solution (millions $)[a] |
|---|---|---|---|---|
| Bailey's Branch[b] | 2,599 | 8.52<br>(4.26 to 17.05) | 1.80 | 12.56<br>(6.28 to 25.11) |
| Doctor's Branch[b] | 15,333 | 45.23<br>(22.62 to 90.46) | 7.70 | 48.45<br>(24.23 to 96.90) |
| Four Mile Run Lower Mainstem | 12,276 | 32.11<br>(16.05 to 64.21) | 9.28 | 54.06<br>(27.03 to 108.11) |
| Lubber Run | 9,882 | 9.22<br>(4.61 to 18.44) | 1.67 | 2.53<br>(1.26 to 5.05) |
| Roaches Run | 16,254 | 71.91<br>(35.96 to 143.82) | 3.79 | 25.60<br>(12.80 to 51.21) |
| Spout Run | 25,589 | 49.04<br>(27.02 to 108.08) | 2.03 | 11.42<br>(5.71 to 22.83) |
| Torreyson Run[b] | 2,709 | 5.99<br>(2.99 to 11.99) | 0.05 | 0.75<br>(0.38 to 1.50) [c] |
| Total (millions $) | | 222.02<br>(113.51 to 444.04) | | 155.37<br>(77.69 to 310.74) |

[a]Class 5 estimates (-50% to +100%), as defined by the AACE International (2020) Recommended Practice No. 18R97 and as designated in ASTM E2516-06, were used to develop the costs. Class 5 cost estimates account for both capital and O&M costs.

[b]Watersheds where pumping, because of a lack of feasible gravity flow connections, were identified within a PA; capital costs therefore include an estimate of costs associated with pumping.

[C]Capital costs in Torreyson Run are for potential new storage options and do not include the recently completed Cardinal School detention vault, which cost $16 million.

MG = million gallon(s)

The total costs and benefits of the projects are accounted for during the useful life of the infrastructure associated with the flood mitigation concepts. For conveyance and storage infrastructure, a useful life of 50 years is assumed. For BCR computations, the present values of the benefits and costs are computed using a discount rate of 7%, which was used for consistency with FEMA guidelines. Figure 5-3 shows the net present values (NPVs) of costs (in red) extending to the left and benefits extending to the right for conveyance solutions (which generally have a higher BCR compared to storage solutions) aggregated by watershed.

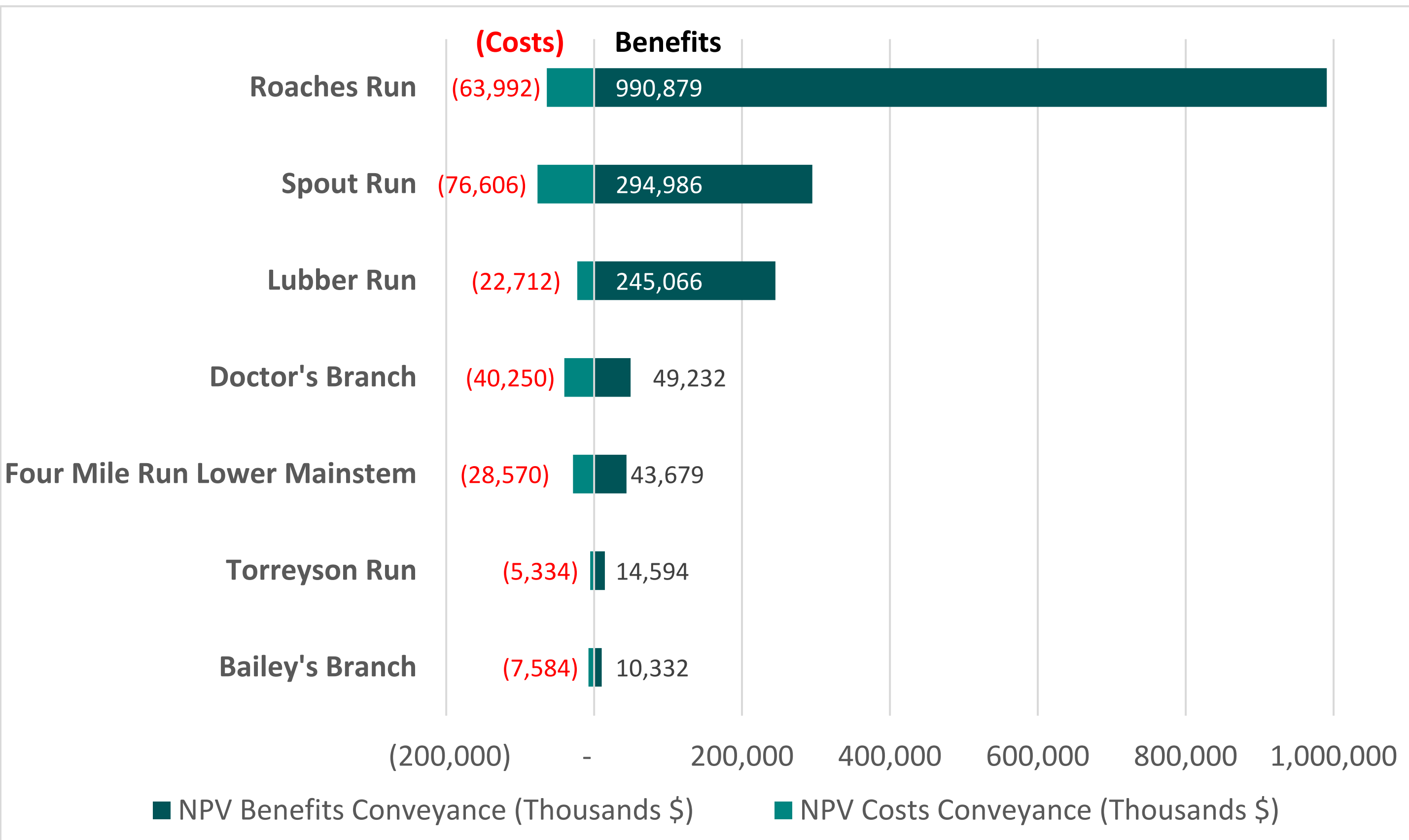



**Figure 5-3. Conveyance Flood Mitigation Concepts: Net Present Value of Costs (Total Capital and O&M) and Benefits (50-year Period with 7% Discount Rate)**

The NPVs of the benefits and costs (total capital and O&M) were used to compute BCRs for each watershed. Ratios were also computed for each PA. Table 5-2 presents the BCRs by watershed. Figure 5-4 and Table 5-2 show that there is a ratio greater than 1.0 for each watershed for at least one of the two concepts explored.

**Table 5-2. Benefit-Cost Ratios for Conveyance and Storage Mitigation Solutions**

| Watershed | BCR Conveyance Concepts | BCR Storage Concepts |
|---|---|---|
| Bailey's Branch | 1.4 | 0.9 |
| Doctor's Branch | 1.2 | 1.1 |
| Four Mile Run Lower Mainstem[a] | 1.5 | 0.6 |
| Lubber Run | 10.8 | 5.6 |
| Roaches Run | 15.5 | 40.2 |
| Spout Run | 3.9 | 19.6 |
| Torreyson Run[b] | 2.7 | 8.7[b] |

[a] The floodwall project currently under evaluation by the U.S. Army Corps of Engineers (USACE) would have a BCR of 2.0, based on USACE's own modeling and analysis (USACE 2022). That floodwall project or an equivalent project is an additional alternative for the Four Mile Run Lower Mainstem watershed.

[b] The County recently completed construction of 4 MG Cardinal School vault, which was included in baseline scenario.

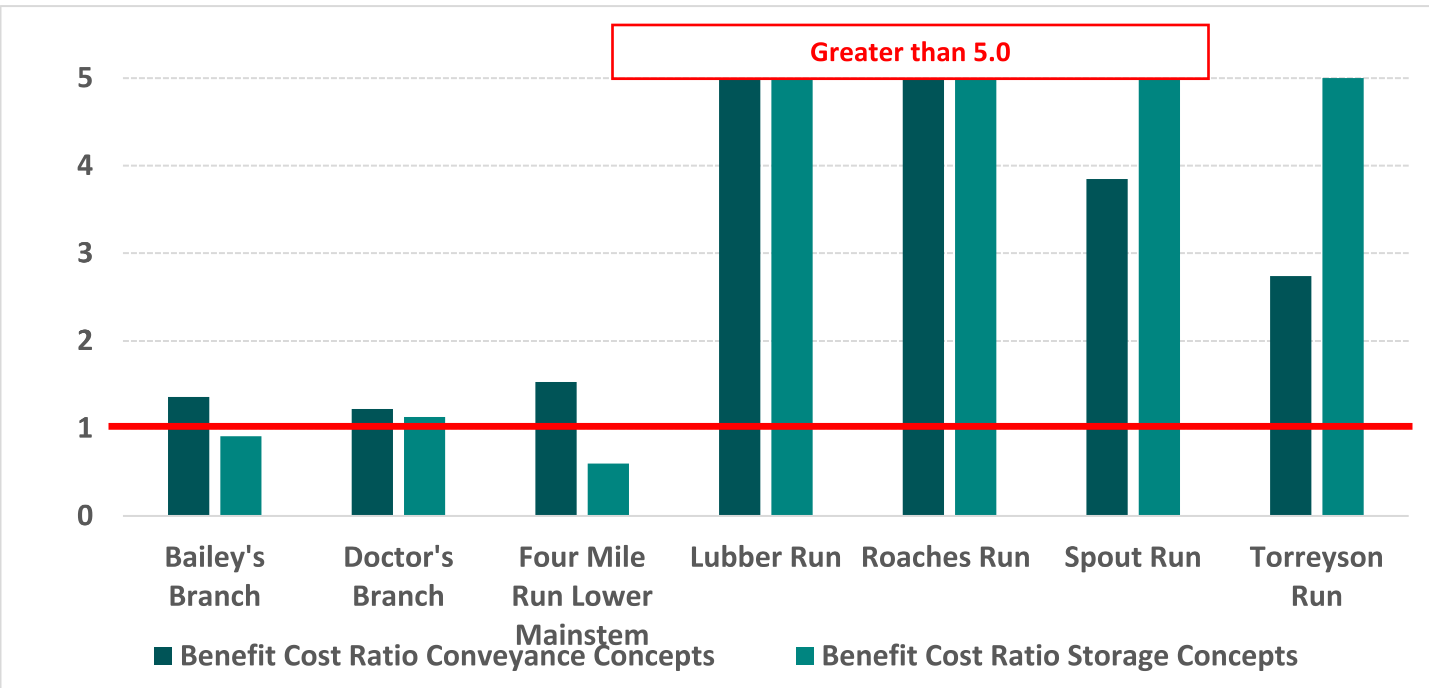



**Figure 5-4. Benefit-Cost Ratios for Conveyance and Storage Flood Mitigation Concepts by Watershed**

Note: Y axis ends at 5.0 to better visualize the 1.0 threshold

## 5.5 Costs and Benefits of Flood Mitigation Concepts for Critical Facilities

Table 5-3 outlines the monetized risk for each facility before flood mitigation and the benefits from implementing flood mitigation concepts (the change in cumulative risk for critical facilities when mitigation strategies are applied). Two alternative solutions, Alternatives 1 and 2 were developed for each facility. Alternative 1 combines strategies for elevating some assets and hardening other buildings. Hardening includes flood-proofing buildings or rooms (also known as wet-proofing alternatives where the room is flooded but the asset is not exposed given its elevation; or dry proofing alternatives where the room is prevented from flooding with different types of flood barriers). Alternative 2 relies only on hardening of facilities. Results in Table 5-3, aggregated at the critical facility level, are derived from the individual building analyses for buildings within a facility.

**Table 5-3. Critical Facility Cumulative Monetized Risk and Benefits with Mitigation Strategies, Based on Direct Equipment Damage**

| Facility | Sum of Cumulative Monetized Risk Without Strategy (2022-2042) (thousands $) | Alternative 1 Benefit (thousands $) | Alternative 2 Benefit (thousands $) |
|---|---|---|---|
| Cherrydale Center | 1 | 1 | 1 |
| Gunston Middle School | 60 | 58 | 58 |
| Little Falls Booster Station | 100 | 52 | 52 |
| Thomas Jefferson Middle School | 1,798 | 1,764 | 1,770 |
| Virginia Hospital Center [a] | 5,659 | 5,586 | 5,586 |
| WPCP (North) | 10,137 | 9,401 | Not computed[b] |
| WPCP (South) | 32,270 | 27,368 | Not computed[b] |

[a] This does not reflect the mitigation provided by the Virginia Hospital Center stormwater improvements, as described in Section 3.4.

[b] The Alternative 2 strategy for the WPCP North and South uses the USACE floodwall. Cumulative monetized risk cannot be accurately calculated with the Task 6 critical facilities model; however, the floodwall would provide significant protection to both North and South facilities.

Table 5-4 outlines the benefits, costs, and BCRs for the two alternative mitigation strategies applied to each critical facility. In addition, each mitigation cost estimate is also presented with a range to represent Class 4 cost estimates. Class 4 relates to a range of -30% to +50% and is presented as defined by AACE International (2020) Recommended Practice No. 18R-97 and as designated in ASTM E2516-06.

As mentioned previously, the ART O&M Facility, Cardinal Elementary School, Trade Center Equipment Bureau, and Trade Center NOCII did not require mitigation strategies. They were evaluated and determined to not need mitigation strategies because of low cumulative monetized risk, as estimated in Task 5. Although these three facilities are in areas where flooding does occur and is projected to occur, results of the flood modeling analysis show limited risk to the assets inside those facilities. However, inundation in the vicinity and on access roads and parking areas for those facilities could still be disruptive for access and general operations, but no flood mitigation concepts were developed as part of Task 6.

The benefits and BCR values presented in Tables 5-3 and 5-4 include only monetized risk and benefits based on avoided risk from direct damage to equipment **and do not include the indirect economic impacts to County residents and businesses should there be a failure of a given facility. Including indirect economic impacts could increase the estimated benefits and BCR for flood mitigation**. To demonstrate this, the risk and benefits were also calculated to include indirect economic impacts associated with a closure of the WPCP. The results indicate that by accounting for avoided losses from both direct equipment damage and indirect economic losses, the estimated benefits could increase by 19%, from $27.4 million to $32.6 million, with a corresponding increase in the BCR.

Results show that, in all facilities except for the Cherrydale Center, there is an alternative with a BCR greater than 1.0. This does not mean that flood mitigation should not be implemented at the Cherrydale Center; other considerations of risk are important in determining the need for flood mitigation at that facility, such as providing safe access roads and parking areas for first responders to support a vulnerable population. The BCR, however, is an indication that additional exploration of concepts may be necessary to maximize cost effectiveness at the Cherrydale Center.

**Table 5-4. Critical Facility Costs, Benefits, and Benefit-Cost Ratios Based on Direct Equipment Damage**

| Critical Facility | Benefit Alternative 1 (thousands $) | Benefit Alternative 2 (thousands $) | Capital Costs Alternative 1[a] (thousands $) | Capital Costs Alternative 2[a] (thousands $) | BCR Alternative 1 | BCR Alternative 2 |
|---|---|---|---|---|---|---|
| Cherrydale Center | 1 | 1 | 7<br>(5 to 11) | 21<br>(14 to 31) | 0.2 | 0.1 |
| Gunston Middle School | 58 | 58 | 252<br>(177 to 378) | 22<br>(15 to 33) | 0.2 | 2.7 |
| Little Falls Booster Station | 52 | 52 | 7<br>(5 to 11) | 21<br>(14 to 31) | 7.2 | 2.6 |
| Thomas Jefferson Middle School | 1,764 | 1,770 | 91<br>(64 to 137) | 49<br>(35 to 74) | 19.3 | 35.9 |
| Virginia Hospital Center [b] | 5,586 | 5,586 | 59<br>(41 to 88) | 164<br>(115 to 246) | 95.4 | 34.1 |
| WPCP (North) [c] | 9,401 | Not Computed[c] | 2,096<br>(1,467 to 3,144) | 3,592<br>(1,347 to 5,388) | 4.5 | 2.0[c] |
| WPCP (South) [c] | 27,368 | Not Computed[c] | 4,537<br>(3,176 to 6,806) | | 6.0 | 2.0[c] |
| Total | 44,230 | Computed[b] | 7,049<br>(4,934 to 10,574) | 3,869<br>(2,708 to 5,804) | N/A | N/A |

[a] Class 4 estimates (-30% to +50%), as defined by AACE International (2020) Recommended Practice No. 18R-97 and as designated in ASTM E2516-06, were used to develop the costs. Class 4 cost estimates account for both capital and O&M costs. Class 5 cost estimates (-50% to +100%) were used for PA costs given the larger uncertainty with implementing projects at the neighborhood scale.

[b] This does not reflect the mitigation provided by the Virginia Hospital Center stormwater improvements, as described in Section 3.4.

[c] The Alternative 2 strategy for the WPCP North and South uses the USACE floodwall. Benefits for Alternative 2 could not be determined; thus, a BCR cannot be determined with the same methods used in Task 6 of the RAMP. USACE, however, reports a BCR of 2.0 for the project (based on protection of the area beyond the WPCP) (USACE 2022).

N/A = not applicable

For the WPCP, Table 5-4 lists the BCR developed by USACE for their floodwall along Four Mile Run. A project to protect from fluvial flooding in the area, such as the USACE floodwall (USACE 2022), would provide flood mitigation benefits and could protect the facility (and vicinity).

Figure 5-5 shows the same information as Table 5-4 in graphical form, with costs in red extending to the left and benefits to the right for the best alternative with the highest BCRs for each facility. This illustrates that benefits far outweigh costs for all but the Cherrydale Center, which might still warrant investment in flood mitigation because of the vulnerability of the community there.

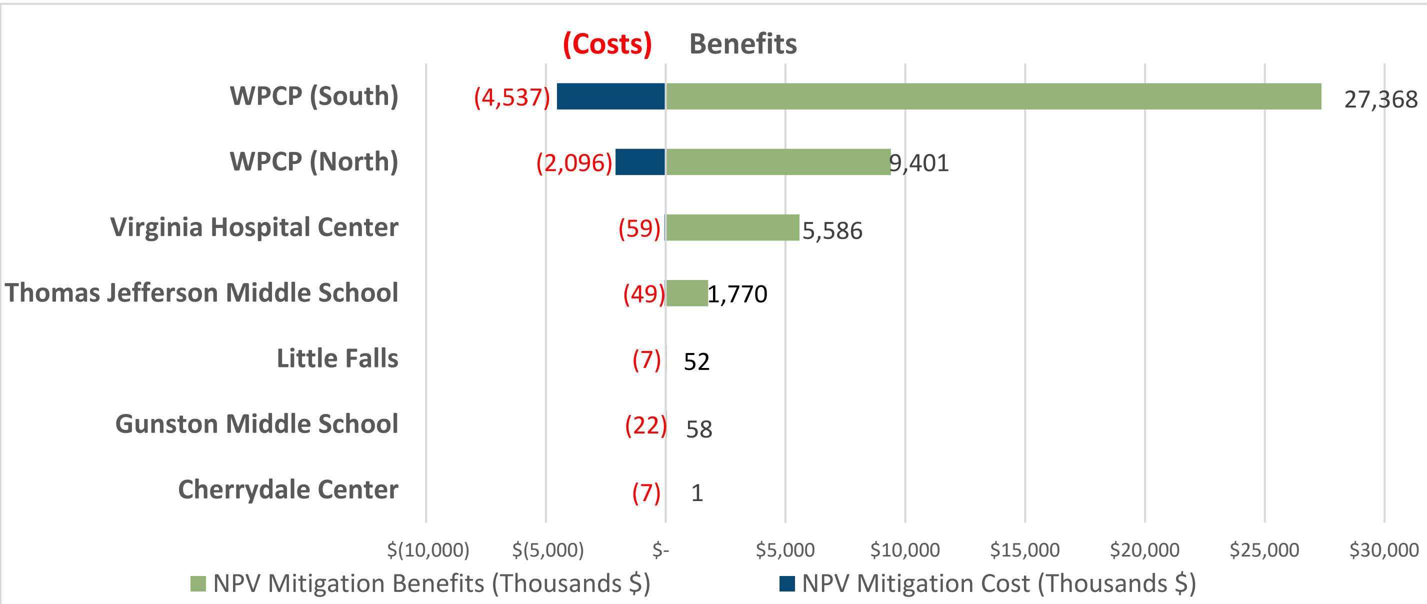



**Figure 5-5. Flood Mitigation at Critical Facilities: Net Present Value of Costs (Total Capital and Annual O&M) and Benefits of Best Alternatives for Elevation and Flood Proofing (20-year Period with 7% Discount Rate)**

# 6. Conclusions, Recommendations, and Next Steps

## 6.1 Conclusions

Areas of significant flood risk were identified in the seven watersheds targeted by the RAMP, as well as at 7 out of 10 critical facilities investigated. In many cases, the areas of flood risk are from interior flooding and lie well outside the floodplain areas mapped by FEMA.

Programmatic and policy solutions, many of which the County currently has in its selection of flood management strategies, can serve as an important tool to address flooding Countywide and in localized areas. Recommended programmatic and policy solutions are summarized in Section 6.2.3 and include a series of policies, actions, procedures, and standards in nine different categories. Additional available programmatic and policy solutions that other jurisdictions are applying can be considered for exploration and potential adoption.

The flood mitigation concepts for PAs developed and evaluated in the RAMP have the potential to significantly reduce flooding. These concepts are summarized by watershed in Section 6.2.4. At the watershed level, at least one alternative with a BCR greater than 1.0 exists for each watershed. For a few individual PAs, some significant challenges for project implementation do exist that require additional analysis.

For the critical facilities where flood mitigation alternatives were developed and assessed, all but one are estimated to have a BCR greater than 1.0. Further exploration of detailed alternatives for the Cherrydale Center is recommended to potentially find more cost-effective options. The flood risk and mitigation strategies for critical facilities are summarized in Section 6.2.5.

The WPCP alternatives provide significant flood risk reduction and have substantial BCRs driven by both the asset replacement costs of vulnerable assets and the significant flood exposure in the facility. There is significant merit in exploring a watershed-level alternative that could protect the WPCP and the neighborhoods in the Four Mile Run flood risk area, which includes some areas outside the FEMA 100-year floodplain. The USACE levee alternative (USACE 2022) is an alternative to consider for enhancement through collaboration.

## 6.2 Recommendations and Next Steps

### 6.2.1 Community Engagement

The County has already been conducting extensive community engagement regarding flood risk and the RAMP. After completing the RAMP, the next steps include conducting additional public engagement workshops and information sessions with County leadership and elected officials to present and discuss results of the RAMP including flood risk assessments and mitigation and adaptation strategies that provide flood reduction benefits beyond the planning-level costs that were developed for implementation of flood mitigation strategies, as well as programmatic and policy recommendations.

### 6.2.2 Project Feasibility Studies, Prioritization, and Financing

Implementation steps after completing the RAMP project should include feasibility-level studies for project implementation and further analysis to refine the flood mitigation concepts and costs. For many PAs, projects are likely to include a combination of conveyance and storage options, as well as GSI for water quality management. For critical facilities, flood mitigation concepts could proceed with predesign and design for facilities buildings and assets at risk. Prioritizing actions for PAs and critical facilities can be informed by the BCRs developed as part of the alternatives analysis. Prioritizing projects for critical facilities can additionally rely on criteria such as criticality of assets and risk exposure identified during the vulnerability assessment. For PAs, project prioritization may be refined to include additional considerations given that those projects protect not only individual assets and their function, but also larger areas where people live, work, and recreate. Environmental and social vulnerability factors, as well as other relevant prioritization criteria, may be taken into consideration. Additional criteria can include public safety, availability of funding opportunities, project bundling opportunities, legal and regulatory mandates, opportunities for partnerships with other agencies, and public support.

### 6.2.3 Programmatic and Policy Recommendations

The analysis and solutions included in the RAMP will help the County make decisions on enhancing existing programmatic and policy solutions with new potential policies, actions, or procedures. Table 6-1 presents a summary of programmatic and policy recommendations that may be considered by Arlington County to improve flood management. These recommendations are based on the review and survey of programmatic and policy strategies adopted or being considered in other jurisdictions, which are documented in more detail in Appendix G.

While the RAMP project was ongoing, the County had already begun advancing more proactive flood mitigation actions and policies as a result of recent flooding events and in recognition of the increased risk due to climate change. For example, the County recently updated the Floodplain Ordinance (Arlington County Code § 48-51, 2023) with new freeboard standards; work has started on a flood-resilient design and construction guidelines manual and potential code amendments for high-vulnerability and high-impact areas; capital infrastructure projects are incorporating flood adaptation elements; preemptive measures are being deployed in advance of forecasted major storms (e.g., identifying parking options for resident and businesses to move vehicles from high risk areas); and the County is working on acquiring strategic rights-of-way efforts to allow for overland relief. The County has been actively participating in regional coordination efforts with regarding coastal exposure assets (such as the airport, (which borders Crystal City/National Landing) and businesses groups regarding flood and climate resilience. Lastly, the County has initiated a program which installs high water sensor devices to warn drivers of flooded roadways. The program incorporates a flow monitoring network to better understand and provide public information regarding conveyance system performance.

The RAMP tasks—which included assessments of flood exposure, vulnerability, and risk under historical and climate change conditions—can inform the County's actions, investments, and communications when updating design guidance and standards for County facilities. This final report for the RAMP serves as an implementation roadmap for guiding risk reduction and resilience in the County's continued stormwater engineering and program investments.

The projects that may result from the engineering concepts presented in Section 5 and summarized by watershed in Section 6.2.4 will be implemented in the context of programmatic and policy solutions both new and currently in place in the County.

**Table 6-1. Summary of Flood Management Programmatic Strategies Recommendations**

| Subject | Recommendations |
|---|---|
| Governance | Explore methods to formalize communication and data sharing among relevant agencies for the specific goal of ongoing flood management. |
| Public information | Consider whether existing flood hazard information, available via FEMA, can be made more accessible to the public using an available mapping tool or whether developing a targeted flood risk tool may be helpful to also provide information on pluvial or urban flooding risk, when available, that is not addressed by FEMA NFIP flood maps.<br>Consider assessing whether National Weather Service notifications or more location specific, real-time alerts would be helpful in avoiding damages or life-safety issues in flood-prone areas.<br>Consider developing coordinated and ongoing community engagement programs that will provide public education on flood risk and flood risk mitigation options. Consider outreach techniques targeted at socially disadvantaged communities.<br>Consider whether more stringent disclosures may be warranted in areas of chronic flooding. |
| Information supporting County flood risk management activities | Explore the benefits of installing real-time rainfall, tide, or stream gauges to inform County operations.<br>Consider whether drainage-focused building permit reviews could be an opportunity to address conditions that may exacerbate lot-to-lot flooding.<br>Identify available records that can be used to assess historical flood impacts, recognize limitations the records may have, and determine whether the data may inform ongoing flood management activities. |
| Equity considerations | Confirm that flood management activities are conducted with appropriate consideration of the County's equity goals. |
| Flood risk mitigation | By tracking flood insurance coverage statistics, understand how the following activities may encourage property owners to purchase flood insurance or flood proof their facilities, or both:<br>▪ Expanding flood hazard and flood risk information<br>▪ Making this information available to the public<br>▪ Using the information to manage flooding<br>Understand how the following may help increase flood insurance coverage for County residents:<br>▪ Parametric microinsurance<br>▪ Premium reductions for low-cost flood mitigation<br>▪ Local flood insurance affordability programs<br>▪ Community assistance combined with a high-deductible NFIP policy<br>▪ Community-based insurance<br>▪ Right-sizing coverage (Kousky and Wiley 2021)<br>Consider whether a technical support program may be helpful in addressing resident flooding or drainage issues. Consider whether the goal of such a program might be limited to improving storm drains or assisting low-income residents with addressing flood-proofing and other private property mitigations.<br>As part of repetitive loss plan, consider whether property acquisition or buyouts should be planned for. |
| Integrating flood risk information with land use planning | Consider what process will be used to integrate flood risk into land use planning, subdivision, and development review. |
| Updating regulations and design standards based on flood risk information and climate change | Proceed with the planned review of regulations and standards to confirm that they are consistent with the resilience and flood management goals of the County. |
| Flood management financing and funding | Consider developing a strategy for funding and financing flood management programmatic strategies and capital projects. |
| Storm drainage asset management | Prioritize identification of the location, condition, remaining service life, and LOS of existing assets to better assess the capital investment needed to maintain that LOS in the future. |

LOS = level of service
NFIP = National Flood Insurance Program

### 6.2.4 Watershed Specific Summaries and Recommendations

A series of watershed-specific maps are provided at the end of this report that summarize flood risk and recommended mitigation strategies for each of the seven watersheds analyzed in detail (see section entitled **Watershed Maps with Climate Scenarios and Proposed Mitigation Concepts**). Each watershed has four sets of maps showing predicted baseline and projected inundation in 2070 for different size storms and proposed flooding mitigation strategies.

The fourth and last set of maps for each watershed shows the proposed individual inundation mitigation concepts for each watershed with details such as project extent, size, and estimated capital cost for the conveyance or storage concepts. The third set of maps shows the reduction in flood extent.

Figure 6-1 shows the annualized risk for all watersheds, which aggregates the risk for all PAs with each watershed. Figure 6-2 shows how the monetary risk increases for a 100-year storm from current condition to the year 2070.

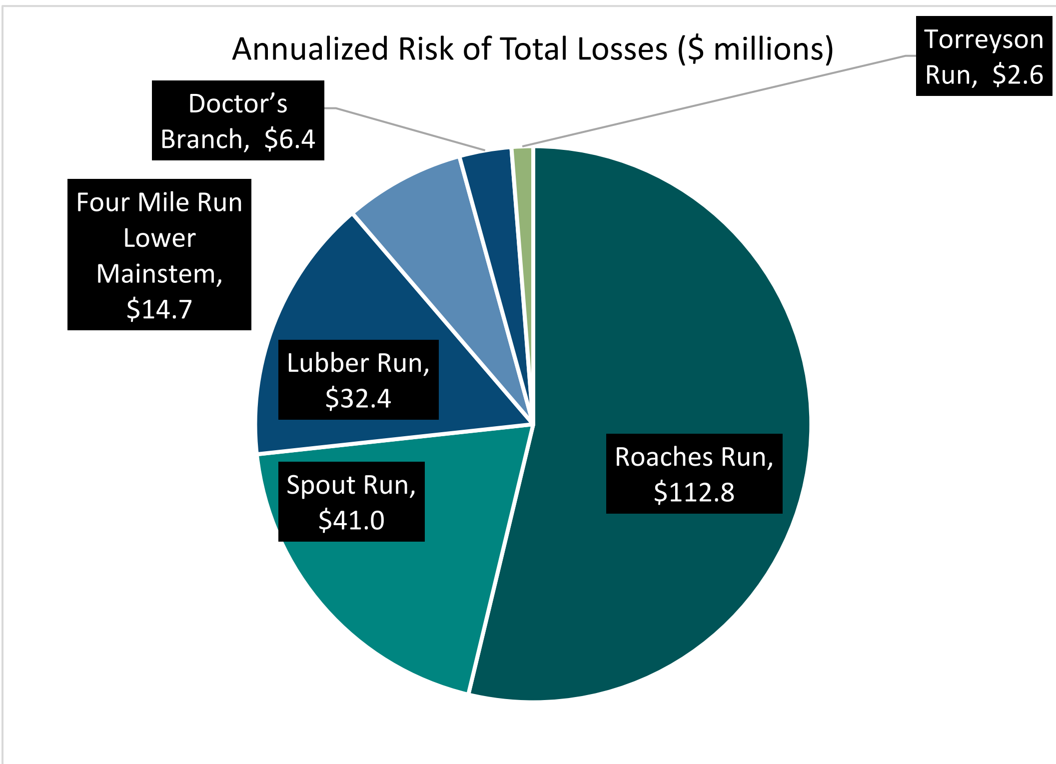



**Figure 6-1. Annualized Risk of Losses by Watershed ($ millions)**

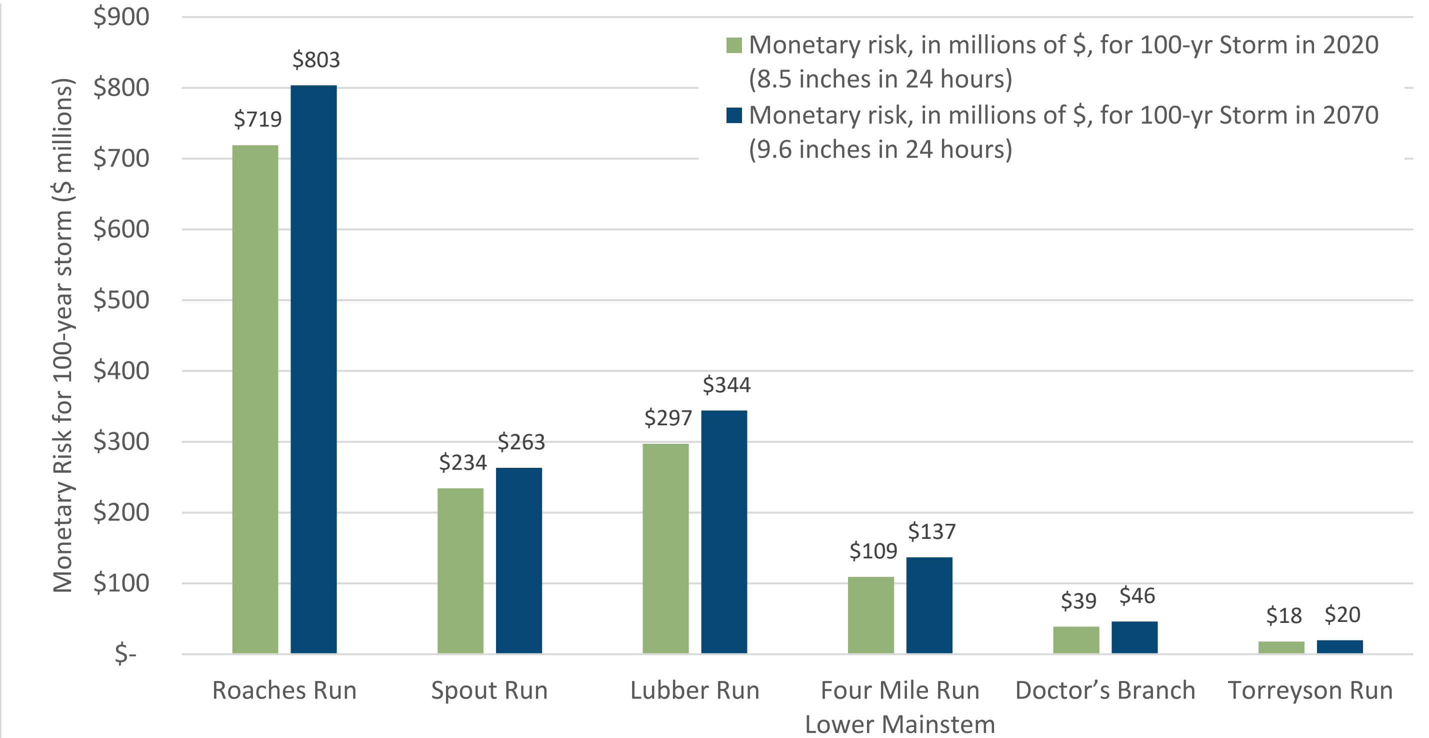



**Figure 6-2. Risk of Losses for 100-year Storm, Current and Projected (2070) ($ millions)**

The total cost of mitigation solutions based on conveyance or storage concepts are summarized on Figure 6-3. The benefits are summarized on Figure 6-4, which are percentage reductions relative to the total current annualized risk shown on Figure 6-1.

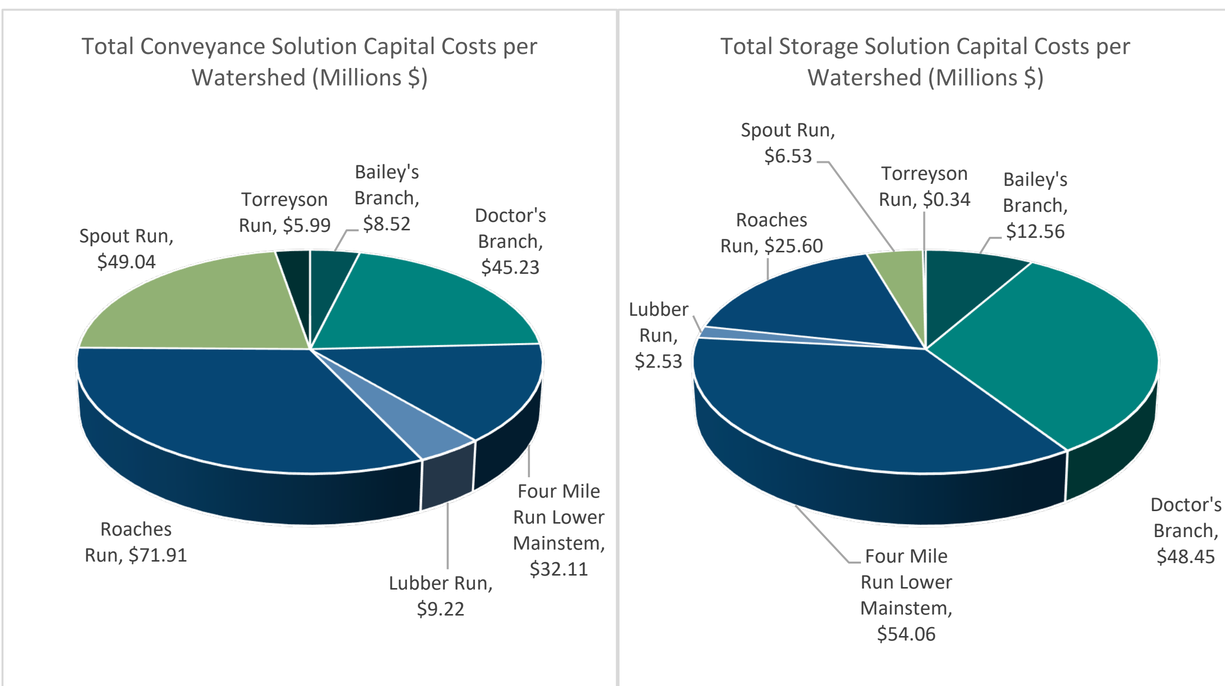



**Figure 6-3. Total Capital Cost for Conveyance and Storage Concepts per Watershed**

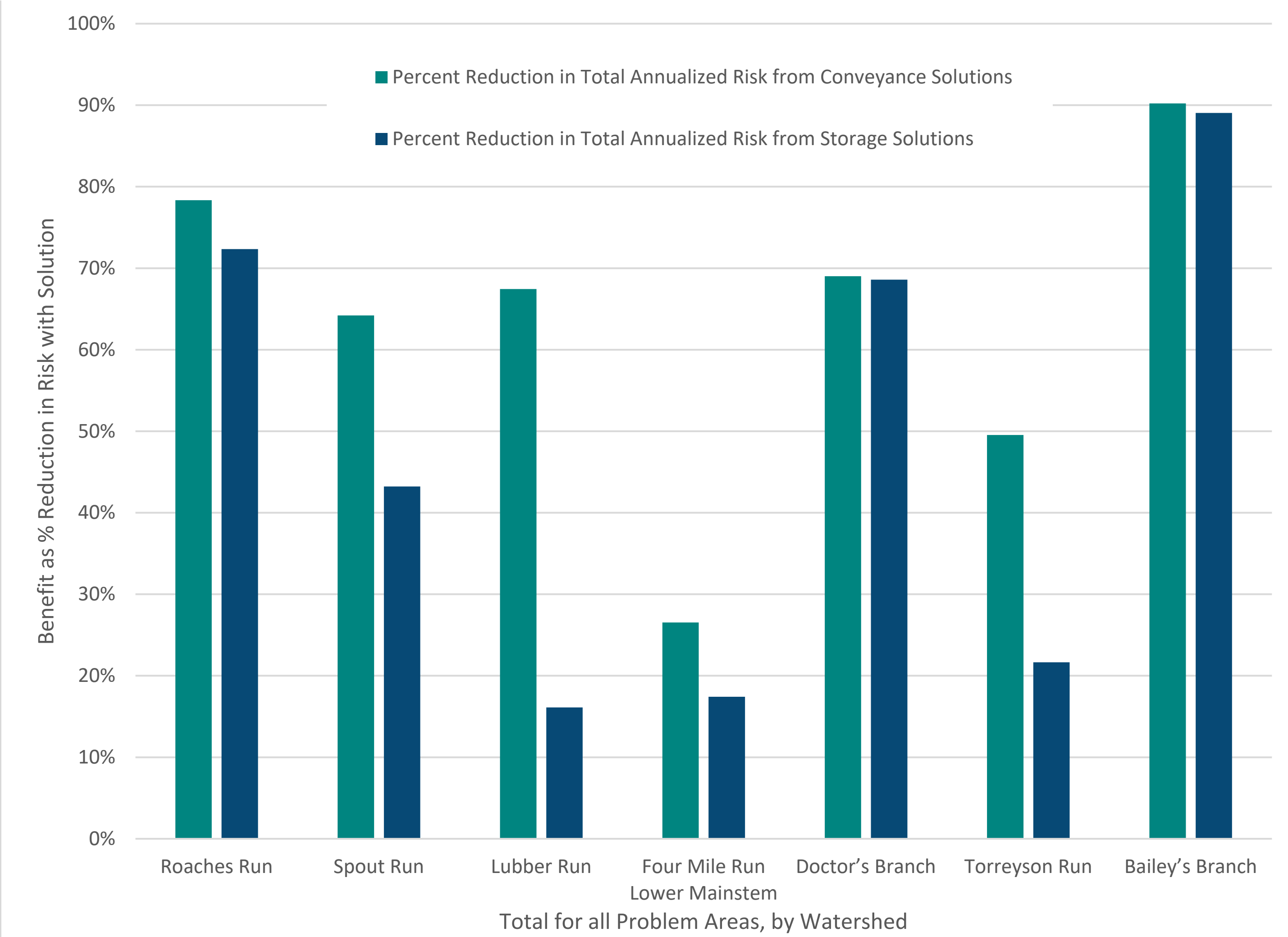



**Figure 6-4. Risk Mitigation (Benefits) from Conveyance and Storage Concepts per Watershed As Percent Reduction in Annualized Risk, Before and After Each Solution is Applied**

### 6.2.5 Critical Facility Recommendations

Seven of the 10 critical facilities had flood risk identified. The WPCP represents the most risk, as shown on Figure 6-5. Figure 6-6 summarizes total capital costs for two conceptual alternatives to address flooding at critical facilities. Alternative 1 includes a mix of elevating and flood-proofing approaches for all seven facilities. Alternative 2 includes mostly flood-proofing approaches and assumed construction of a floodwall proposed by USACE to protect the WPCP. The overall total capital costs were estimated to be $7 million and $4 million, respectively.

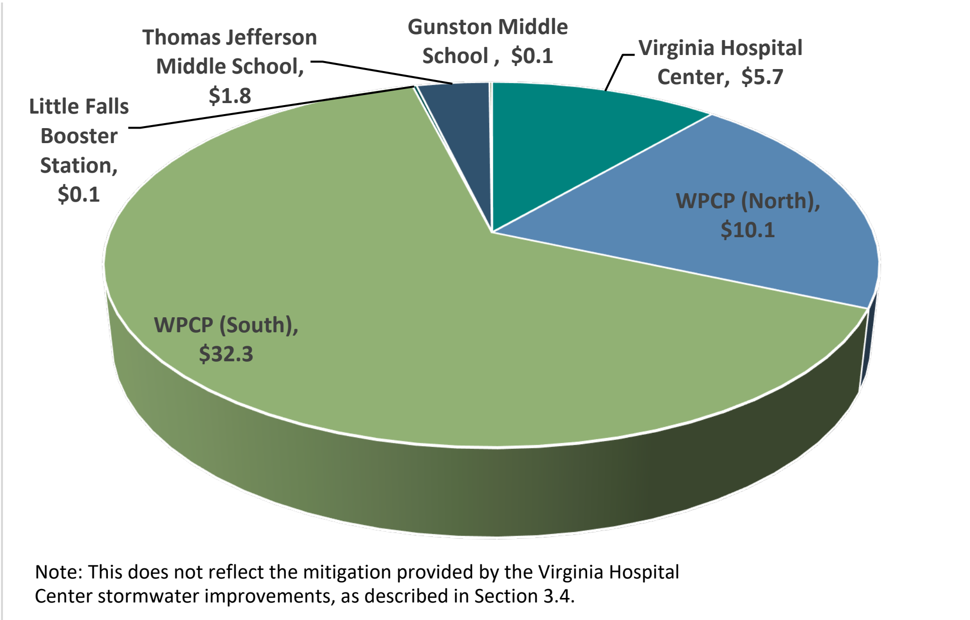
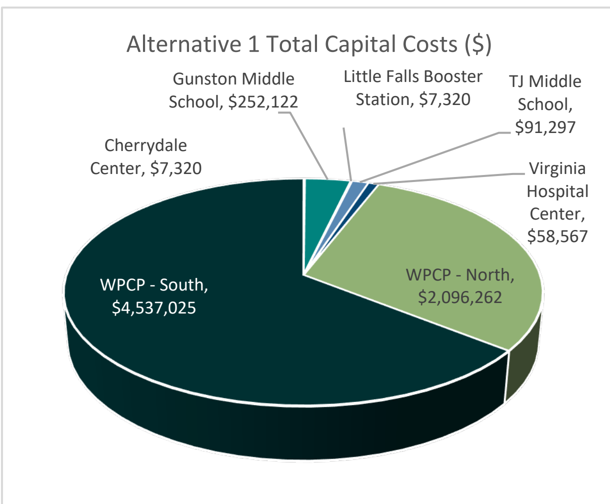



**Figure 6-5. Annualized Risk of Losses by Critical Facility ($ millions)**



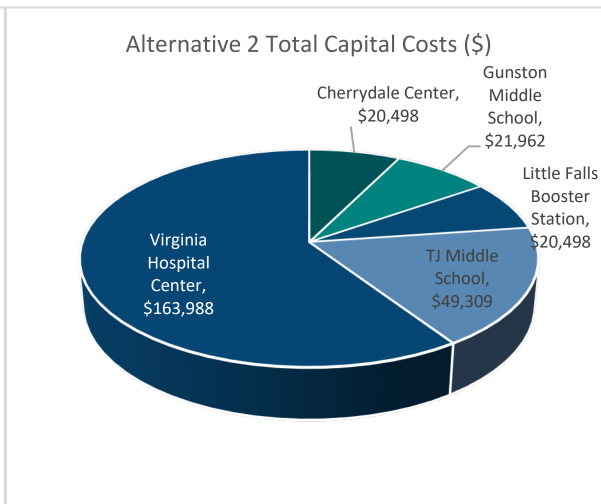




**Figure 6-6. Total Capital Cost for Alternatives 1 and 2 for Flood Mitigation at Critical Facilities**

(Notes:
This does not reflect the mitigation provided by the Virginia Hospital Center stormwater improvements, as described in Section 3.4.
Alternative 2 costs not available for WPCP. The Alternative 2 strategy for the WPCP North and South uses the USACE floodwall)

# 7. References

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# Watershed Maps with Climate Scenarios and Proposed Mitigation Concepts

This section presents map exhibits for the seven watersheds analyzed in detail. The watershed maps show the baseline flooding conditions, projected inundation for selected climate scenarios, and proposed flooding mitigation strategies. The maps illustrate the predicted inundation in each of the seven watersheds and what options may be considered to mitigate the risk of flooding. After each watershed's title page, the maps will follow this sequence:

## Map Set 1: Baseline and Projected 2070 Inundation Conditions for 10-Year Storm

The first set of maps includes two maps for each watershed, as follows:

1. **Baseline Inundation Conditions for 10-year storm (5.16 inches in 24 hours)** - This shows flooding in the event of a 10-year storm, which is a storm with a 10% chance of occurring in **current** times.
2. **Projected 2070 Inundation Conditions for 10-year storm (5.81 inches in 24 hours)** - This shows flooding projected to occur in the event of a 10-year storm in the **future** based on changing climate conditions.

## Map Set 2: Baseline and Projected 2070 Inundation Conditions for 100-Year Storm

The second set of maps for each watershed shows two maps similar to Map Set 1 for baseline and proposed inundation. However, Map Set 2 is for the 100-year event scenario, which is for a storm with a 1% chance of occurring in **current times (8.48 inches in 24 hours)** versus in the **future (9.57 inches in 24 hours)** based on changing climate conditions.

## Map Set 3: 10-Year Event Inundation with Proposed Conveyance or Storage Concepts

The third set of maps show a 10-year storm event scenario under current conditions as compared to full implementation of conveyance or storage concepts for each watershed.

- The map on the left shows predicted inundation under a 10-year storm event scenario and no action taken (current condition)
- The middle map depicts the flooded area (in acres) and the percent reduction in flooding if all proposed **conveyance** concepts are implemented
- The map on the right depicts the flooded area (in acres) and the percent reduction in flooding if all proposed **storage** concepts are implemented

## Map Set 4: Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost

The fourth and last set of maps (consisting of two separate consecutive pages) for each watershed show the proposed individual inundation mitigation projects with details such as project extent, size, and estimated capital cost for the conveyance or storage concepts.

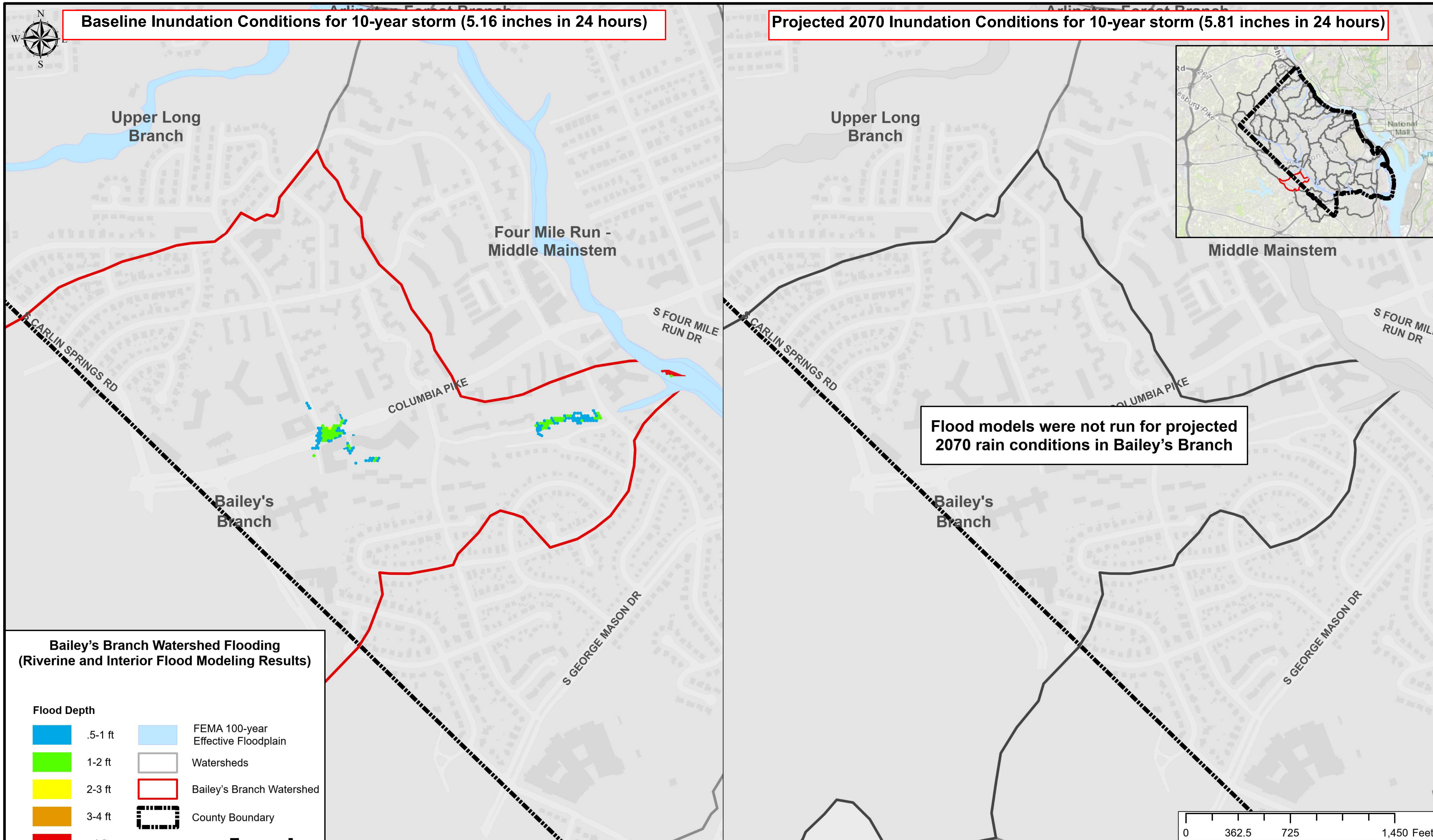
# Bailey's Branch

**Baseline and Projected 2070 Inundation Conditions for 10-year storm**

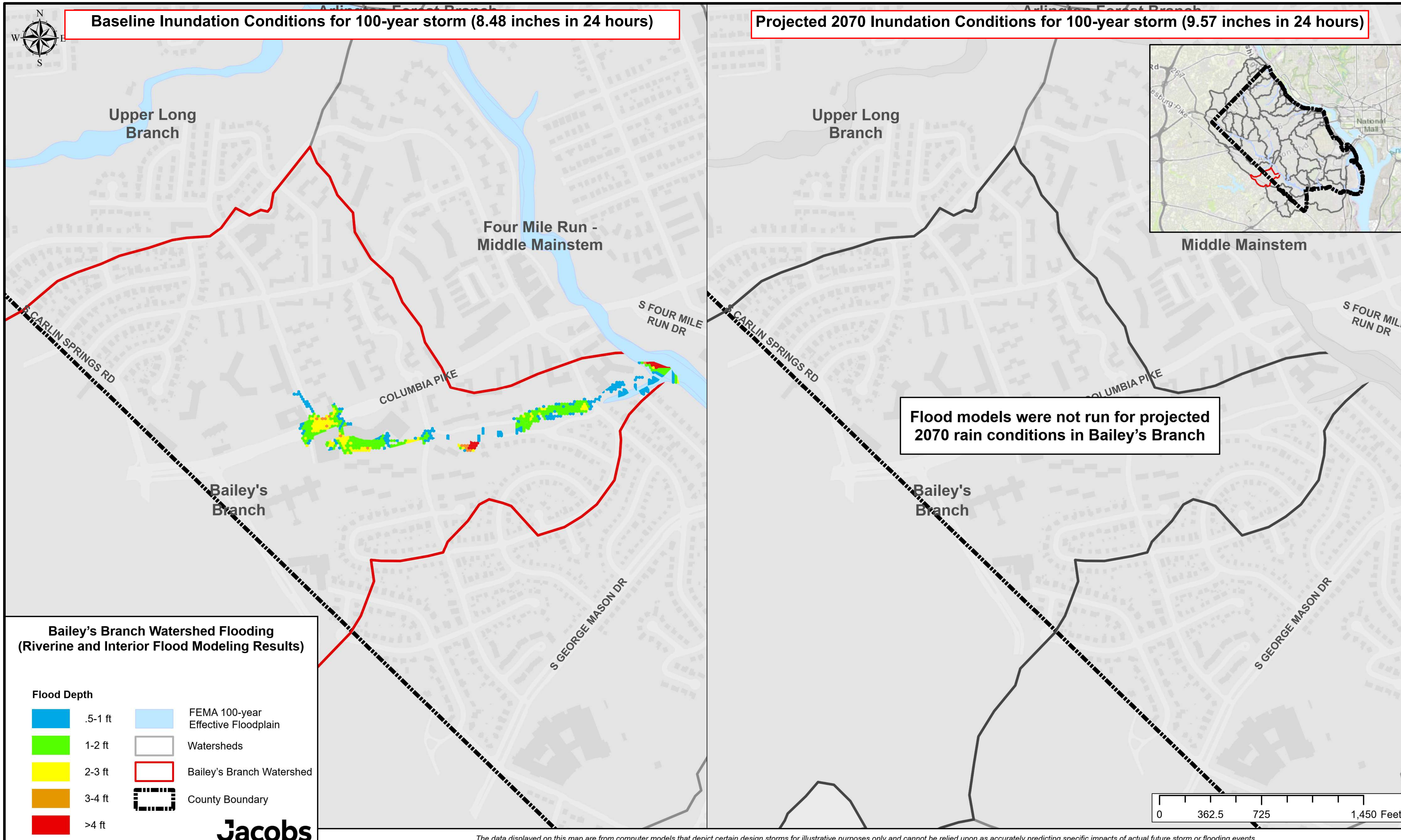
**Baseline and Projected 2070 Inundation Conditions for 100-year storm**

**10-year event Inundation with Proposed Conveyance or Storage Concepts**

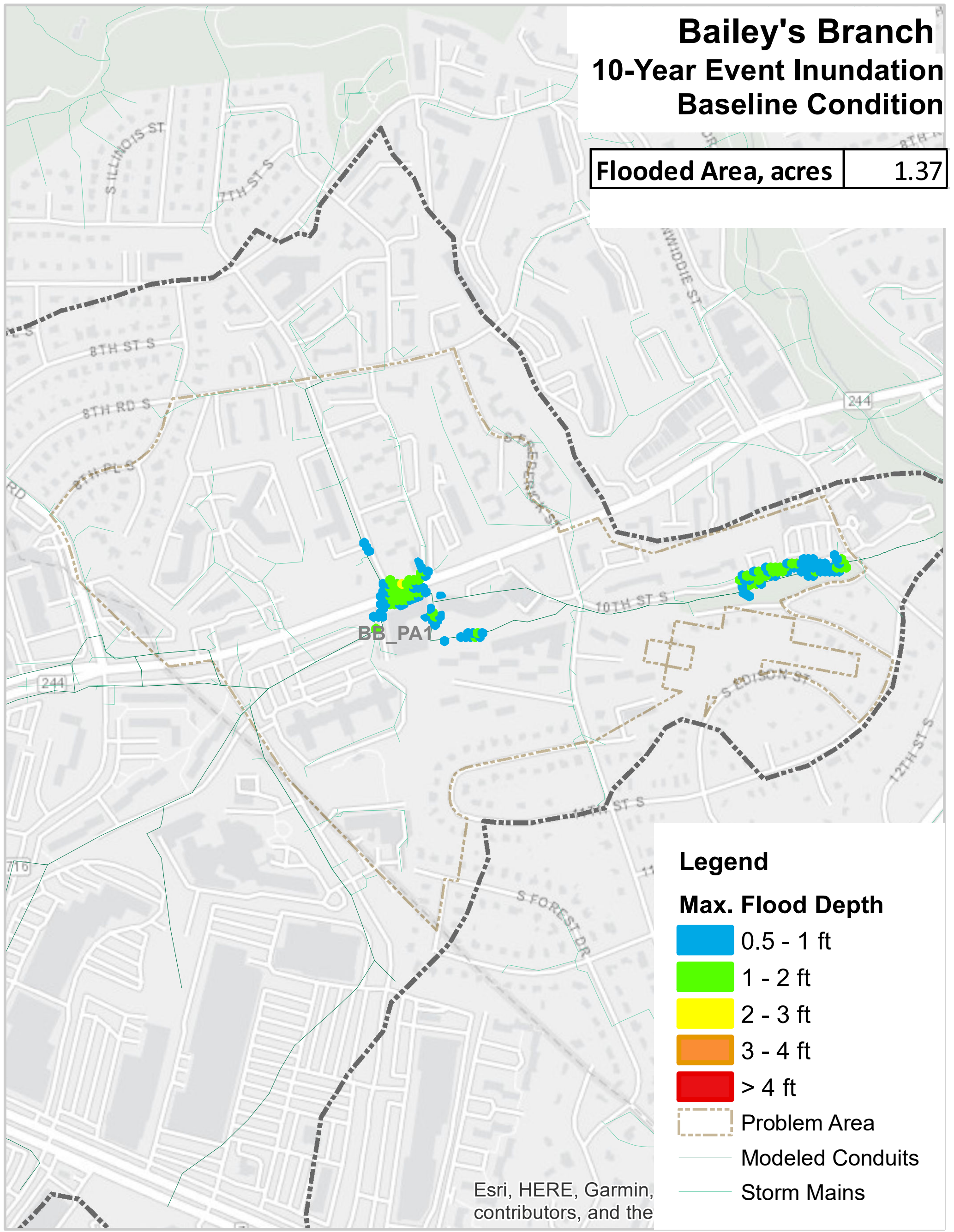
**Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost**

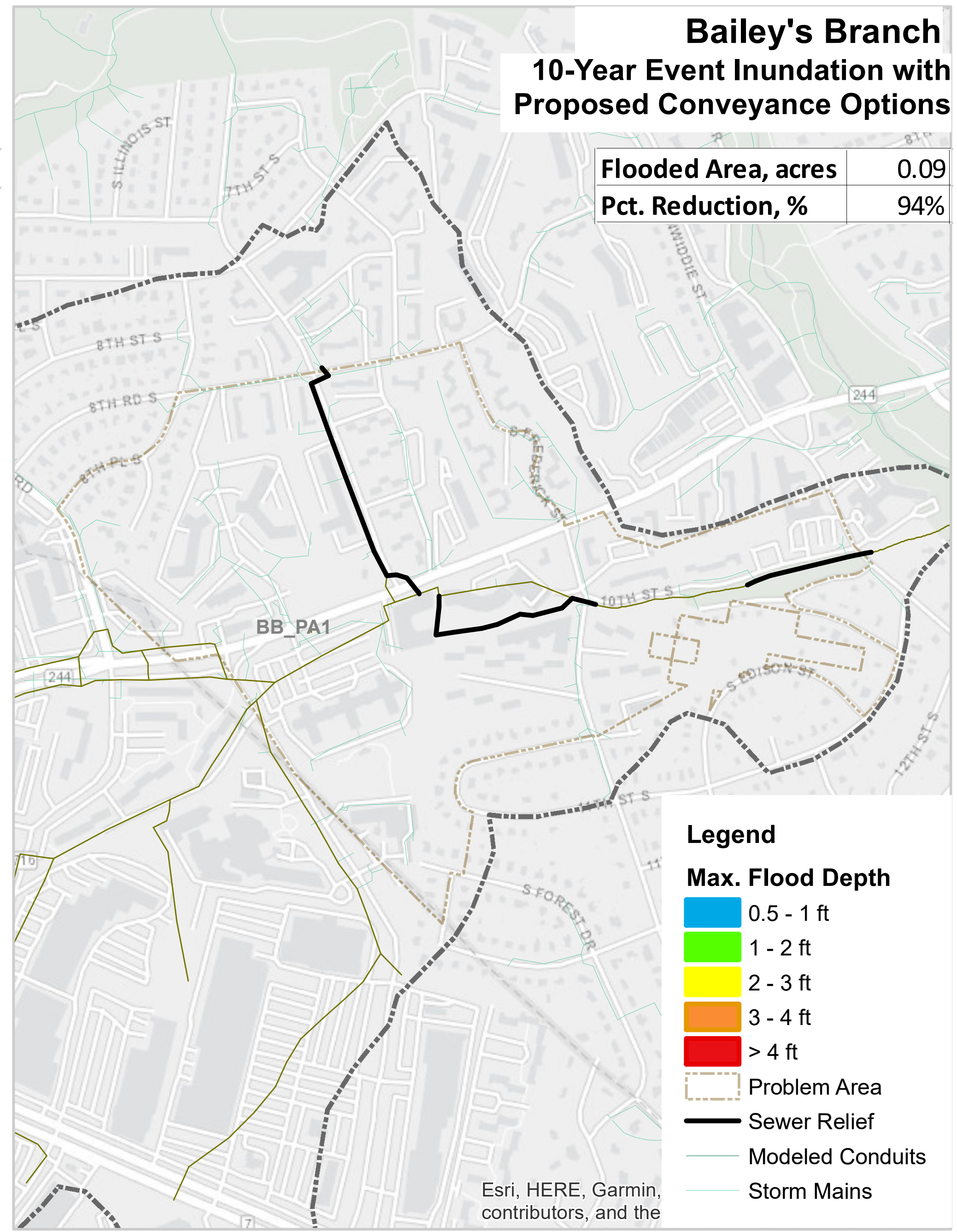


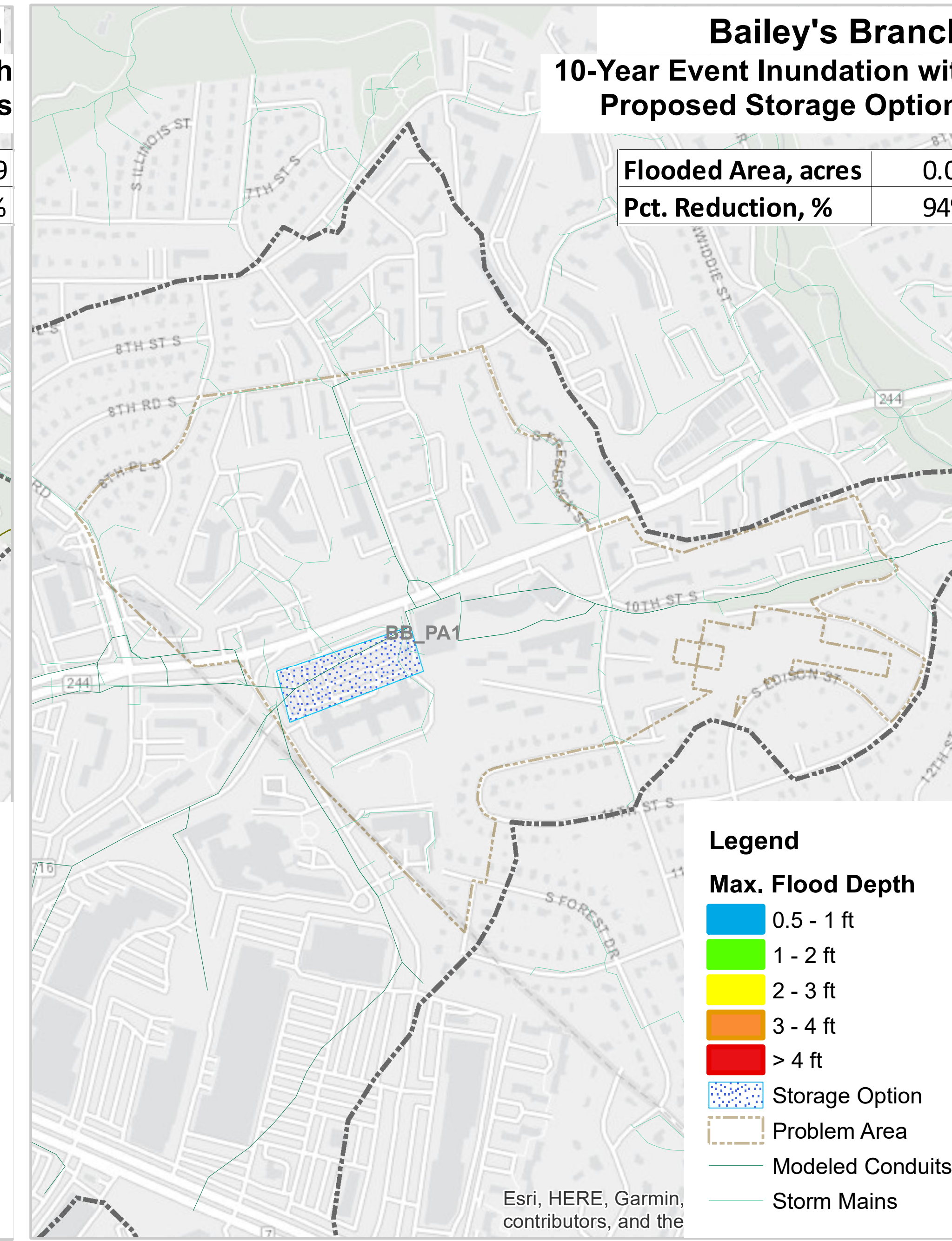

*The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events*


Baseline Inundation Conditions for 100-year storm (8.48 inches in 24 hours)
Projected 2070 Inundation Conditions for 100-year storm (9.57 inches in 24 hours)
N
S
W
E
Upper Long Branch
Four Mile Run - Middle Mainstem
Middle Mainstem
Bailey's Branch
S CARLIN SPRINGS RD
COLUMBIA PIKE
S FOUR MILE RUN DR
S GEORGE MASON DR
National Mall
Flood models were not run for projected 2070 rain conditions in Bailey's Branch
Bailey's Branch Watershed Flooding (Riverine and Interior Flood Modeling Results)
Flood Depth
.5-1 ft
1-2 ft
2-3 ft
3-4 ft
>4 ft
FEMA 100-year Effective Floodplain
Watersheds
Bailey's Branch Watershed
County Boundary
Jacobs
0
362.5
725
1,450 Feet
The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events

# Baseline, Conveyance Solutions and Storage Solutions

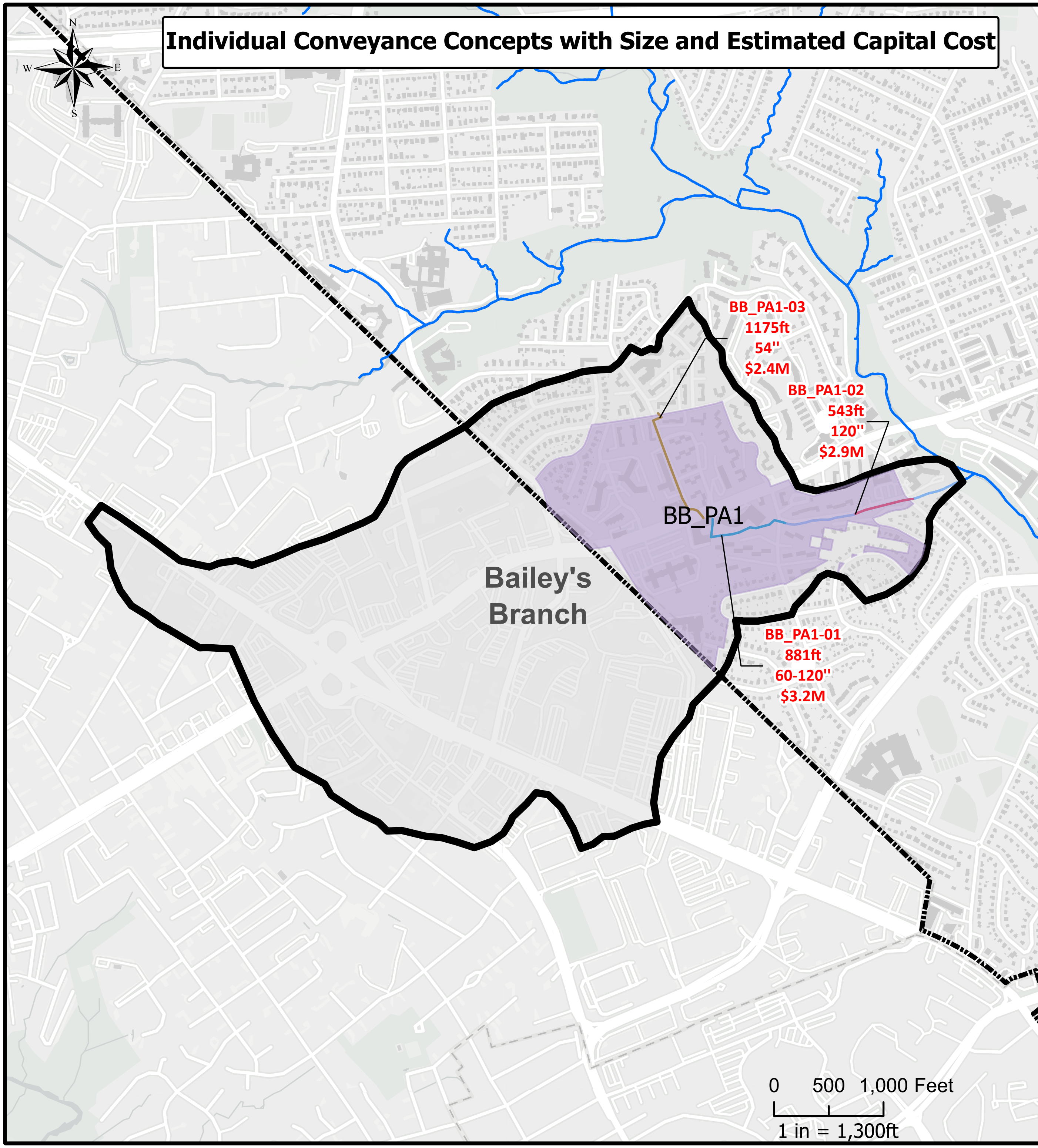


# Individual Conveyance Concepts with Size and Estimated Capital Cost

| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| BB_PA1-01 | 881 | 60-120" | $3.2 |
| BB_PA1-02 | 543 | 120" | $2.9 |
| BB_PA1-03 | 1,175 | 54" | $2.4 |




## LEGEND

Conveyance Concepts Label: (in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

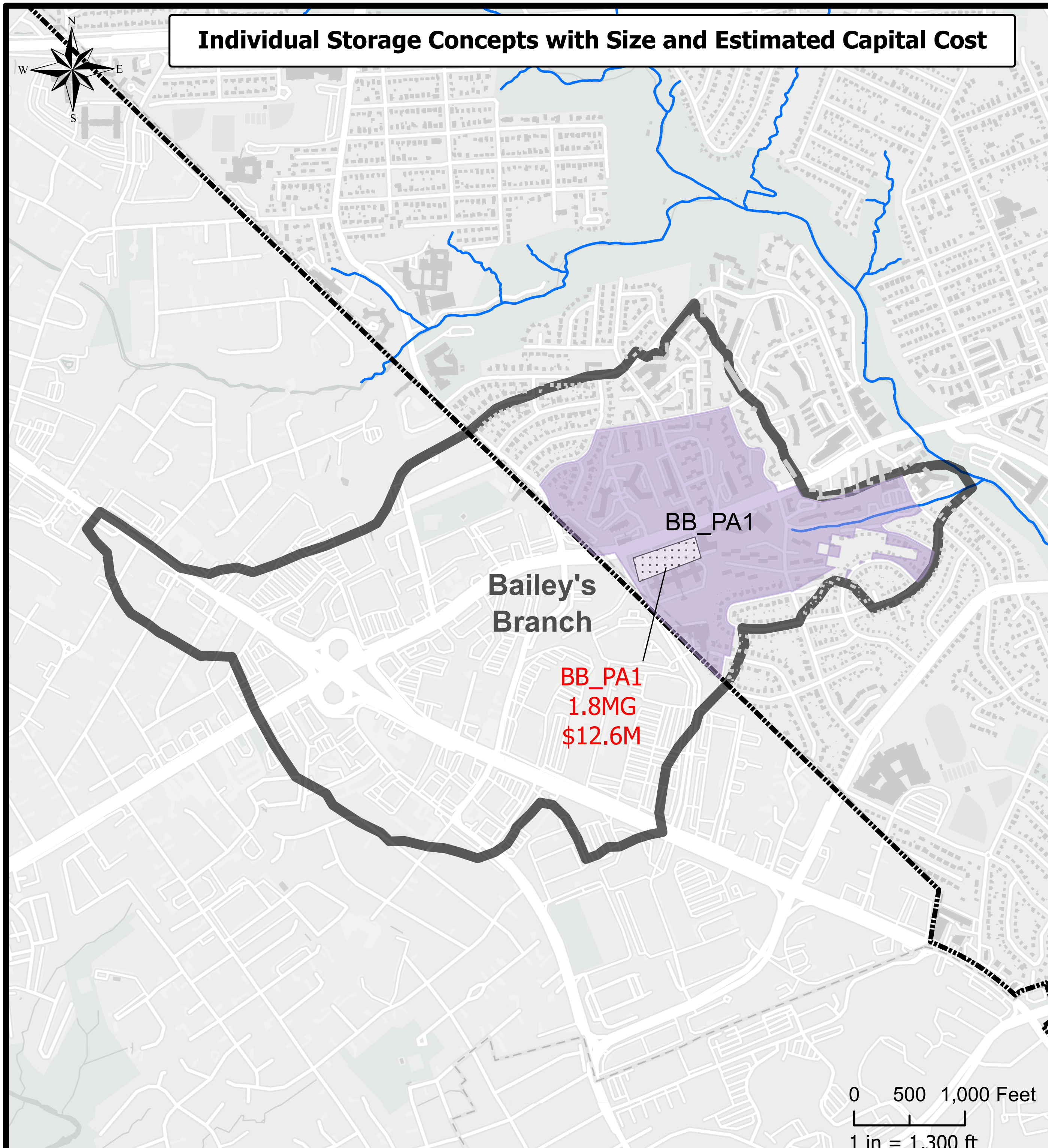
Basemap:
Watershed
County Boundary
Buildings
Hydrology

Data:
Problem Areas
Conveyance Concept Pipes

ARLINGTON VIRGINIA

**Conveyance Concepts: Bailey's Branch**

# Individual Storage Concepts with Size and Estimated Capital Cost




| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| BB_PA1 | 1.8 | Mixed | 12.6 |

**LEGEND**

Storage Concepts Label:
(in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Storage Concepts: Bailey's Branch**

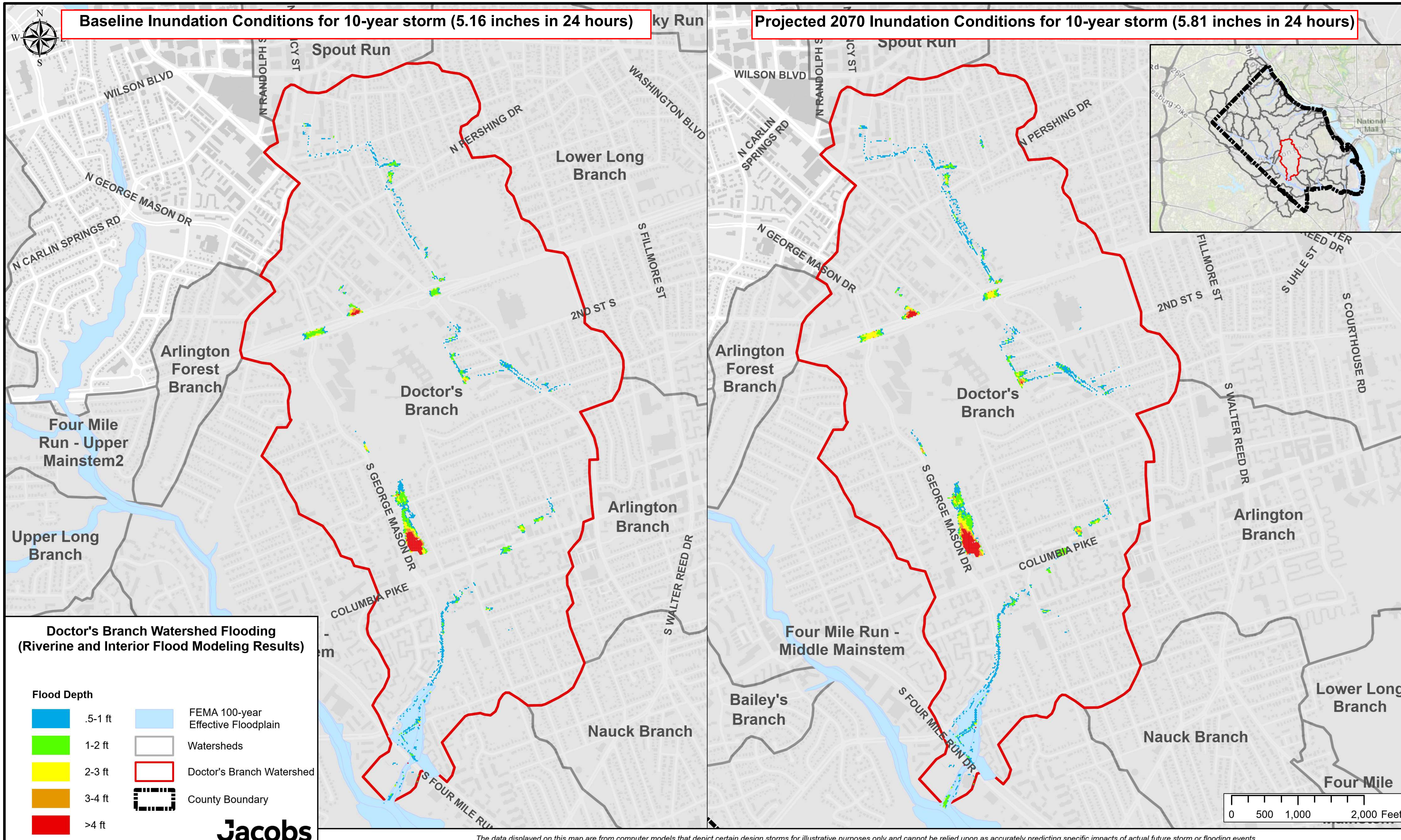
# Doctor’s Branch

**Baseline and Projected 2070 Inundation Conditions for 10-year storm**

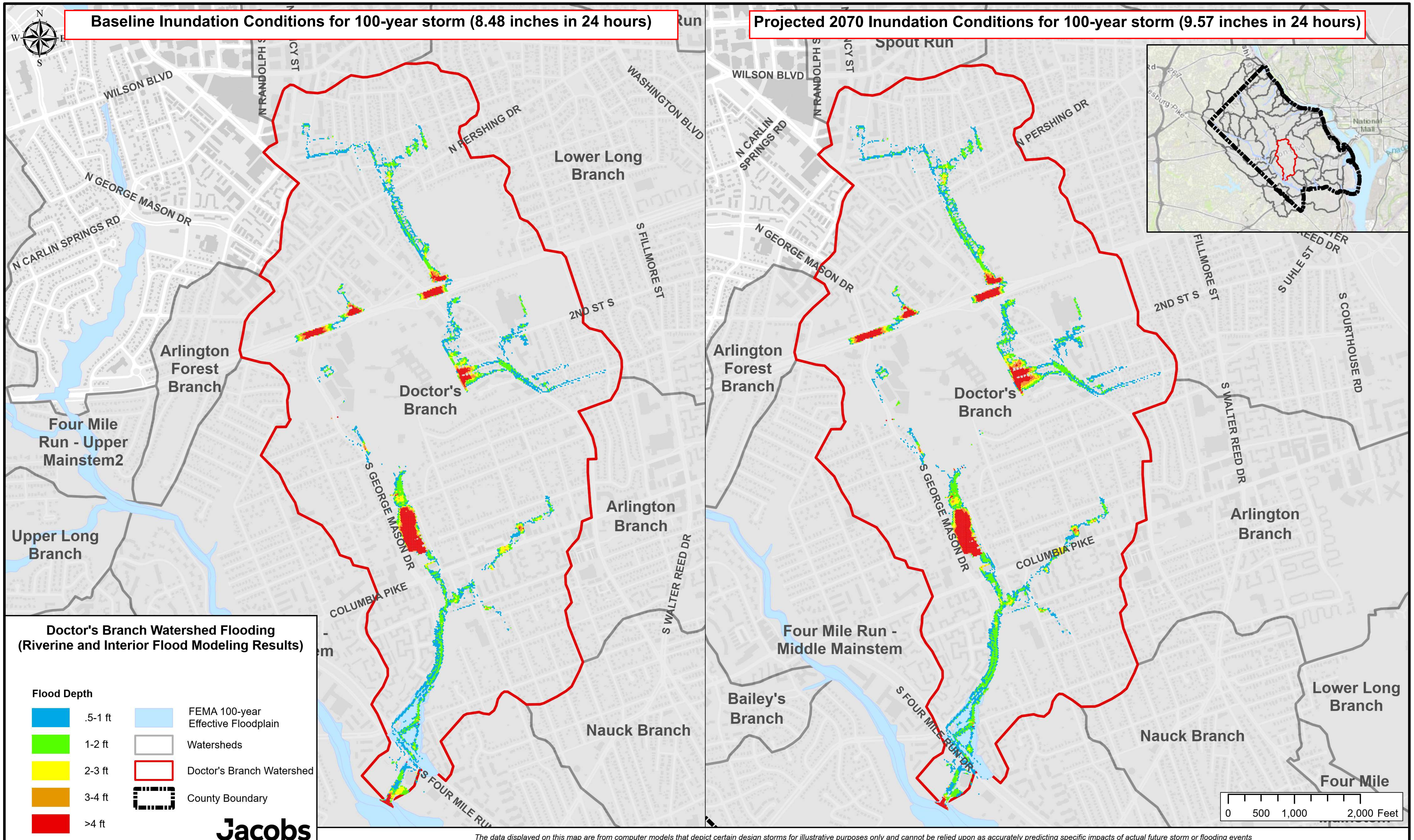
**Baseline and Projected 2070 Inundation Conditions for 100-year storm**

**10-year event Inundation with Proposed Conveyance or Storage Concepts**

**Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost**

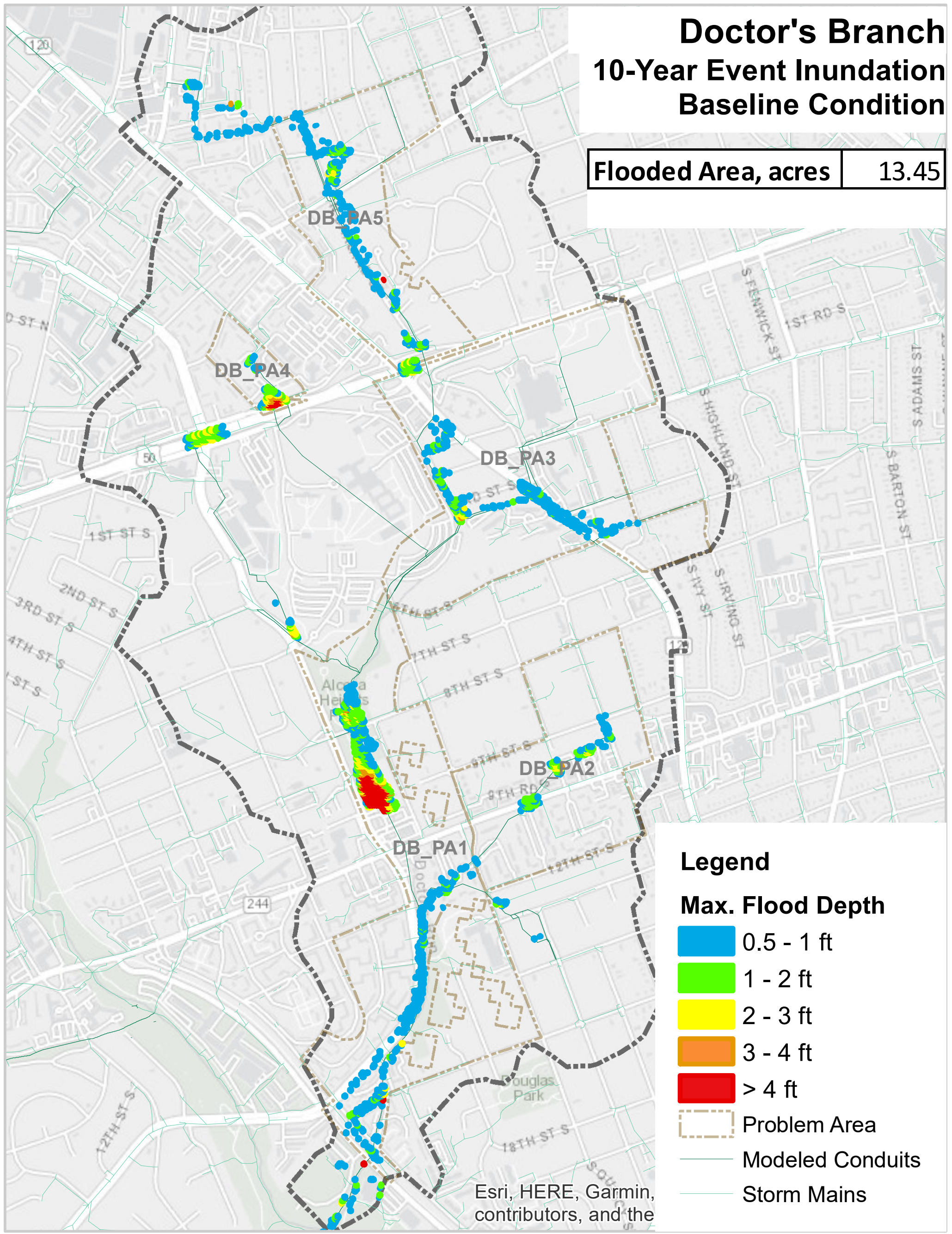


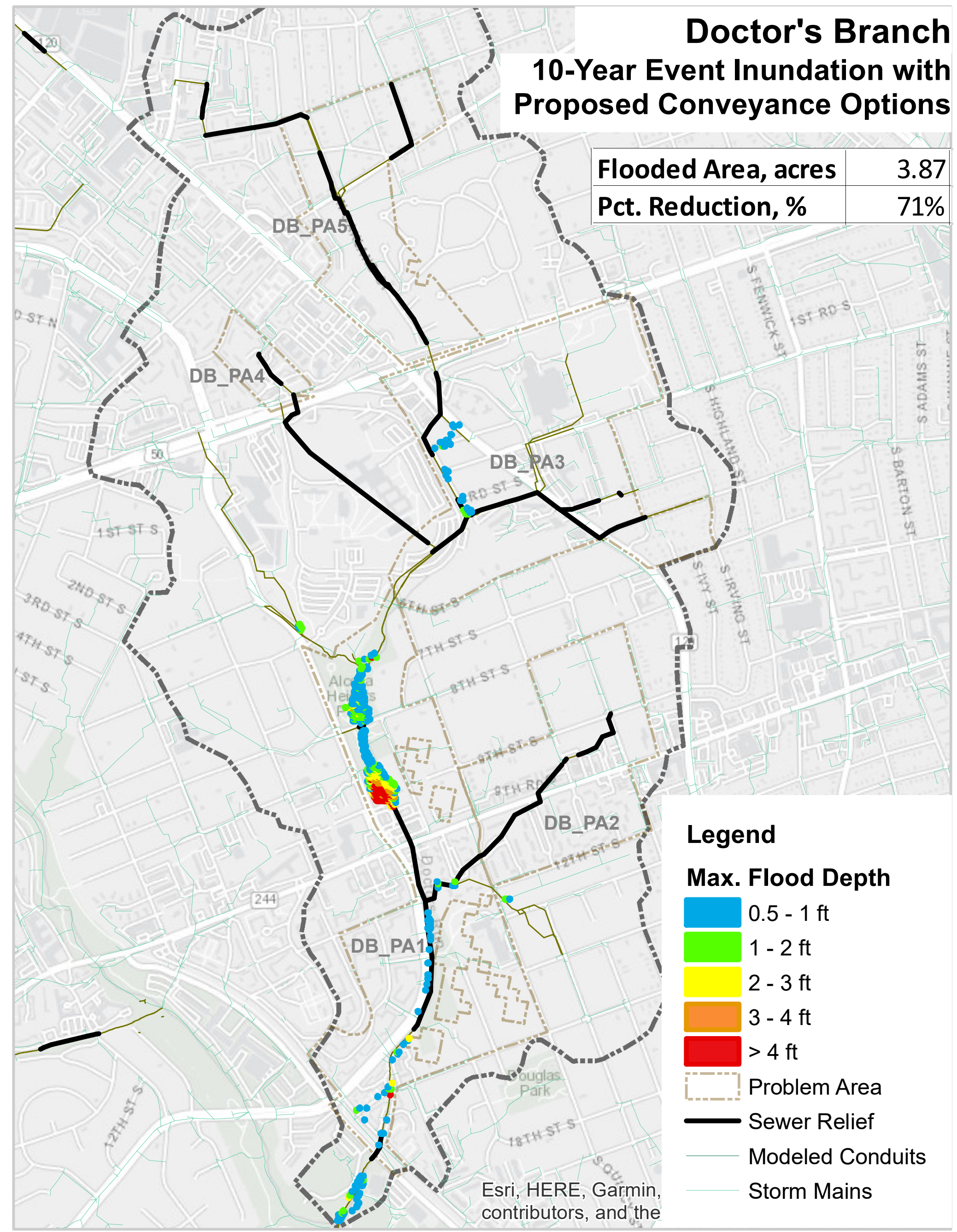
Baseline Inundation Conditions for 10-year storm (5.16 inches in 24 hours)
Projected 2070 Inundation Conditions for 10-year storm (5.81 inches in 24 hours)
N
S
W
Spout Run
WILSON BLVD
N RANDOLPH ST
N PERSHING DR
WASHINGTON BLVD
Lower Long Branch
N GEORGE MASON DR
N CARLIN SPRINGS RD
S FILLMORE ST
2ND ST S
Arlington Forest Branch
Doctor's Branch
Four Mile Run - Upper Mainstem2
Upper Long Branch
S GEORGE MASON DR
Arlington Branch
S WALTER REED DR
COLUMBIA PIKE
Nauck Branch
S FOUR MILE RUN DR
Four Mile Run - Middle Mainstem
Bailey's Branch
S UHLE ST
S COURTHOUSE RD
National Mall
Four Mile
Doctor's Branch Watershed Flooding
(Riverine and Interior Flood Modeling Results)
Flood Depth
.5-1 ft
1-2 ft
2-3 ft
3-4 ft
>4 ft
FEMA 100-year Effective Floodplain
Watersheds
Doctor's Branch Watershed
County Boundary
Jacobs
0 500 1,000 2,000 Feet
The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events

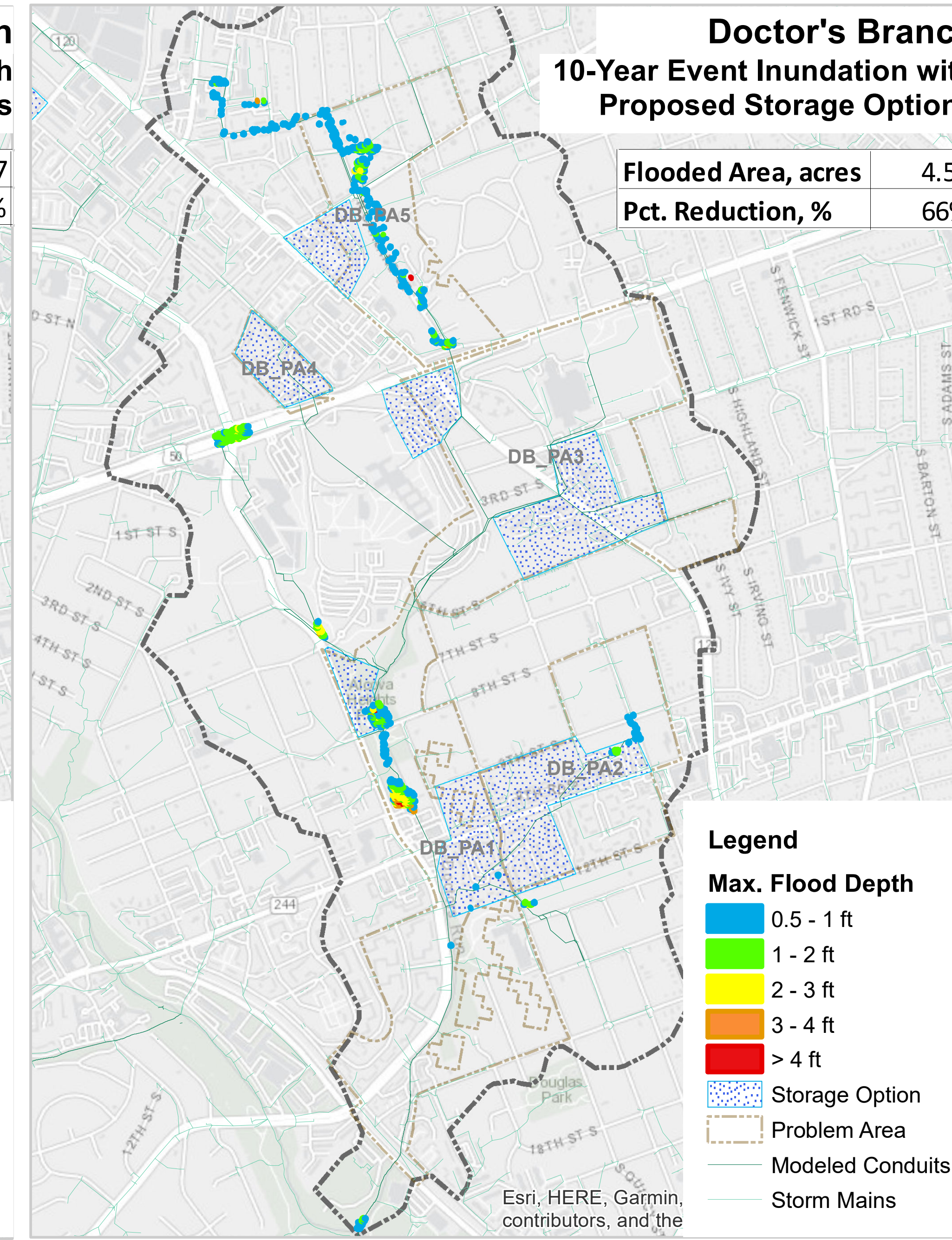


Baseline Inundation Conditions for 100-year storm (8.48 inches in 24 hours)
Projected 2070 Inundation Conditions for 100-year storm (9.57 inches in 24 hours)
WILSON BLVD
N RANDOLPH ST
N GEORGE MASON DR
N CARLIN SPRINGS RD
N PERSHING DR
WASHINGTON BLVD
Lower Long Branch
S FILLMORE ST
2ND ST S
Arlington Forest Branch
Doctor's Branch
Four Mile Run - Upper Mainstem2
S GEORGE MASON DR
Arlington Branch
Upper Long Branch
COLUMBIA PIKE
S WALTER REED DR
Nauck Branch
S FOUR MILE RUN DR
Spout Run
S COURTHOUSE RD
S UHLE ST
Four Mile Run - Middle Mainstem
Bailey's Branch
Four Mile
National Mall
0 500 1,000 2,000 Feet
Doctor's Branch Watershed Flooding
(Riverine and Interior Flood Modeling Results)
Flood Depth
.5-1 ft
1-2 ft
2-3 ft
3-4 ft
>4 ft
FEMA 100-year Effective Floodplain
Watersheds
Doctor's Branch Watershed
County Boundary
Jacobs
The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events

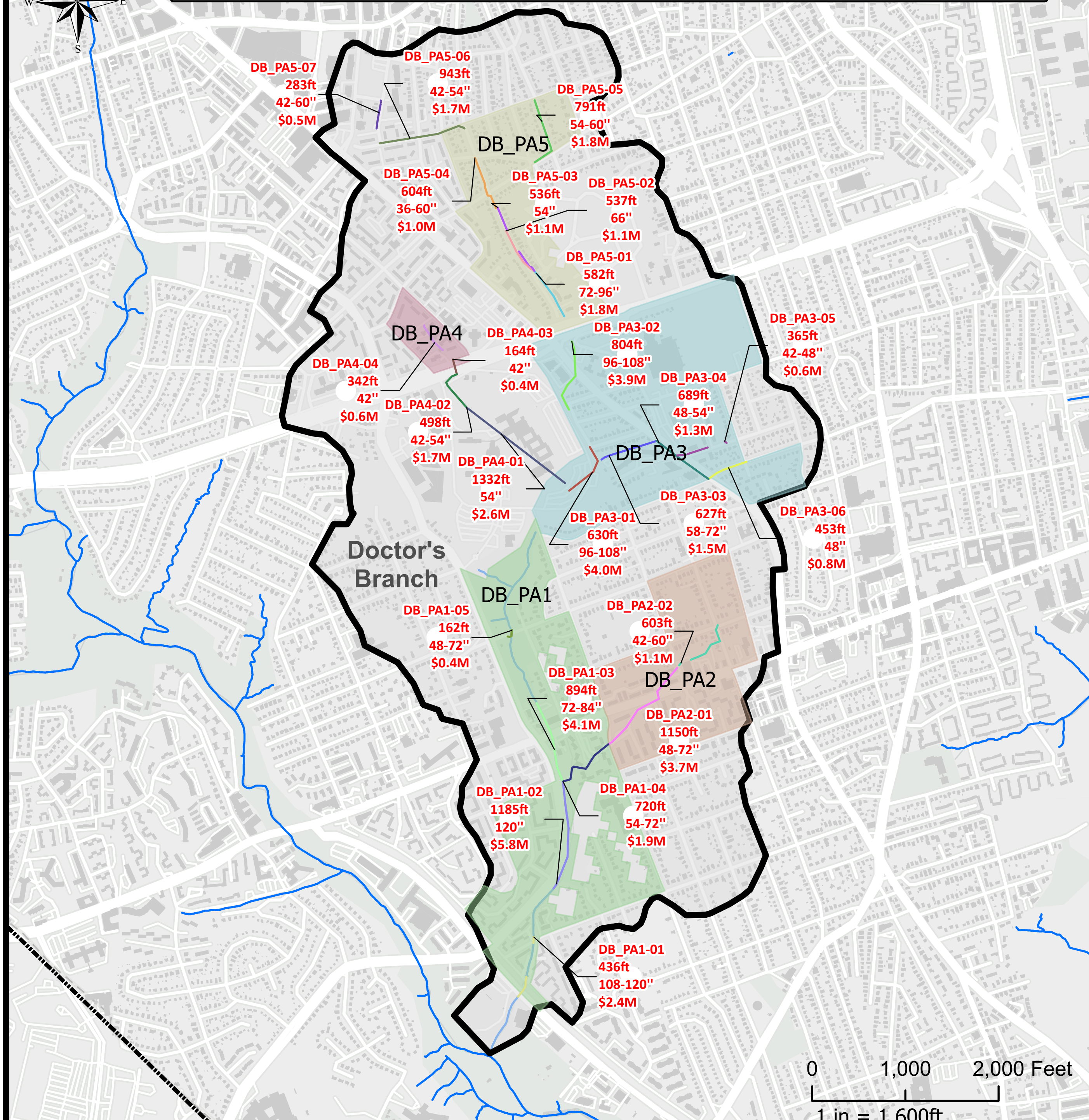
# Baseline, Conveyance Solutions and Storage Solutions



# Individual Conveyance Concepts with Size and Estimated Capital Cost




| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| DB_PA1-01 | 436 | 108-120" | $2.4 |
| DB_PA1-02 | 1,185 | 120" | $5.8 |
| DB_PA1-03 | 894 | 72-84" | $4.1 |
| DB_PA1-04 | 720 | 54-72" | $1.9 |
| DB_PA1-05 | 162 | 48-72" | $0.4 |
| DB_PA2-01 | 1,150 | 48-72" | $3.7 |
| DB_PA2-02 | 603 | 42-60" | $1.1 |
| DB_PA3-01 | 630 | 96-108" | $4.0 |
| DB_PA3-02 | 804 | 96-108" | $3.9 |
| DB_PA3-03 | 627 | 58-72" | $1.5 |
| DB_PA3-04 | 689 | 48-54" | $1.3 |
| DB_PA3-05 | 365 | 42-48" | $0.6 |
| DB_PA3-06 | 453 | 48" | $0.8 |
| DB_PA4-01 | 1,332 | 54" | $2.6 |
| DB_PA4-02 | 498 | 42-54" | $1.4 |
| DB_PA4-03 | 164 | 42" | $0.4 |
| DB_PA4-04 | 342 | 42" | $0.6 |
| DB_PA5-01 | 582 | 72-96" | $1.8 |
| DB_PA5-02 | 537 | 66" | $1.1 |
| DB_PA5-03 | 536 | 54" | $1.1 |
| DB_PA5-04 | 604 | 36-60" | $1.0 |
| DB_PA5-05 | 791 | 54-60" | $1.8 |
| DB_PA5-06 | 943 | 42-54" | $1.7 |
| DB_PA5-07 | 283 | 42-60" | $0.5 |

## LEGEND

Conveyance Concepts Label:
(in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

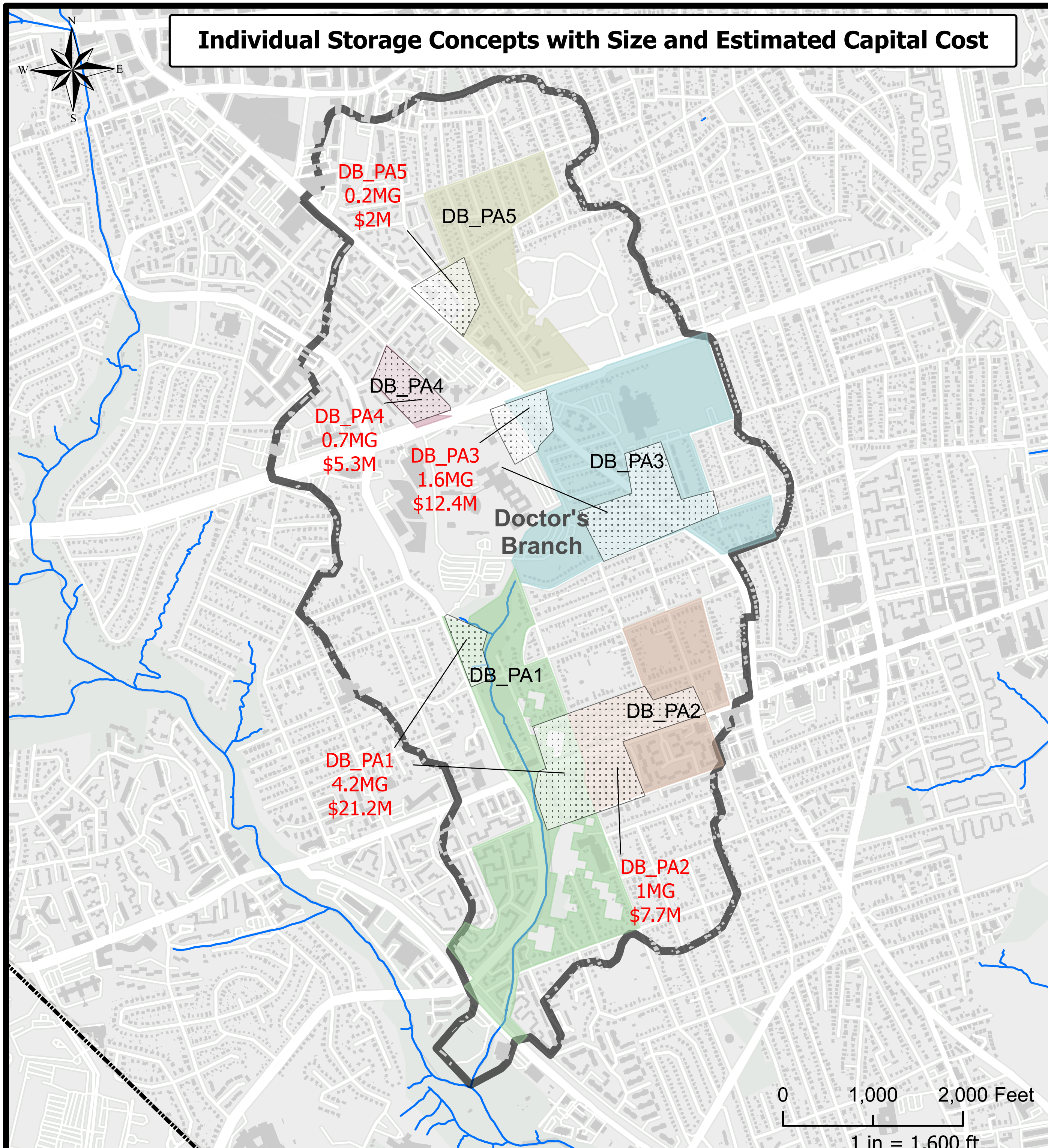
Data:
Problem Areas
Conveyance Concept Pipes

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON
VIRGINIA

**Conveyance Concepts: Doctor's Branch**

# Individual Storage Concepts with Size and Estimated Capital Cost




| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| DB_PA1 | 4.2 | Mixed | 21.2 |
| DB_PA2 | 1.0 | Mixed | 7.7 |
| DB_PA3 | 1.6 | Mixed | 12.4 |
| DB_PA4 | 0.7 | Mixed | 5.3 |
| DB_PA5 | 0.2 | Mixed | 2.0 |

## LEGEND

Storage Concepts Label:
(in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Storage Concepts: Doctor's Branch**

# Four Mile Run Lower Mainstem

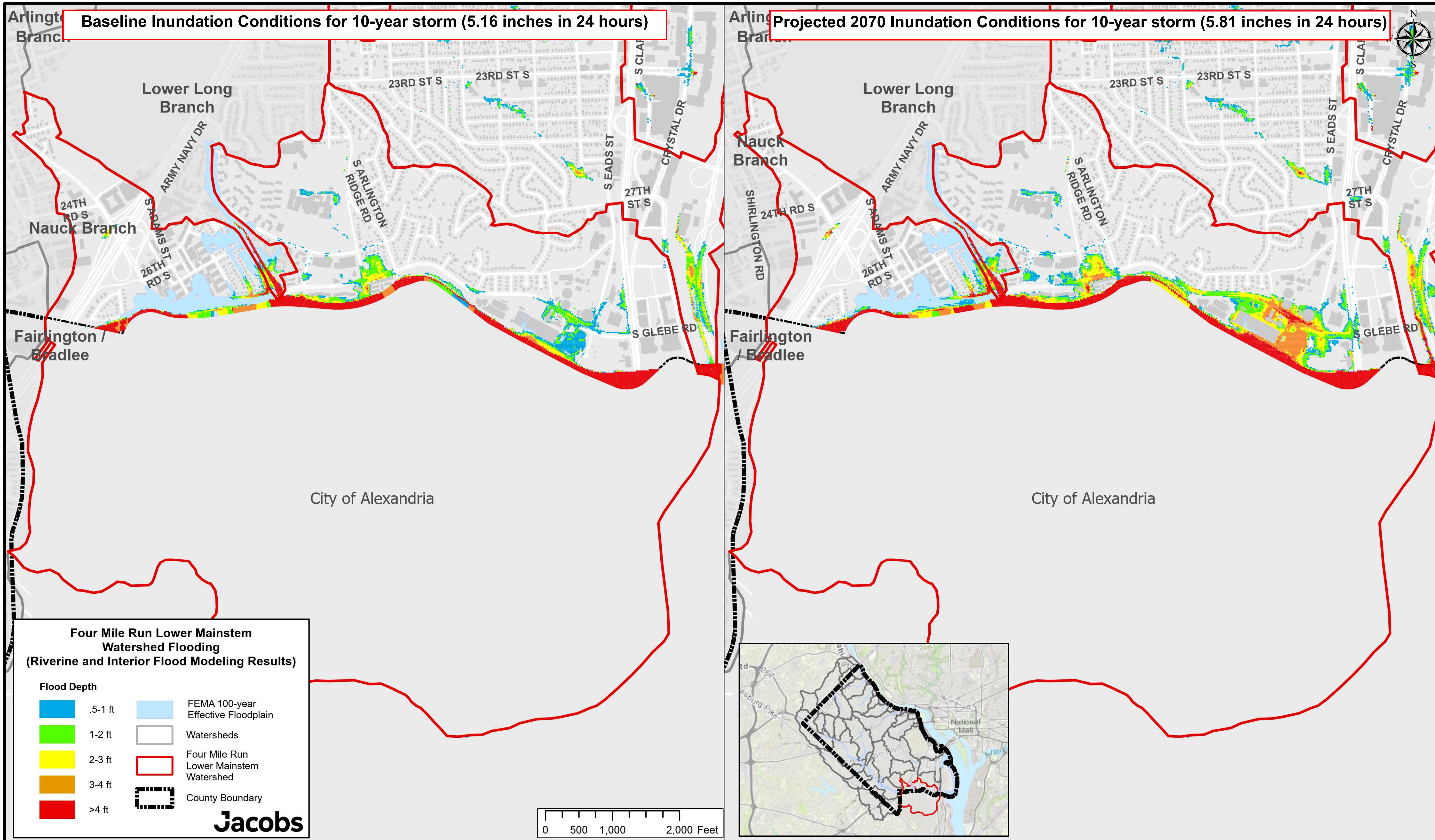
**Baseline and Projected 2070 Inundation Conditions for 10-year storm**

**Baseline and Projected 2070 Inundation Conditions for 100-year storm**

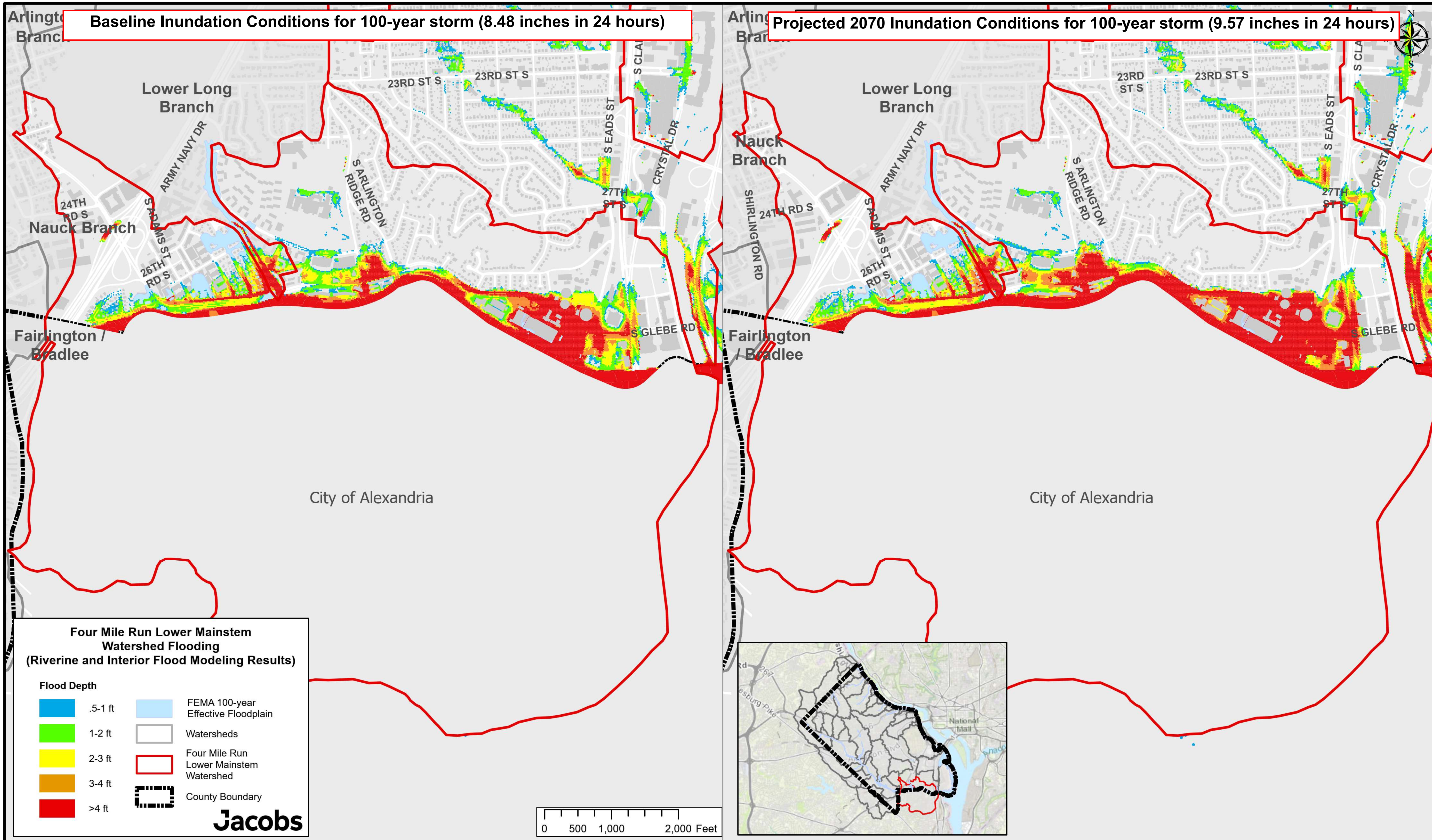
**10-year event Inundation with Proposed Conveyance or Storage Concepts**

**Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost**

ARLINGTON
VIRGINIA

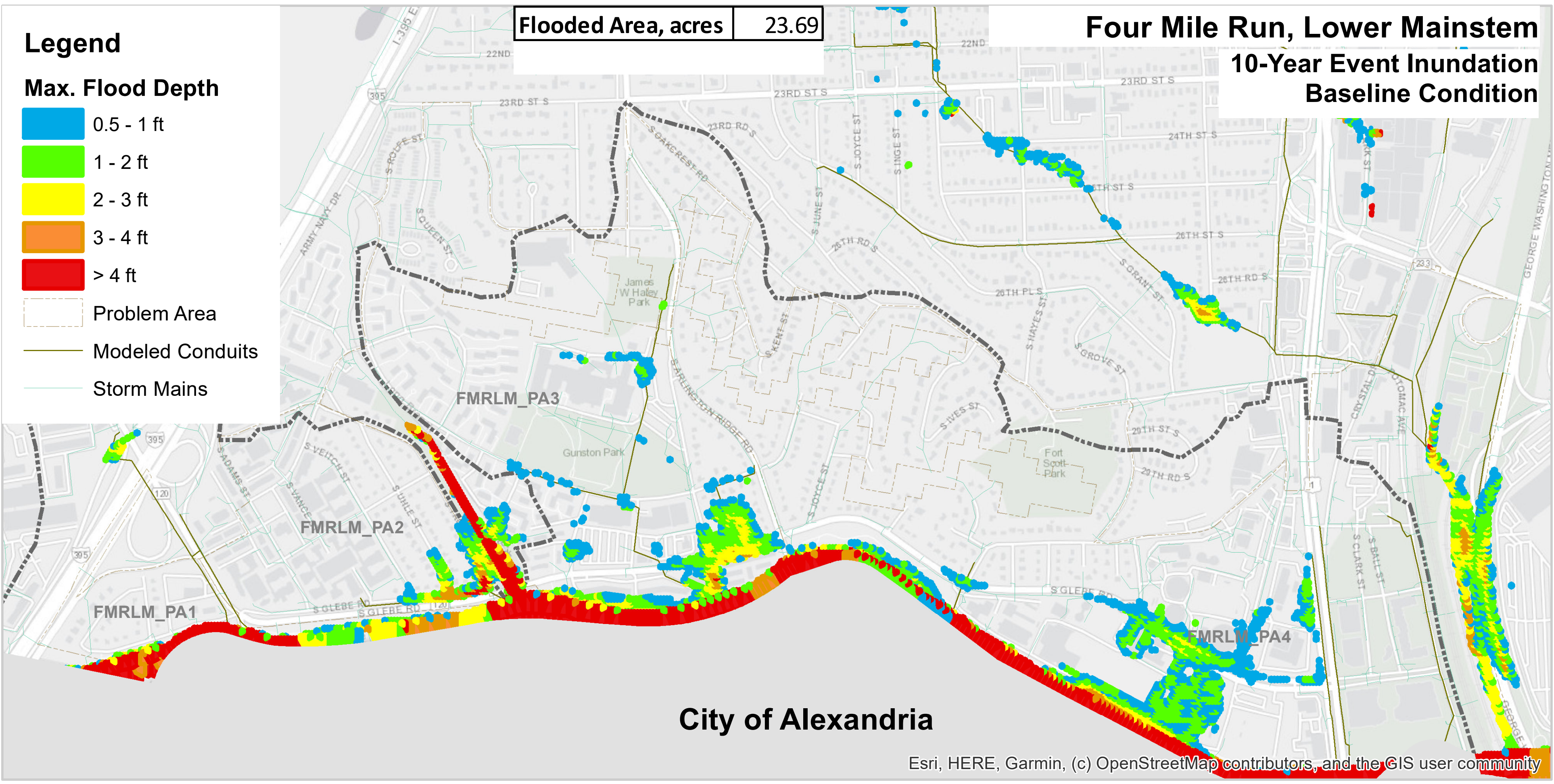


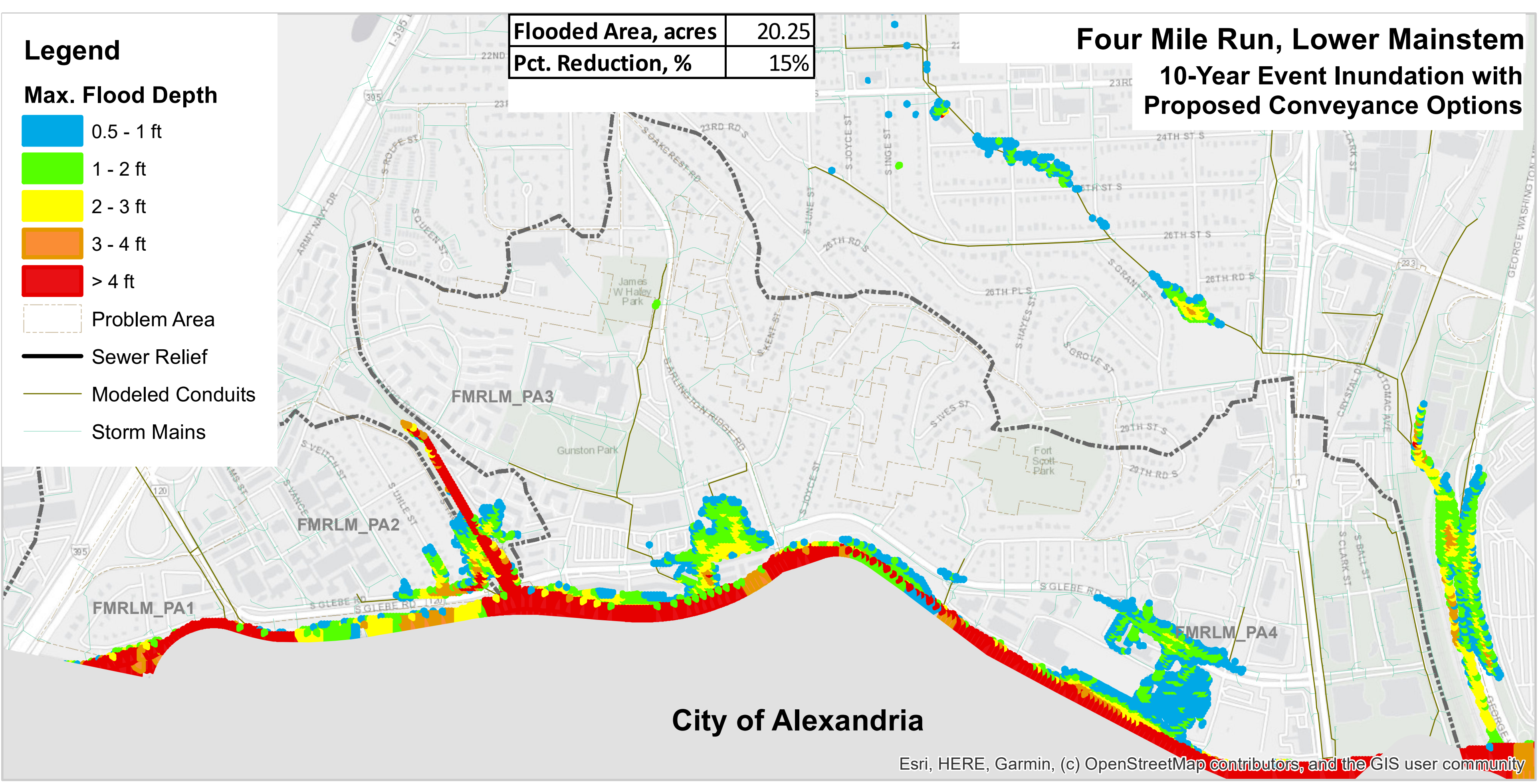

*The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events*

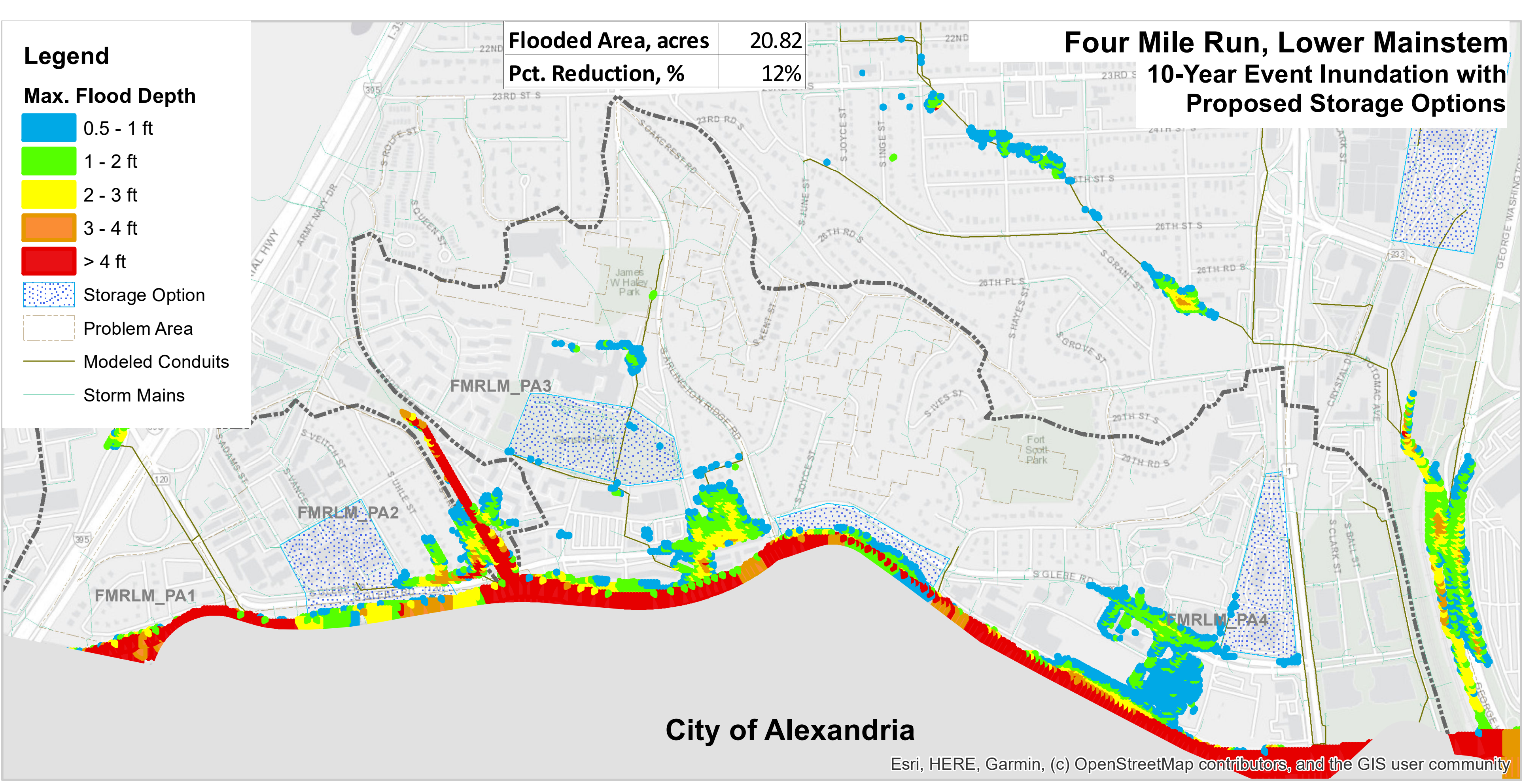



*The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events*

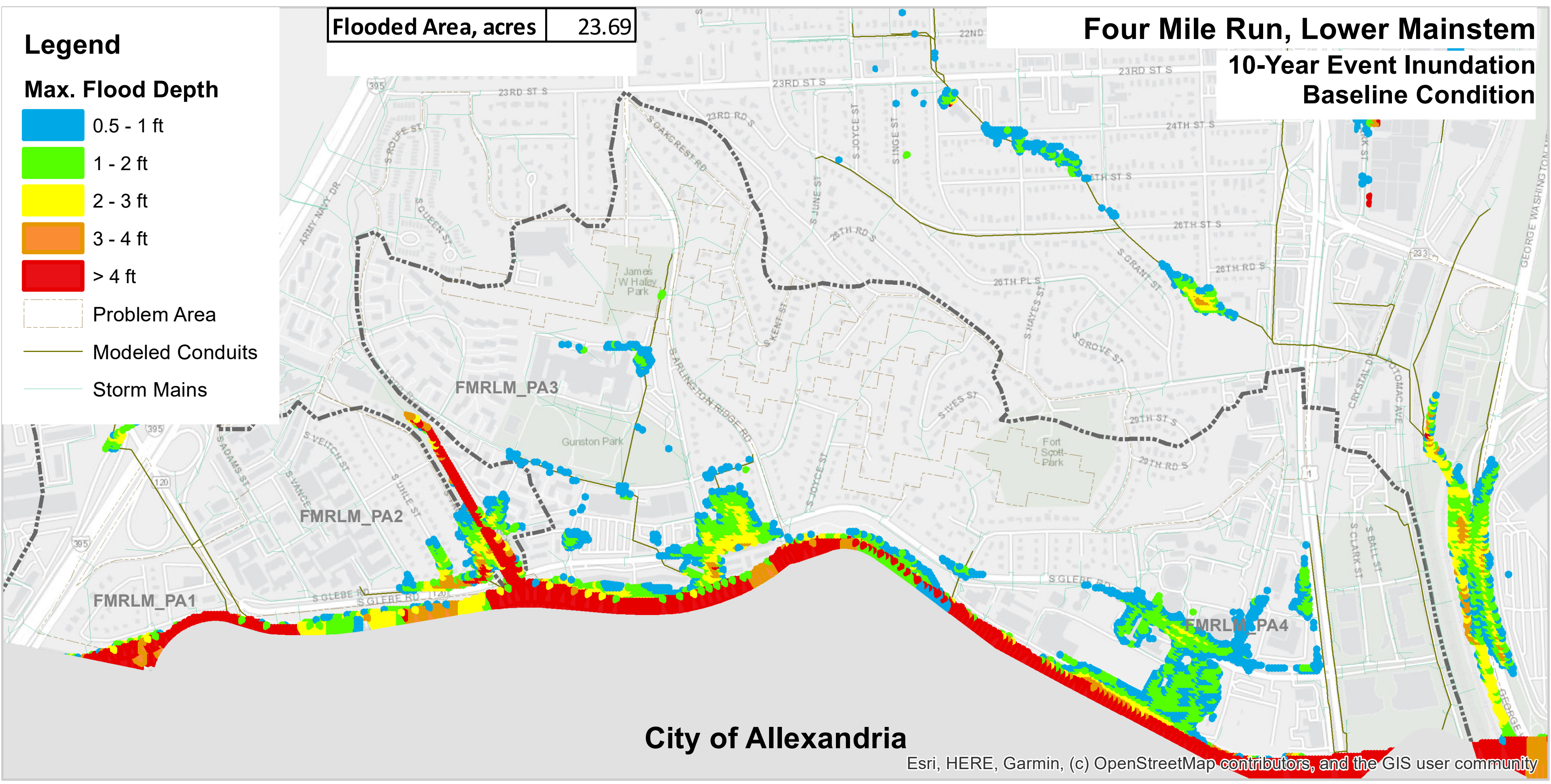
# Baseline, Conveyance Solutions, and Storage Solutions

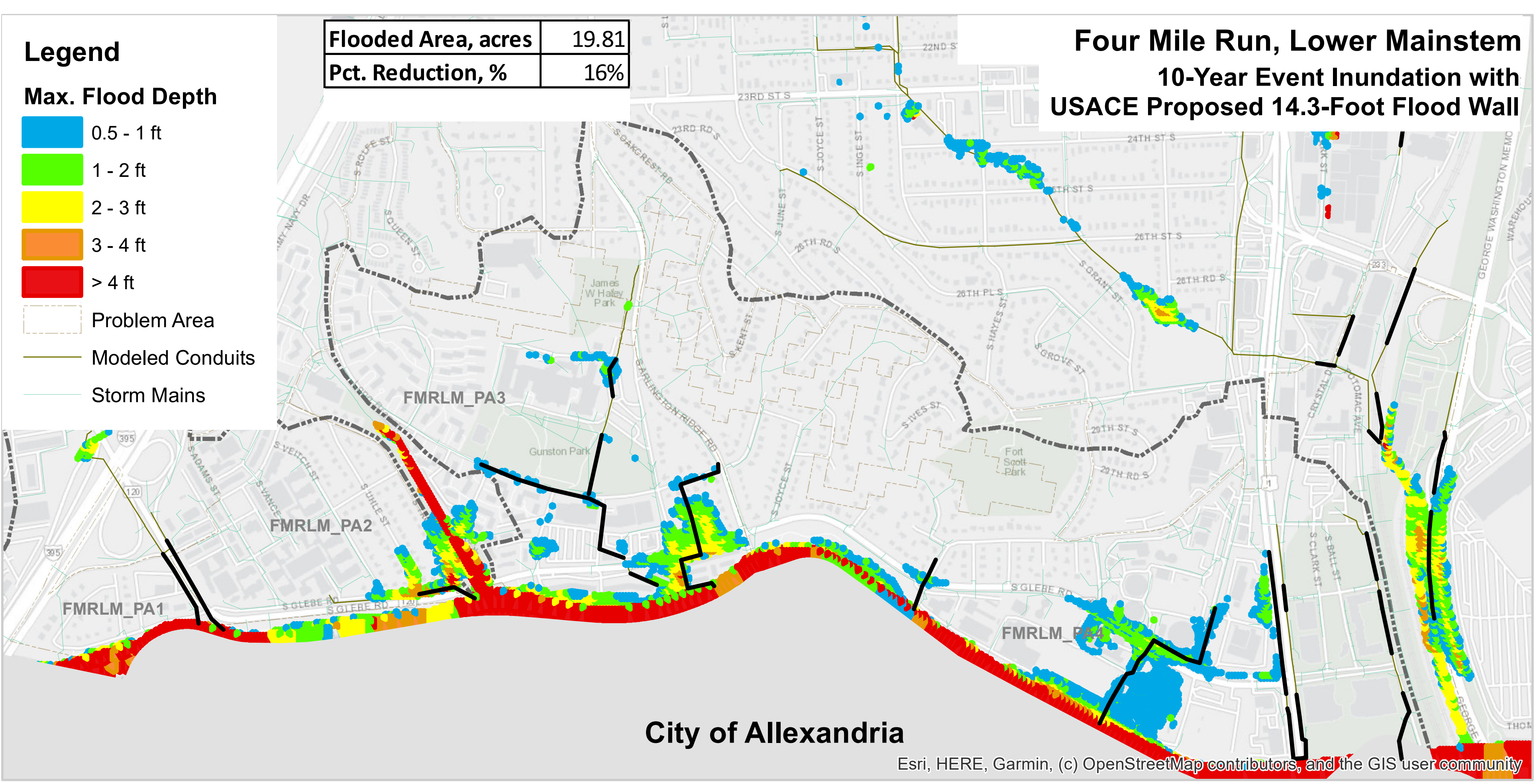


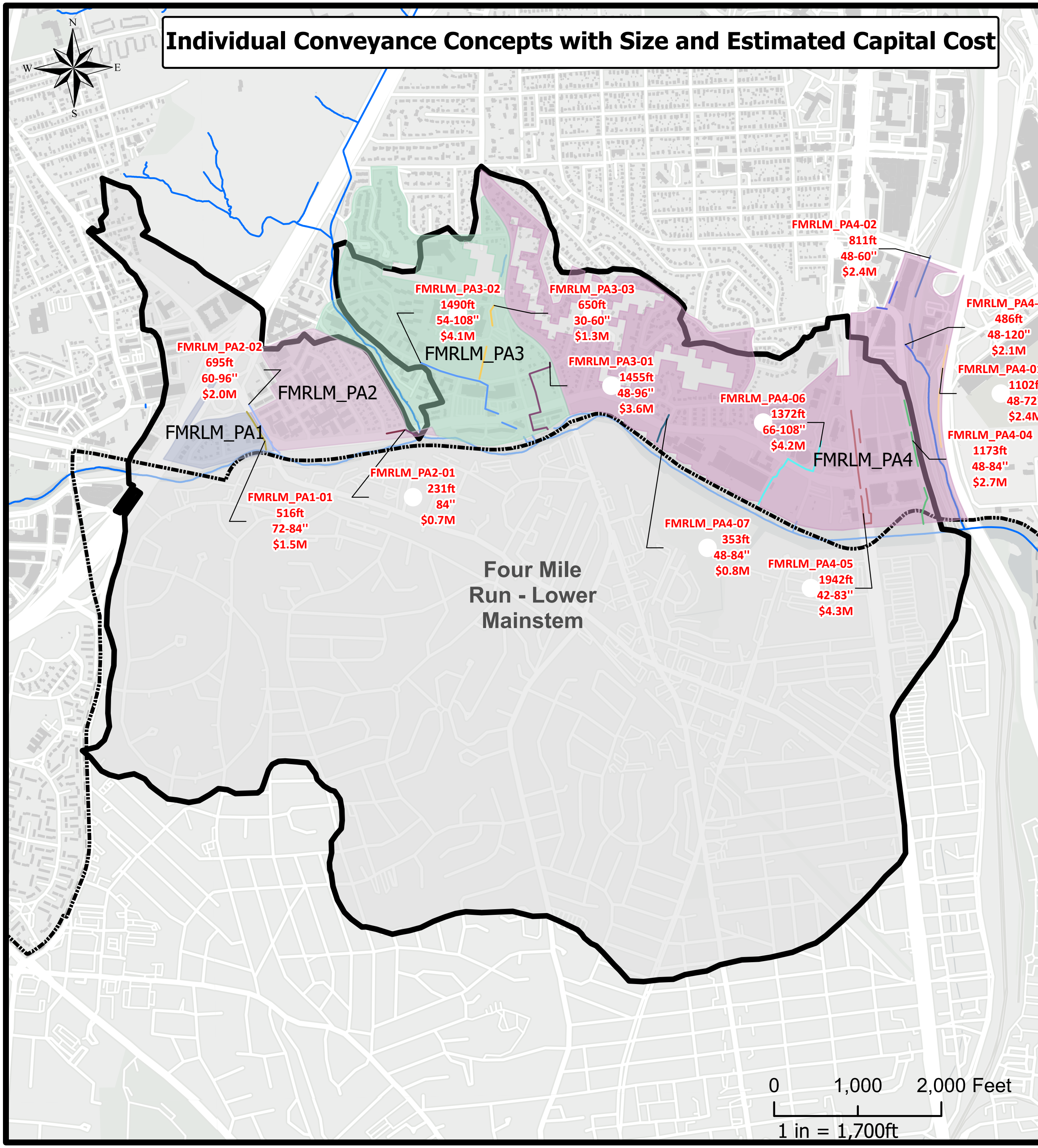
# Baseline and USACE Proposed Mitigation with 14.3-Foot Flood Wall



# Individual Conveyance Concepts with Size and Estimated Capital Cost

| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| FMRLM_PA1-01 | 516 | 72-84" | $1.5 |
| FMRLM_PA2-01 | 231 | 84" | $0.7 |
| FMRLM_PA2-02 | 695 | 60-96" | $2.0 |
| FMRLM_PA3-01 | 1,455 | 48-96" | $3.6 |
| FMRLM_PA3-02 | 1,490 | 54-108" | $4.1 |
| FMRLM_PA3-03 | 650 | 30-60" | $1.3 |
| FMRLM_PA4-01 | 1,102 | 48-72" | $2.4 |
| FMRLM_PA4-02 | 811 | 48-60" | $2.4 |
| FMRLM_PA4-03 | 486 | 48-120" | $2.1 |
| FMRLM_PA4-04 | 1,173 | 48-84" | $2.7 |
| FMRLM_PA4-05 | 1,942 | 42-83" | $4.3 |
| FMRLM_PA4-06 | 1,372 | 66-108" | $4.2 |
| FMRLM_PA4-07 | 353 | 48-84" | $0.8 |




## LEGEND

Conveyance Concepts Label:
(in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

Data:
Problem Areas
Conveyance Concept Pipes

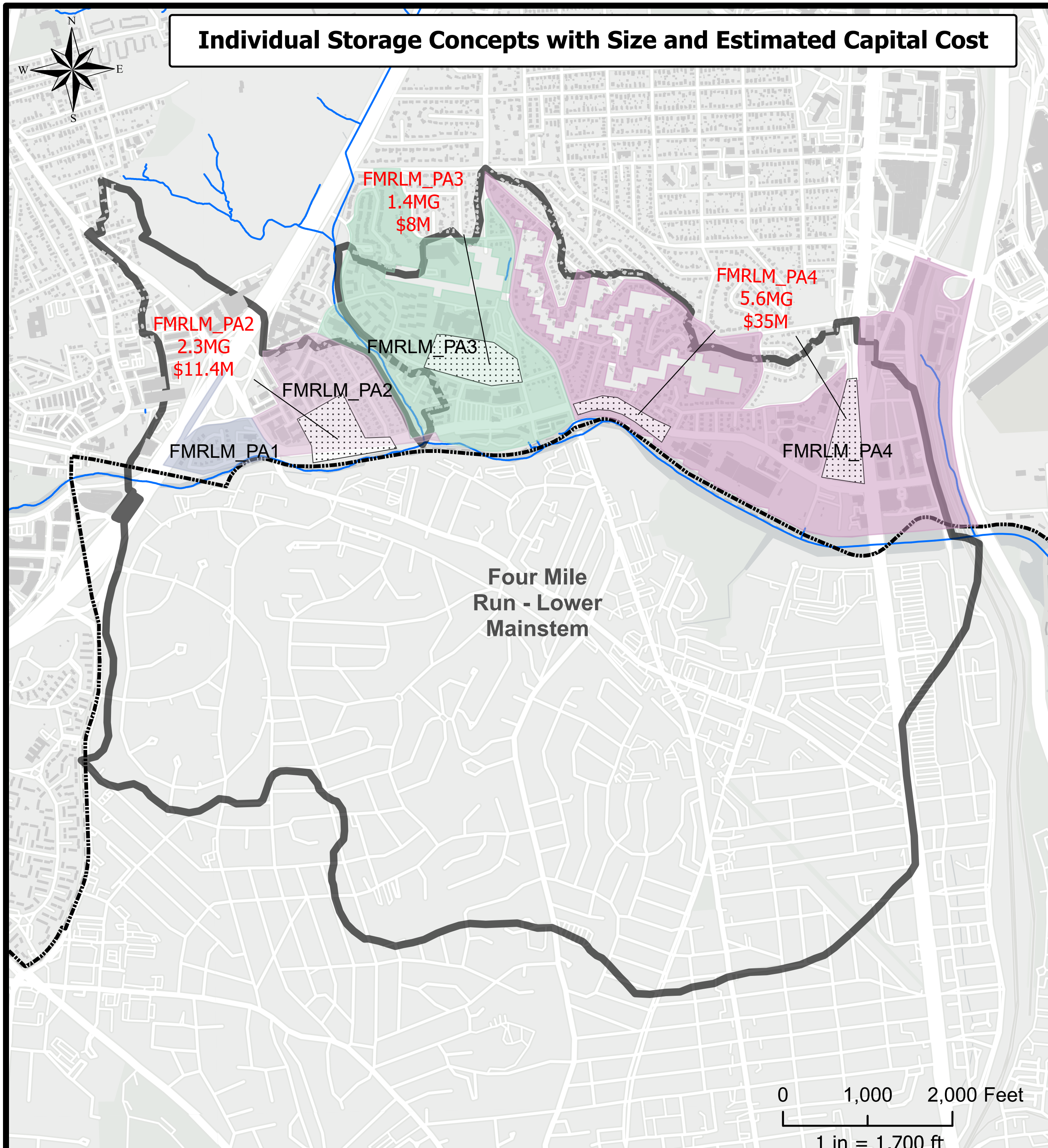
Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Conveyance Concepts: Four Mile Run, Lower Mainstem**

# Individual Storage Concepts with Size and Estimated Capital Cost

| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| FMRLM_PA2 | 2.3 | Mixed | 11.4 |
| FMRLM_PA3 | 1.4 | Mixed | 8.0 |
| FMRLM_PA4 | 5.6 | Mixed | 35.0 |




## LEGEND

Storage Concepts Label: (in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Storage Concepts: Four Mile Run Lower Mainstem**

# Lubber Run

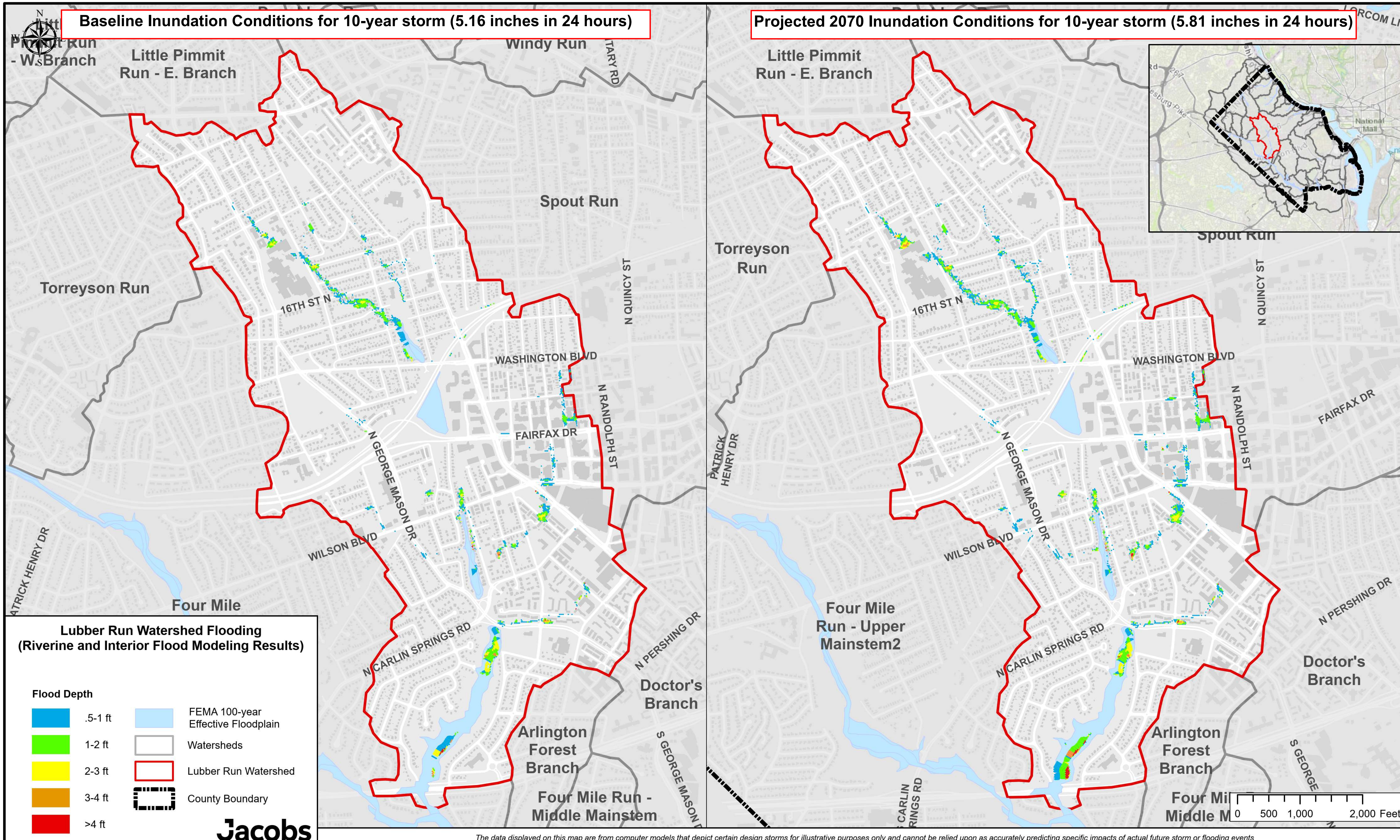
## Baseline and Projected 2070 Inundation Conditions for 10-year storm

## Baseline and Projected 2070 Inundation Conditions for 100-year storm

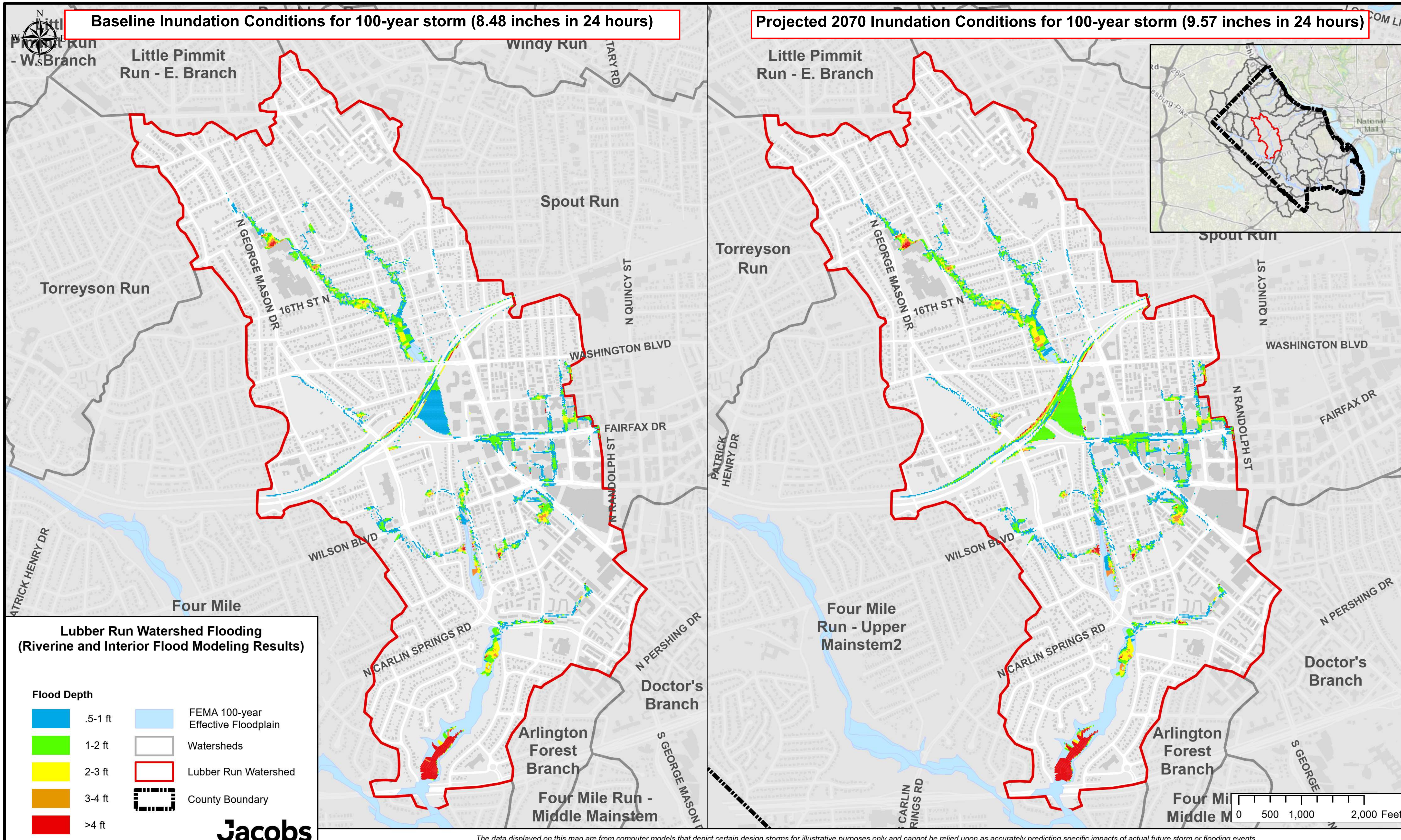
## 10-year event Inundation with Proposed Conveyance or Storage Concepts

## Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost

Note: the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus. The timing of that project did not allow the improvements to be included in the RAMP modeling.

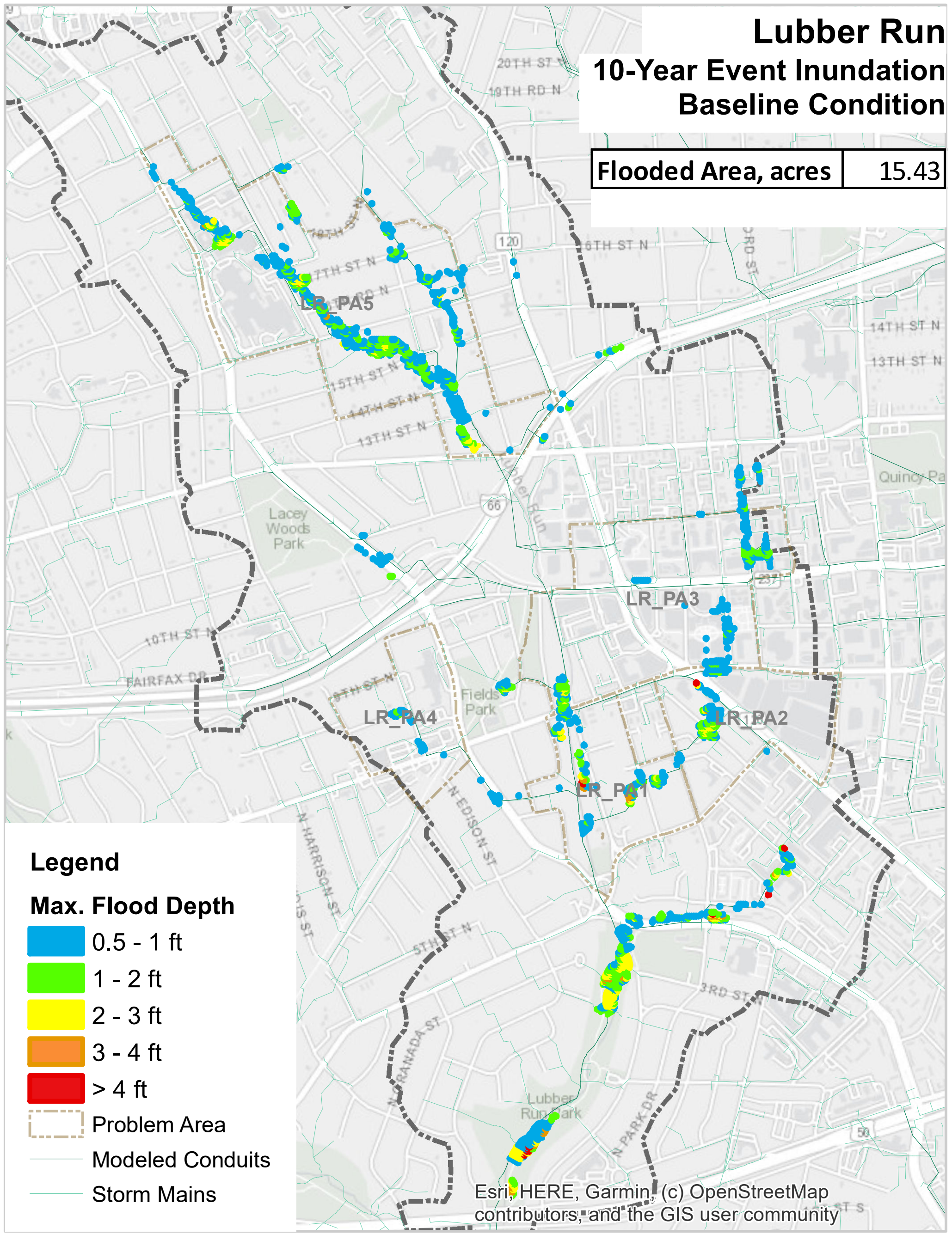


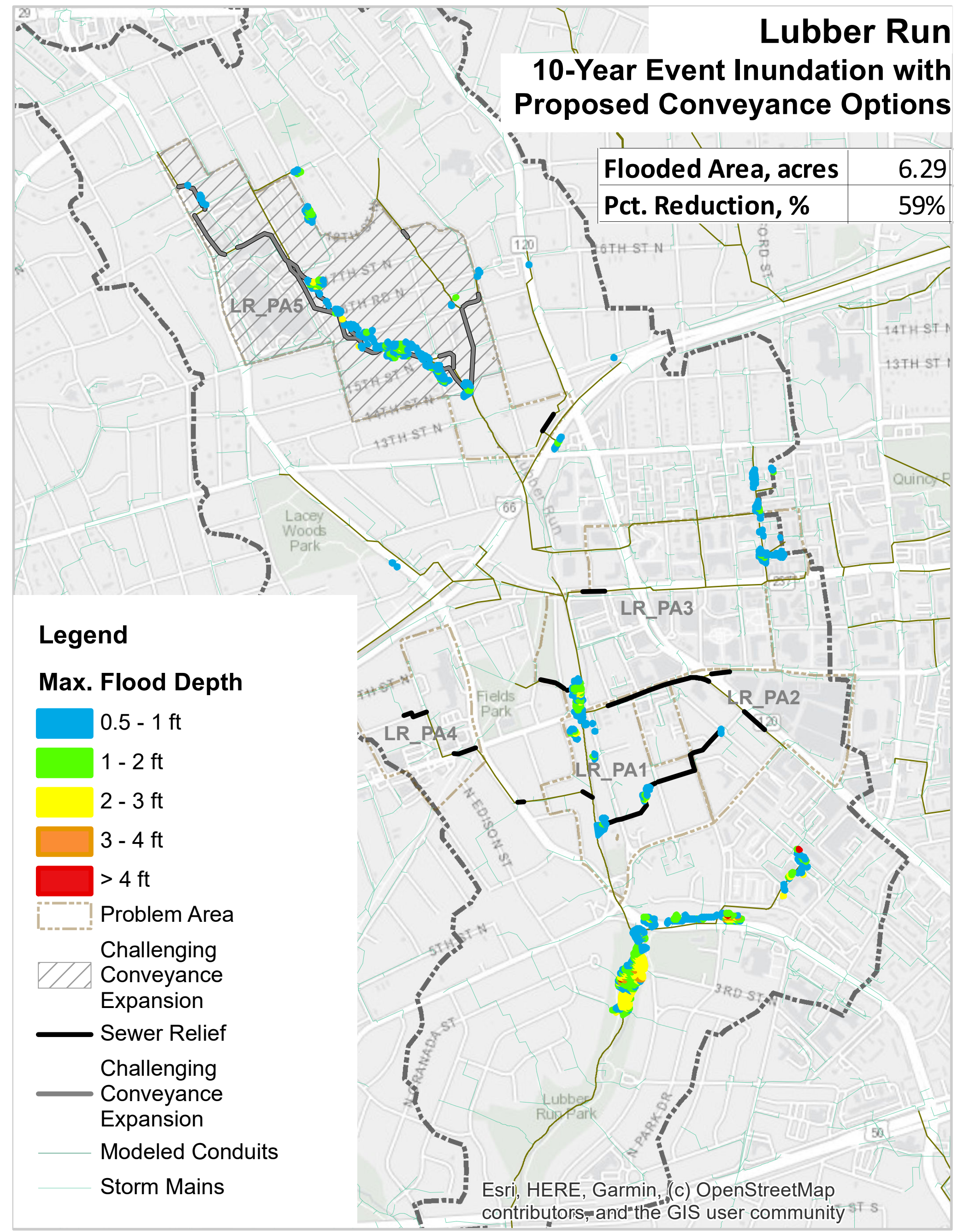

Note: the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus. The timing of that project did not allow the improvements to be included in the RAMP modeling.

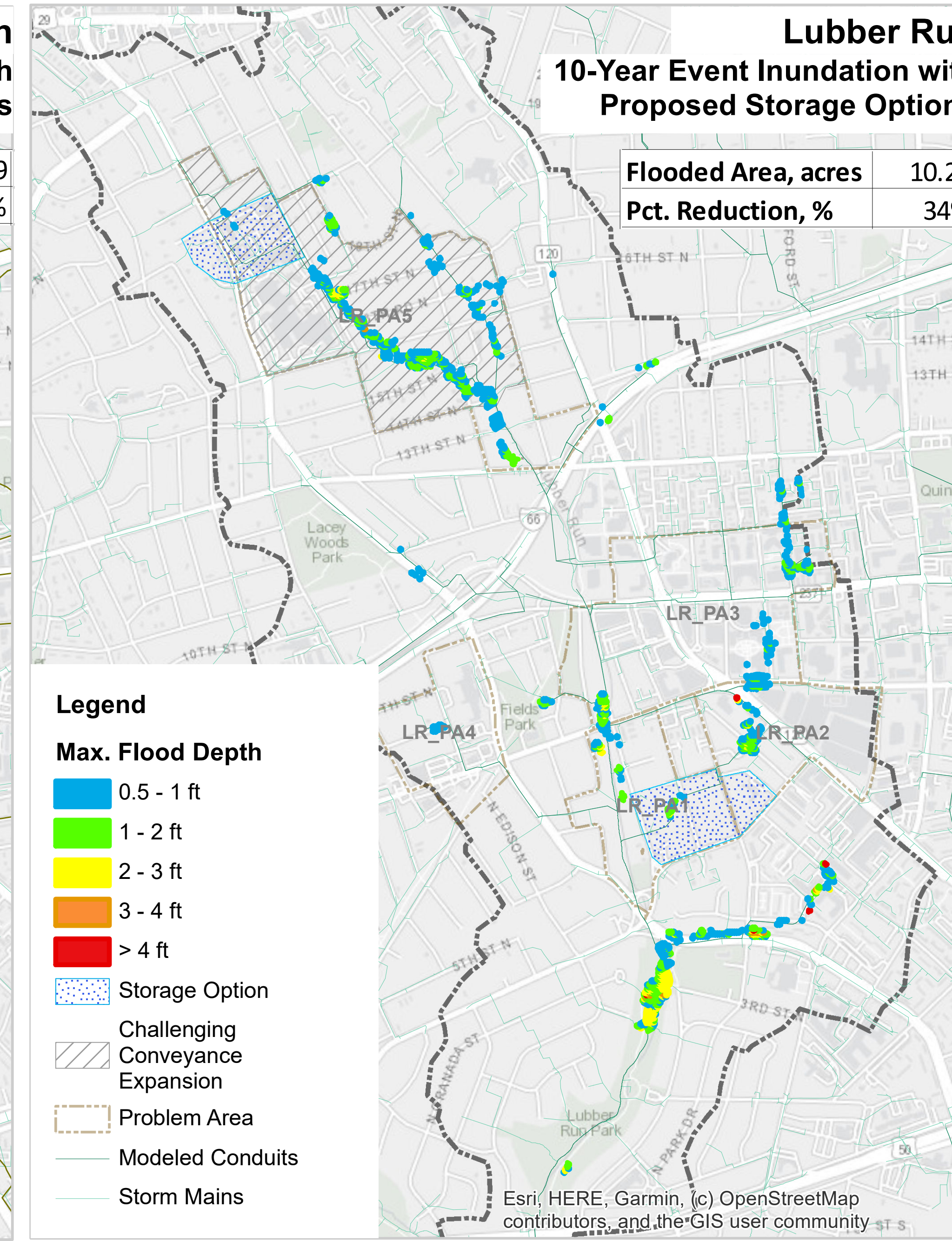



Note: the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus. The timing of that project did not allow the improvements to be included in the RAMP modeling.

# Baseline, Conveyance Solutions and Storage Solutions

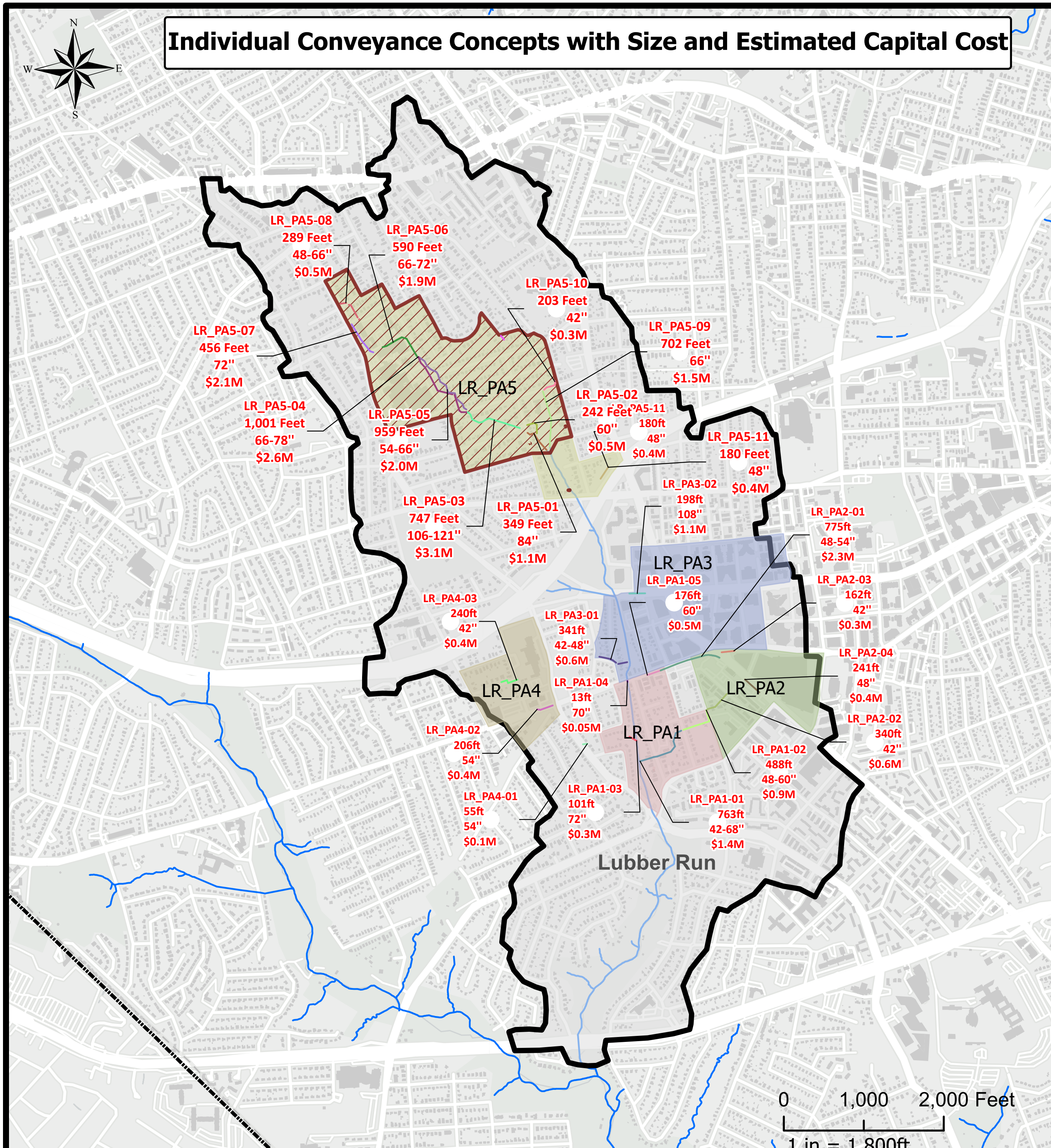



Note: the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus. The timing of that project did not allow the improvements to be included in the RAMP modeling.

# Individual Conveyance Concepts with Size and Estimated Capital Cost




| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| LR_PA1-01 | 763 | 42-68" | $1.4 |
| LR_PA1-02 | 488 | 48-60" | $0.9 |
| LR_PA1-03 | 101 | 72" | $0.3 |
| LR_PA1-04 | 13 | 70" | $0.1 |
| LR_PA1-05 | 176 | 60" | $0.5 |
| LR_PA2-01 | 775 | 48-54" | $2.3 |
| LR_PA2-02 | 340 | 42" | $0.6 |
| LR_PA2-03 | 162 | 42" | $0.3 |
| LR_PA2-04 | 241 | 48" | $0.4 |
| LR_PA3-01 | 341 | 42-48" | $0.6 |
| LR_PA3-02 | 198 | 108" | $1.1 |
| LR_PA4-01 | 55 | 54" | $0.1 |
| LR_PA4-02 | 206 | 54" | $0.4 |
| LR_PA4-03 | 240 | 42" | $0.4 |
| LR_PA5-01 | 349 | 84" | $1.1 |
| LR_PA5-02 | 242 | 60" | $0.5 |
| LR_PA5-03 | 747 | 106-121" | $3.1 |
| LR_PA5-04 | 1,001 | 66-78" | $2.6 |
| LR_PA5-05 | 959 | 54-66" | $2.0 |
| LR_PA5-06 | 590 | 66-72" | $1.9 |
| LR_PA5-07 | 456 | 72" | $2.1 |
| LR_PA5-08 | 289 | 48-66" | $0.5 |
| LR_PA5-09 | 702 | 66" | $1.5 |
| LR_PA5-10 | 203 | 42" | $0.3 |
| LR_PA5-11 | 180 | 48" | $0.4 |
| LR_PA5-12 | 65 | 48-54" | $0.1 |

Note: the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus. The timing of that project did not allow the improvements to be included in the RAMP modeling.

## LEGEND

Conveyance Concepts Label: (in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

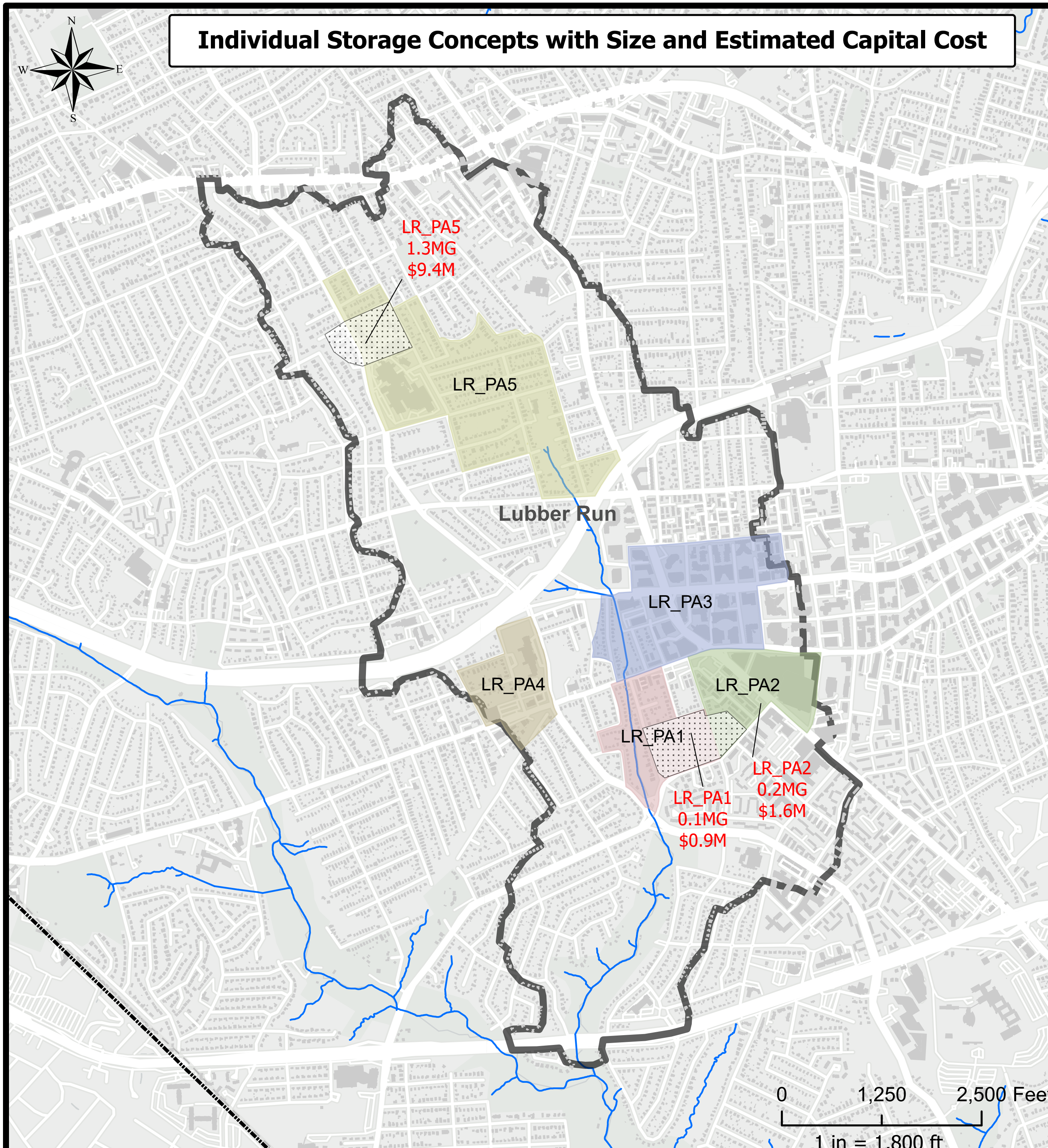
Basemap:
- Watershed
- County Boundary
- Buildings
- Hydrology

Data:
- Problem Areas
- Conveyance Concept Pipes
- Challenging Conveyance Expansion

ARLINGTON VIRGINIA

**Conveyance Concepts: Lubber Run**

# Individual Storage Concepts with Size and Estimated Capital Cost




| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| LR_PA1 | 0.1 | Mixed | 0.9 |
| LR_PA2 | 0.2 | Mixed | 1.6 |
| LR_PA5 | 1.3 | Mixed | 9.4 |

Note: the Virginia Hospital Center has recently constructed significant stormwater improvements on their campus. The timing of that project did not allow the improvements to be included in the RAMP modeling.

## LEGEND

Storage Concepts Label:
(in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Storage Concepts: Lubber Run**

# Roaches Run

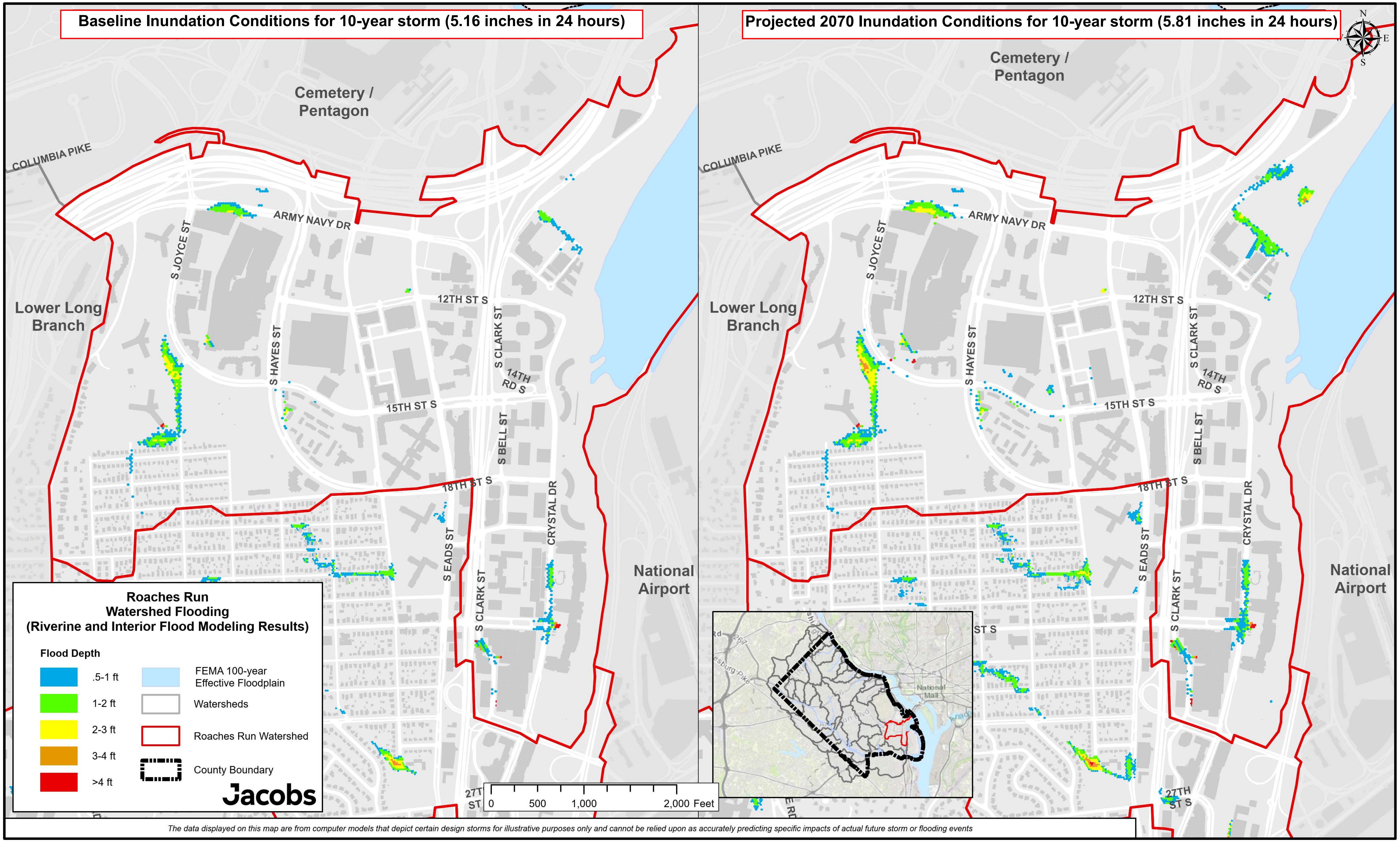
**Baseline and Projected 2070 Inundation Conditions for 10-year storm**

**Baseline and Projected 2070 Inundation Conditions for 100-year storm**

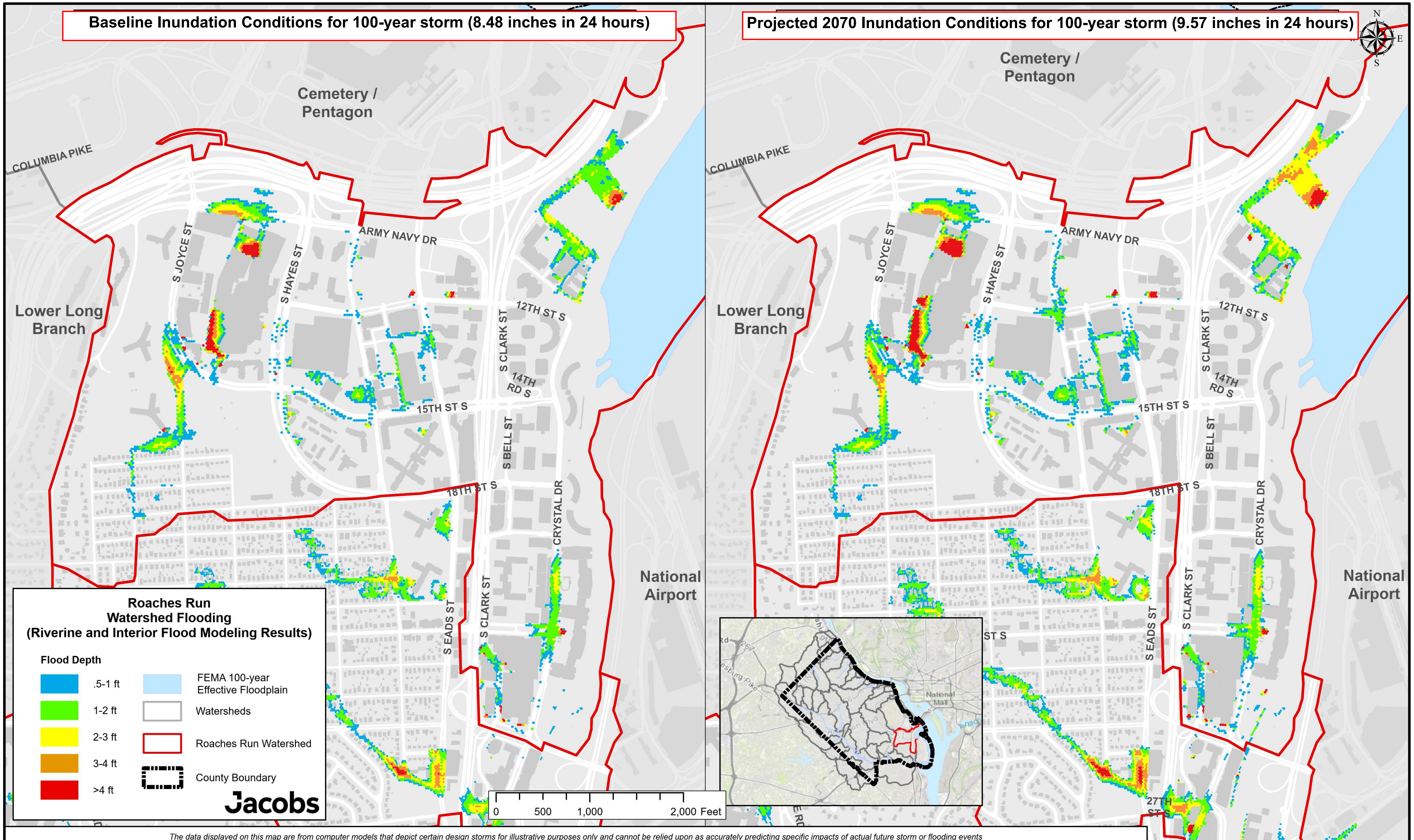
**10-year event Inundation with Proposed Conveyance or Storage Concepts**

**Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost**

ARLINGTON
VIRGINIA

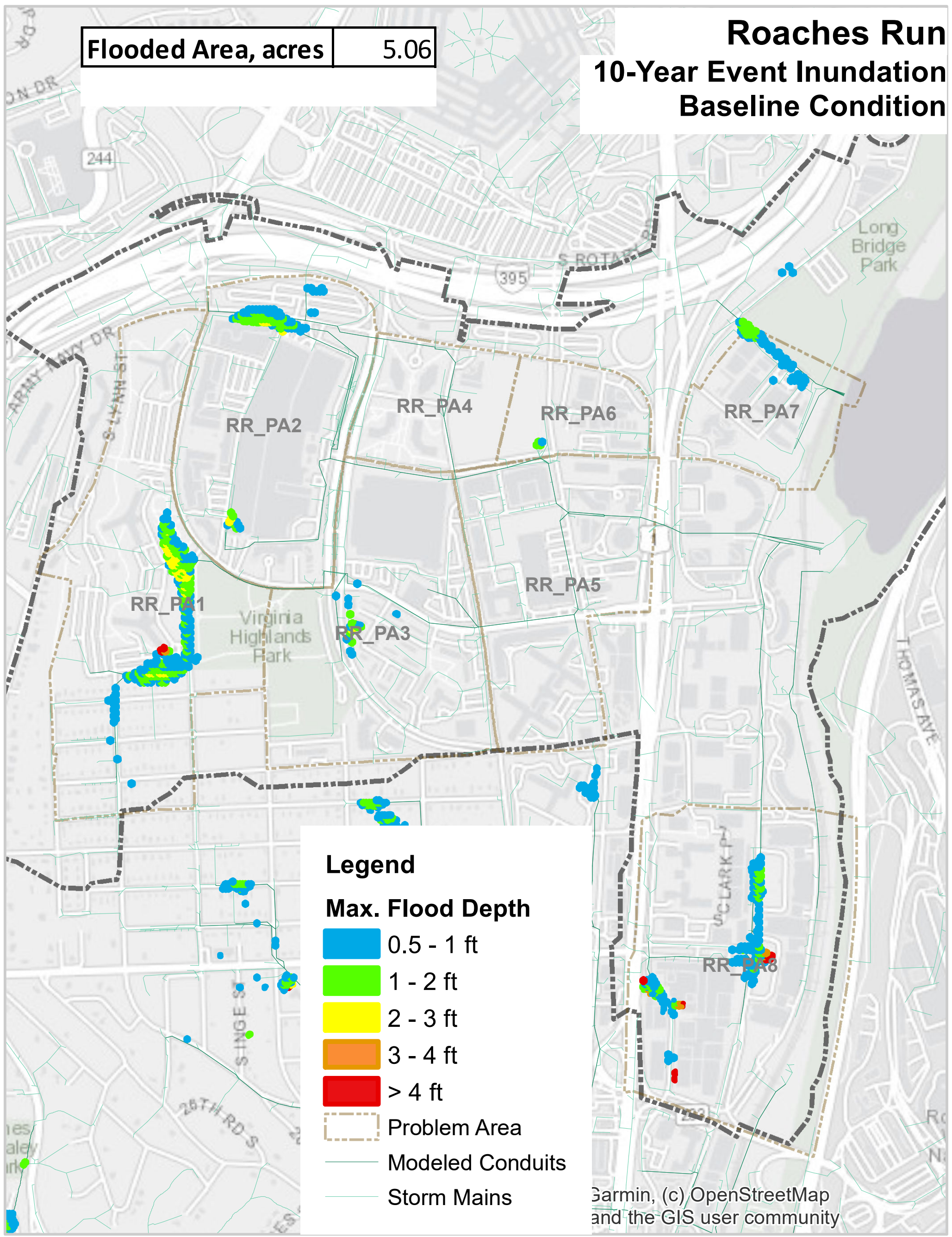


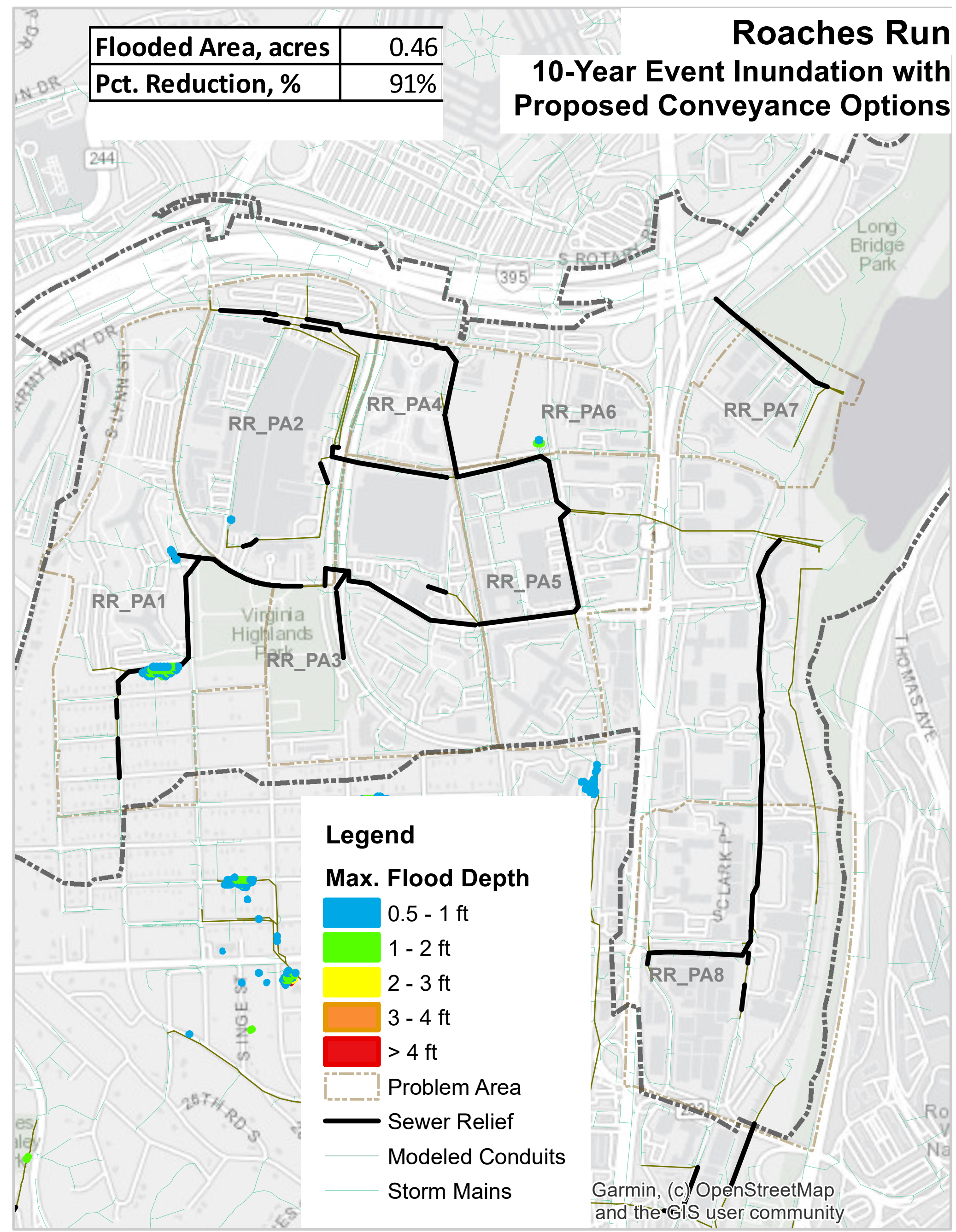
Baseline Inundation Conditions for 10-year storm (5.16 inches in 24 hours)
Projected 2070 Inundation Conditions for 10-year storm (5.81 inches in 24 hours)
Cemetery / Pentagon
COLUMBIA PIKE
ARMY NAVY DR
S JOYCE ST
Lower Long Branch
12TH ST S
S HAYES ST
S CLARK ST
14TH RD S
15TH ST S
S BELL ST
18TH ST S
CRYSTAL DR
S EADS ST
National Airport
27TH ST S
Roaches Run
Watershed Flooding
(Riverine and Interior Flood Modeling Results)
Flood Depth
.5-1 ft
1-2 ft
2-3 ft
3-4 ft
>4 ft
FEMA 100-year Effective Floodplain
Watersheds
Roaches Run Watershed
County Boundary
Jacobs
0
500
1,000
2,000 Feet
National Mall
N
E
S
The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events

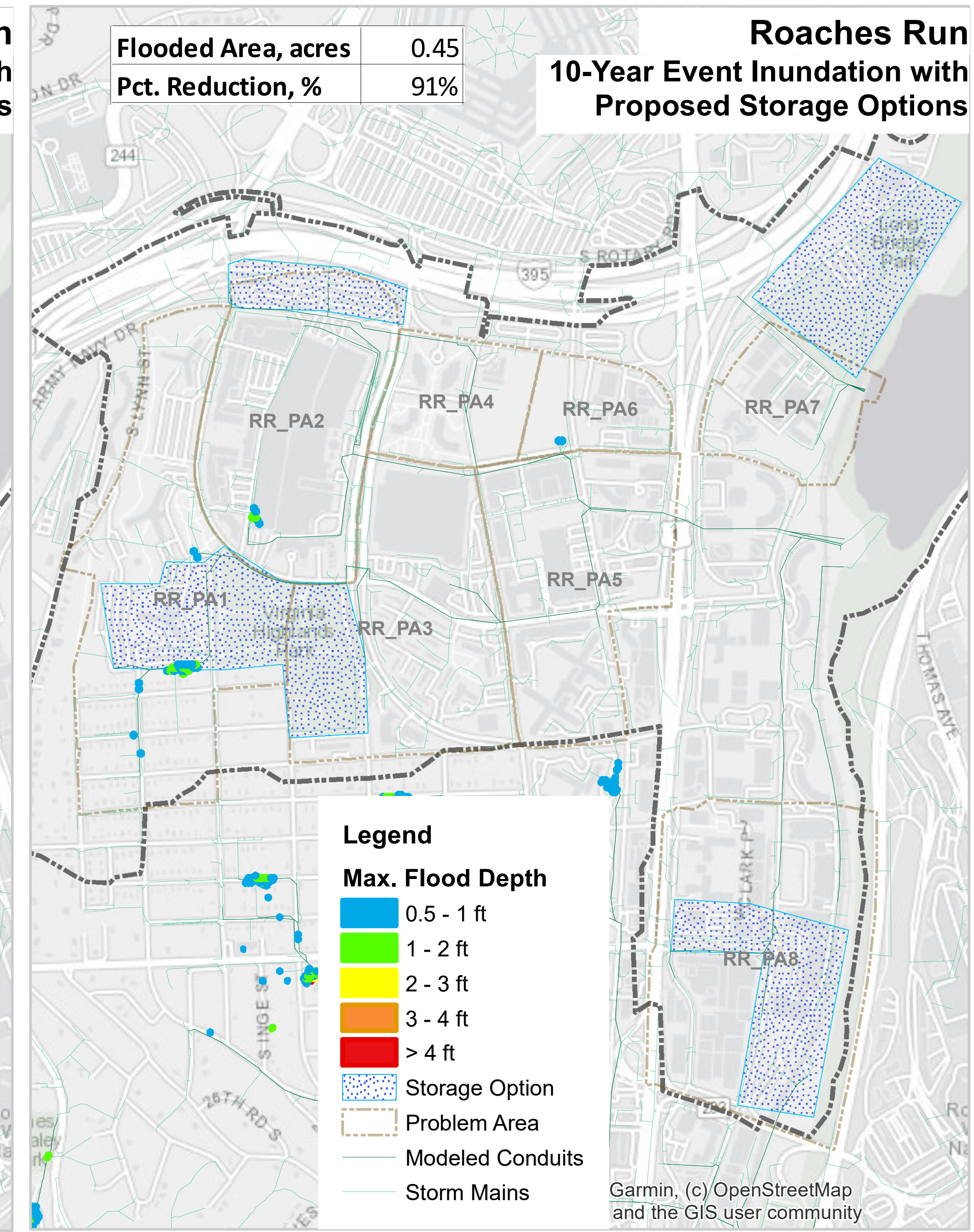


Baseline Inundation Conditions for 100-year storm (8.48 inches in 24 hours)
Projected 2070 Inundation Conditions for 100-year storm (9.57 inches in 24 hours)
Cemetery / Pentagon
COLUMBIA PIKE
ARMY NAVY DR
S JOYCE ST
S HAYES ST
12TH ST S
S CLARK ST
14TH RD S
15TH ST S
S BELL ST
18TH ST S
CRYSTAL DR
S EADS ST
27TH ST S
Lower Long Branch
National Airport
National Mall
Roaches Run
Watershed Flooding
(Riverine and Interior Flood Modeling Results)
Flood Depth
.5-1 ft
1-2 ft
2-3 ft
3-4 ft
>4 ft
FEMA 100-year Effective Floodplain
Watersheds
Roaches Run Watershed
County Boundary
Jacobs
0 500 1,000 2,000 Feet
N
E
S
The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events

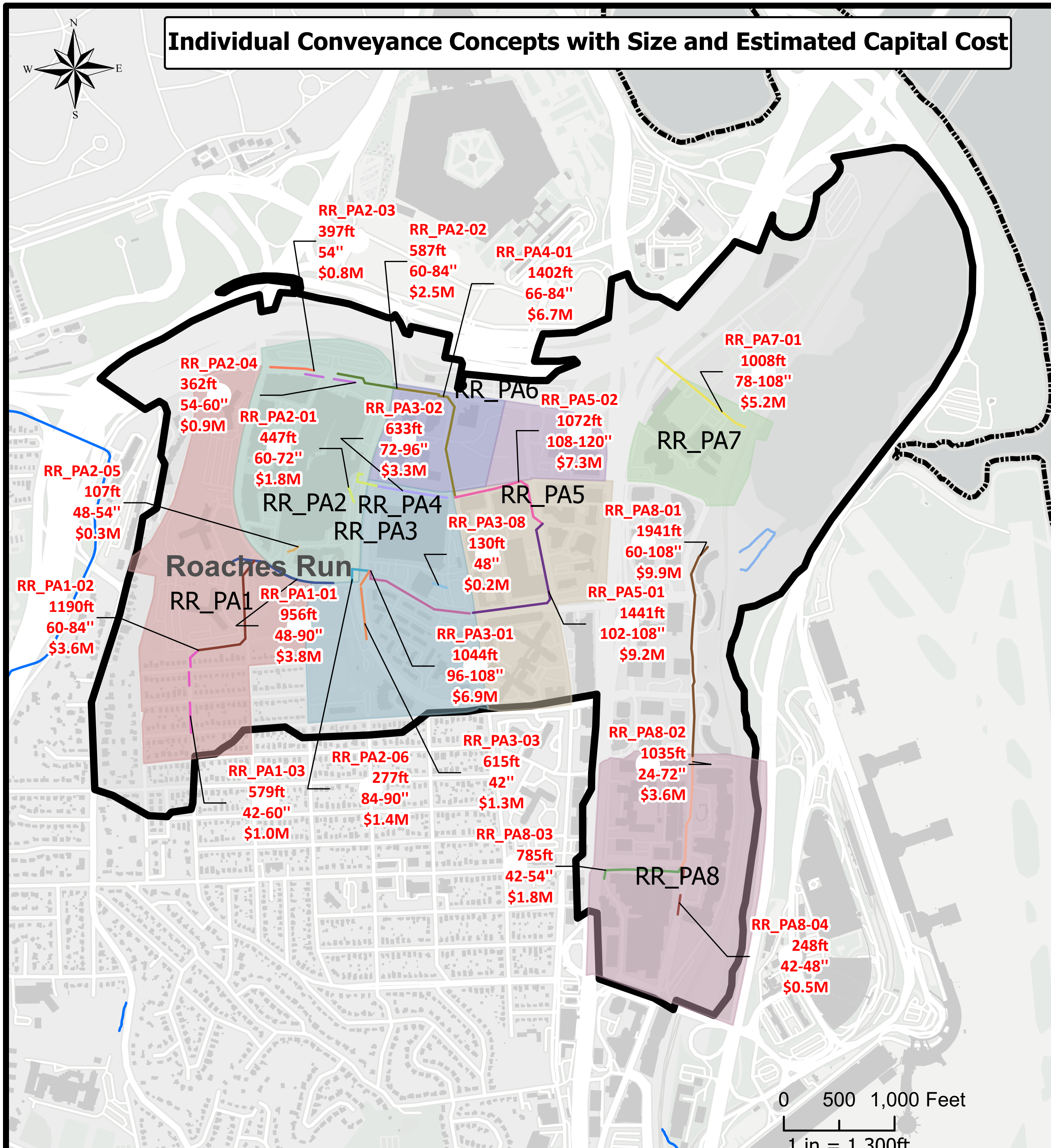
# Baseline, Conveyance Solutions and Storage Solutions



# Individual Conveyance Concepts with Size and Estimated Capital Cost




| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| RR_PA1-01 | 956 | 48-90" | $3.8 |
| RR_PA1-02 | 1,190 | 60-84" | $3.6 |
| RR_PA1-03 | 579 | 42-60" | $1.0 |
| RR_PA2-01 | 447 | 60-72" | $1.8 |
| RR_PA2-02 | 587 | 60-84" | $2.5 |
| RR_PA2-03 | 397 | 54" | $0.8 |
| RR_PA2-04 | 362 | 54-60" | $0.9 |
| RR_PA2-05 | 107 | 48-54" | $0.3 |
| RR_PA2-06 | 277 | 84-90" | $1.4 |
| RR_PA3-01 | 1,044 | 96-108" | $6.9 |
| RR_PA3-02 | 633 | 72-96" | $3.3 |
| RR_PA3-03 | 615 | 42" | $1.3 |
| RR_PA3-08 | 130 | 48" | $0.2 |
| RR_PA4-01 | 1,402 | 66-84" | $6.7 |
| RR_PA5-01 | 1,441 | 102-108" | $9.2 |
| RR_PA5-02 | 1,072 | 108-120" | $7.3 |
| RR_PA7-01 | 1,008 | 78-108" | $5.2 |
| RR_PA8-01 | 1,941 | 60-108" | $9.9 |
| RR_PA8-02 | 1,035 | 24-72" | $3.6 |
| RR_PA8-03 | 785 | 42-54" | $1.8 |
| RR_PA8-04 | 248 | 42-48" | $0.5 |

## LEGEND

Conveyance Concepts Label: (in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

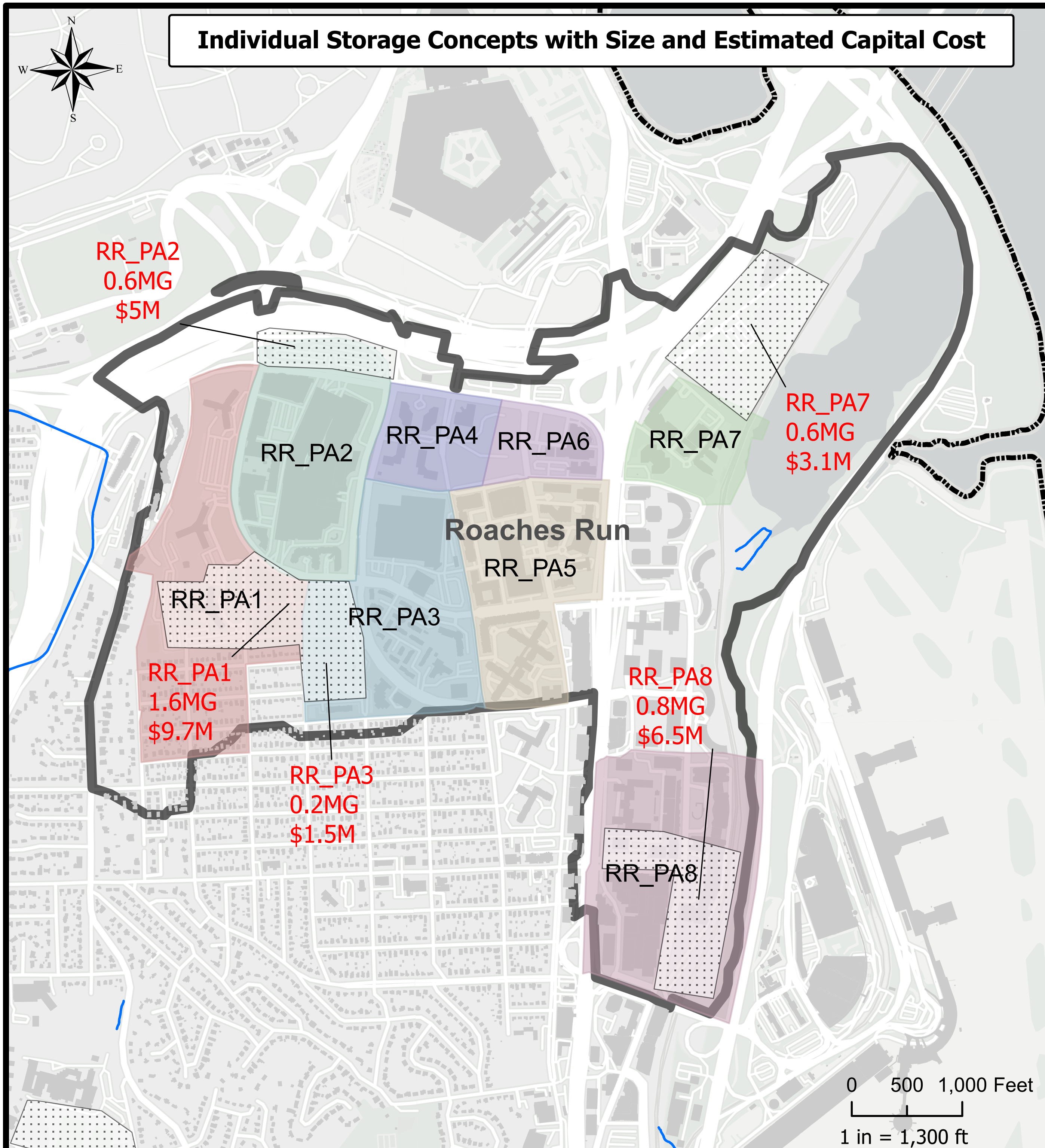
Data:
Problem Areas
Conveyance Concept Pipes

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Conveyance Concepts: Roaches Run**

# Individual Storage Concepts with Size and Estimated Capital Cost




| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| RR_PA1 | 1.6 | Mixed | 9.7 |
| RR_PA2 | 0.6 | Mixed | 5.0 |
| RR_PA3 | 0.2 | Mixed | 1.5 |
| RR_PA7 | 0.6 | Mixed | 3.1 |
| RR_PA8 | 0.8 | Mixed | 6.5 |

## LEGEND

Storage Concepts Label:
(in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

ARLINGTON VIRGINIA

**Storage Concepts: Roaches Run**

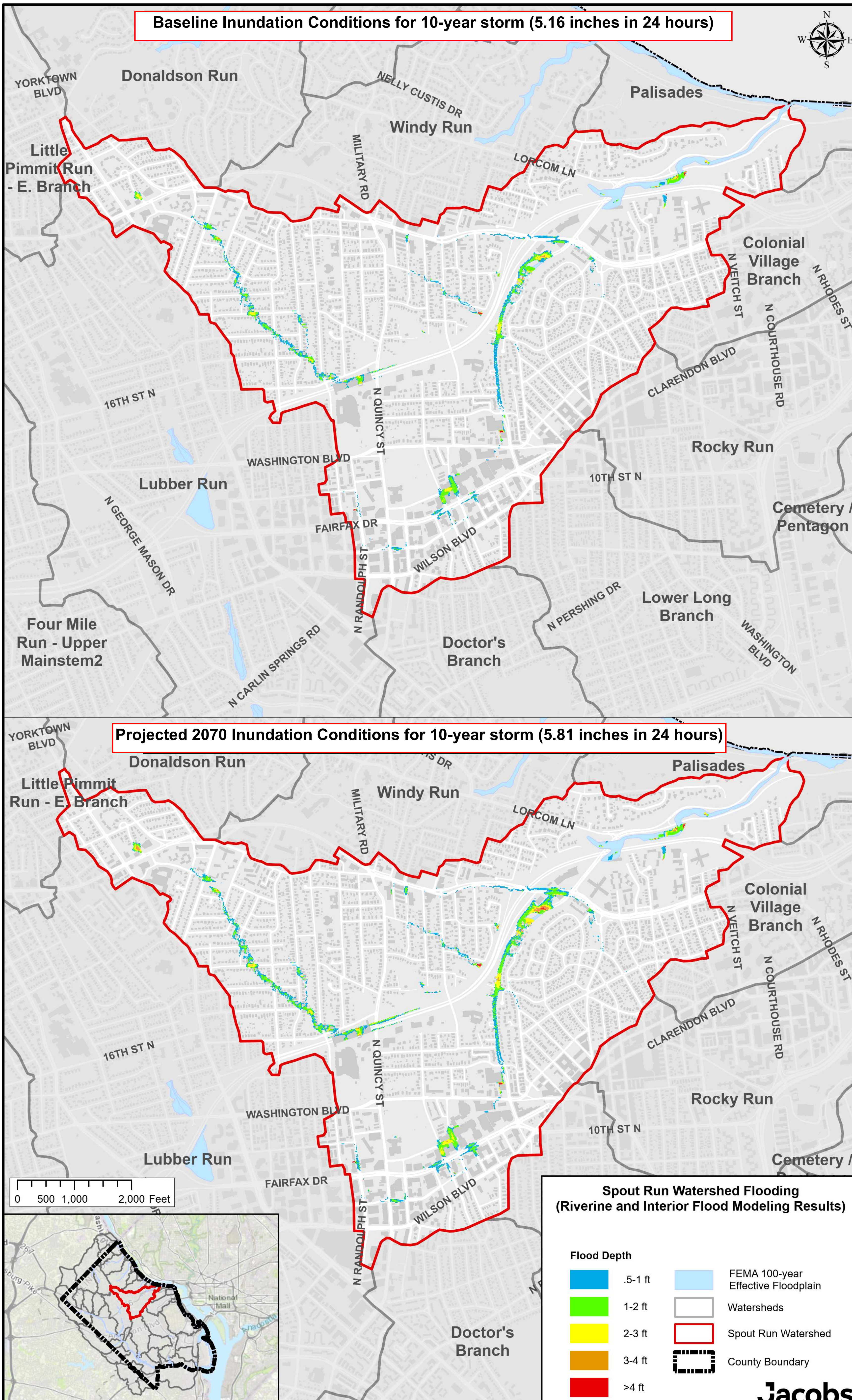
# Spout Run

**Baseline and Projected 2070 Inundation Conditions for 10-year storm**

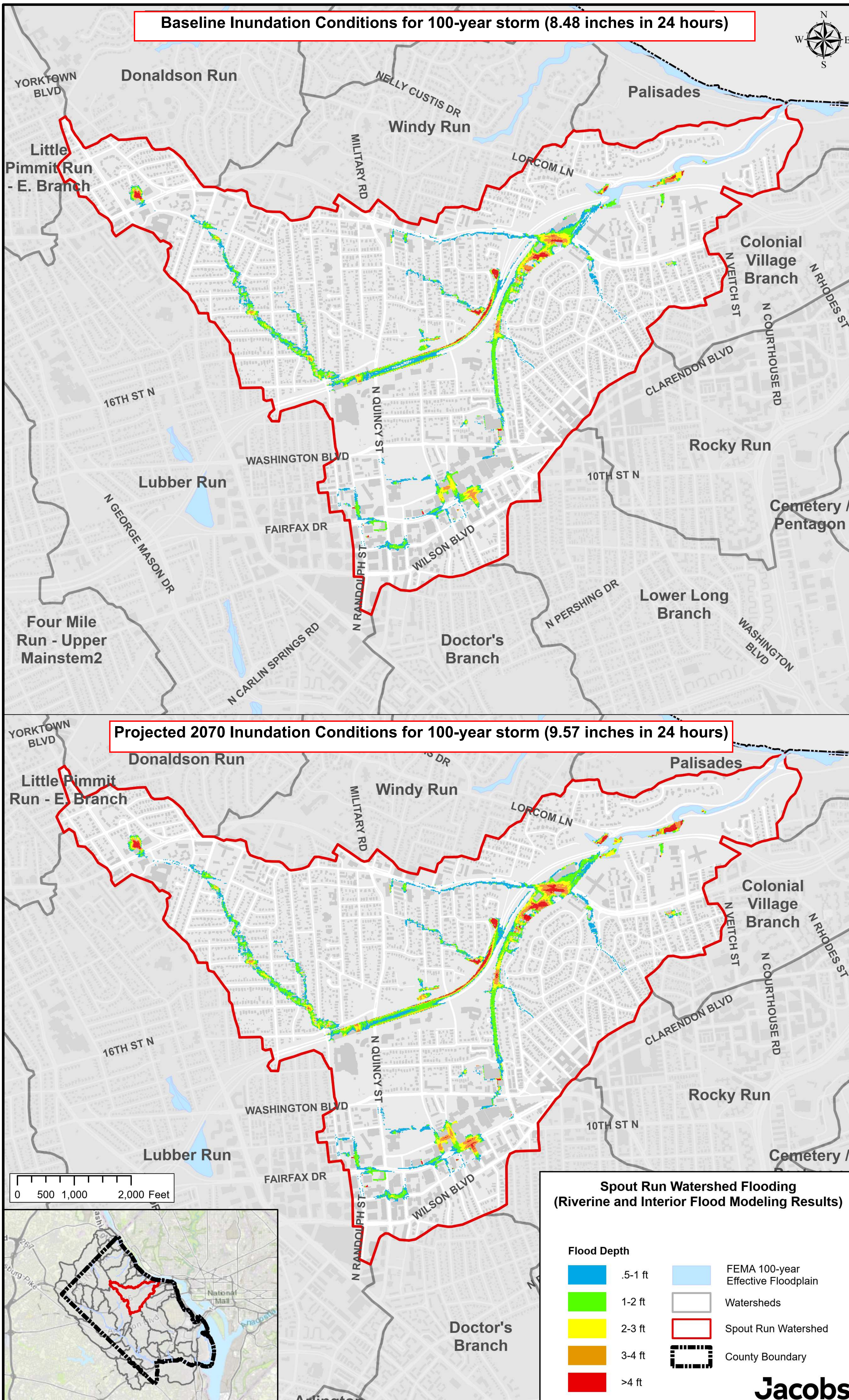
**Baseline and Projected 2070 Inundation Conditions for 100-year storm**

**10-year event Inundation with Proposed Conveyance or Storage Concepts**

**Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost**

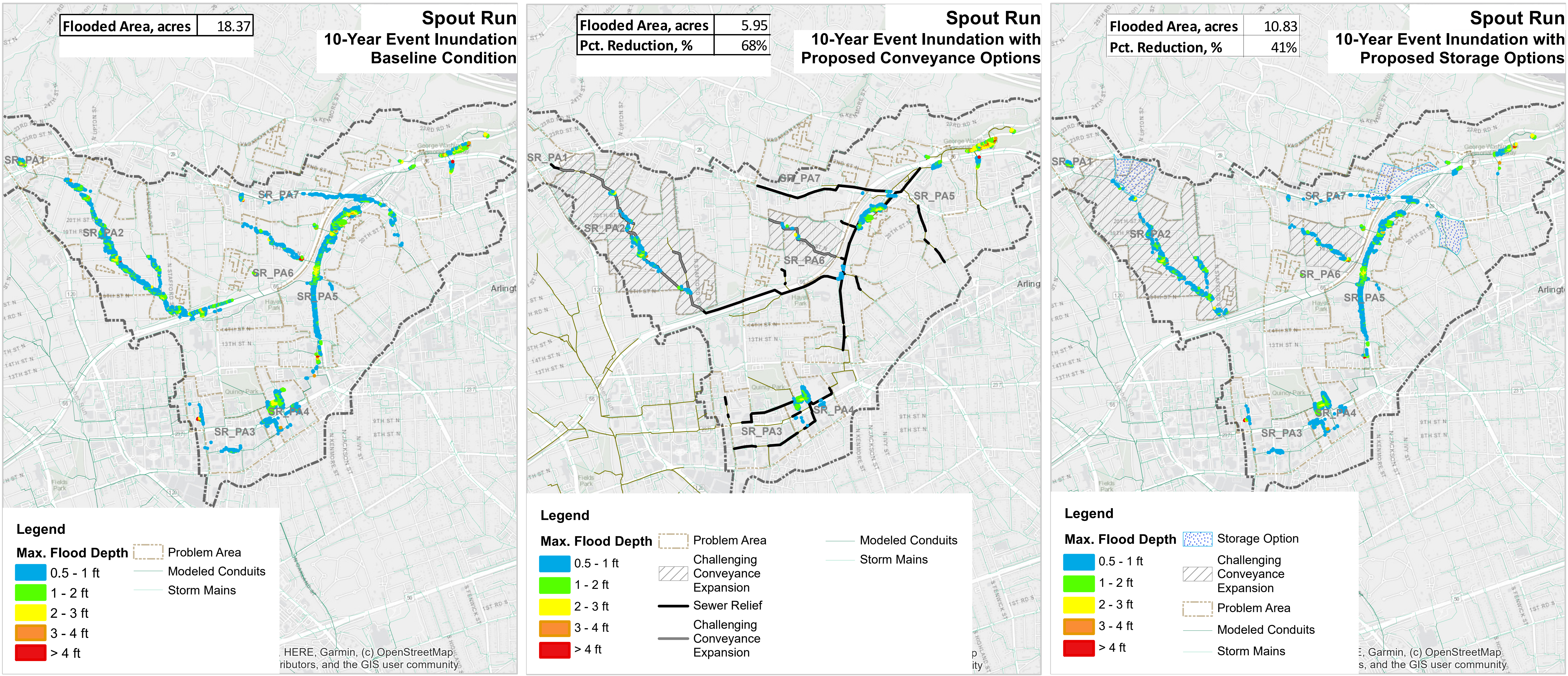



*The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events*

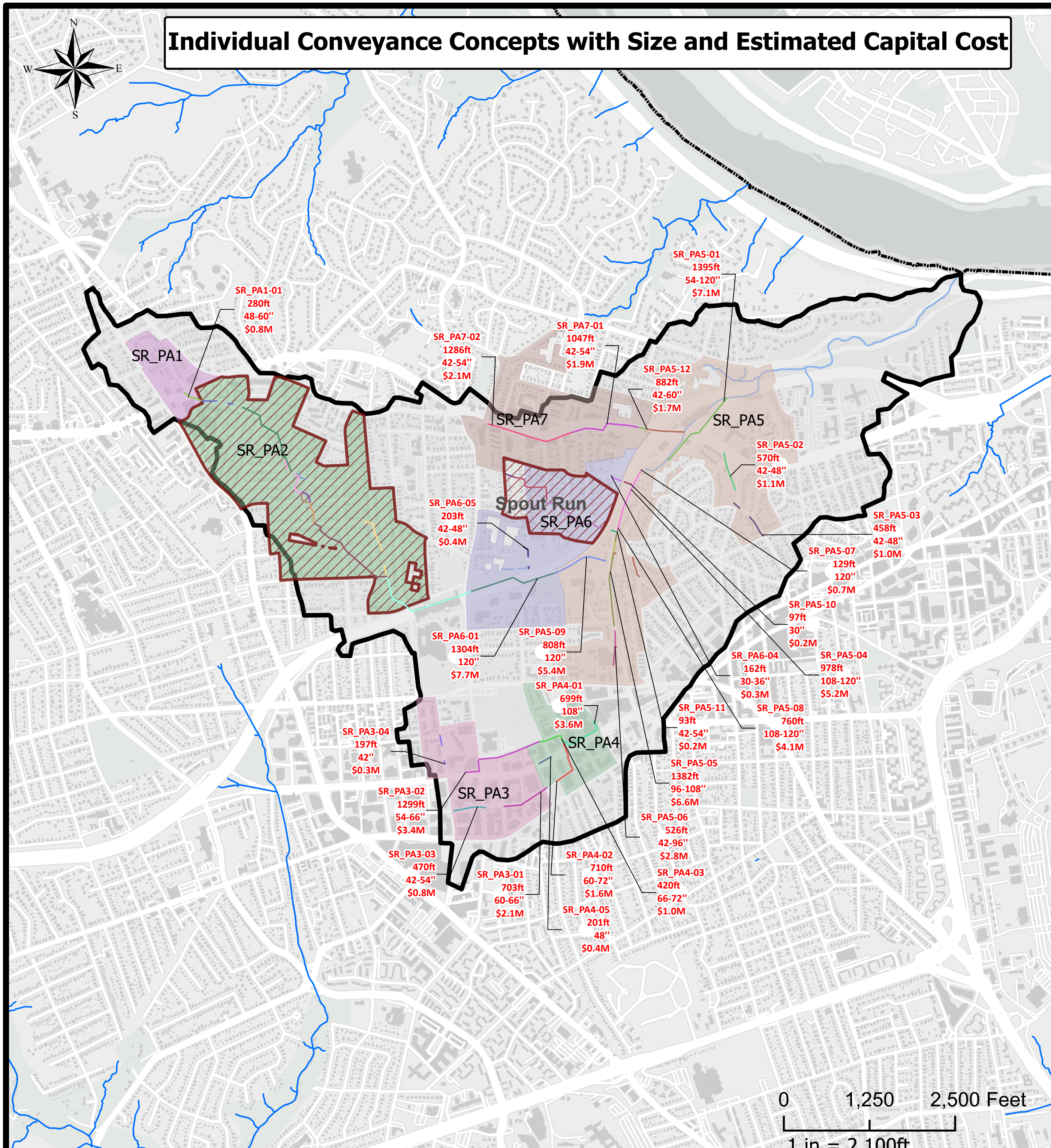



*The data displayed on this map are from computer models that depict certain design storms for illustrative purposes only and cannot be relied upon as accurately predicting specific impacts of actual future storm or flooding events*

# Baseline, Conveyance Solutions and Storage Solutions



# Individual Conveyance Concepts with Size and Estimated Capital Cost




| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| SR_PA1-01 | 280 | 48-60" | $0.8 |
| SR_PA2-01 | 1,587 | 96-108" | $7.8 |
| SR_PA2-02 | 1,394 | 84-113" | $4.7 |
| SR_PA2-03 | 319 | 48-54" | $0.6 |
| SR_PA2-04 | 238 | 72" | $0.6 |
| SR_PA2-05 | 219 | 54" | $0.4 |
| SR_PA2-06 | 516 | 60-72" | $1.1 |
| SR_PA2-07 | 172 | 54-72" | $0.4 |
| SR_PA2-08 | 1,278 | 54-84" | $3.0 |
| SR_PA2-09 | 287 | 48-72" | $0.6 |
| SR_PA2-10 | 696 | 42-54" | $1.2 |
| SR_PA3-01 | 703 | 60-66" | $2.1 |
| SR_PA3-02 | 1,299 | 54-66" | $3.4 |
| SR_PA3-03 | 470 | 42-54" | $0.8 |
| SR_PA3-04 | 197 | 42" | $0.3 |
| SR_PA4-01 | 699 | 108" | $3.6 |
| SR_PA4-02 | 710 | 60-72" | $1.6 |
| SR_PA4-03 | 420 | 66-72" | $1.0 |
| SR_PA4-05 | 201 | 48" | $0.4 |
| SR_PA5-01 | 1,395 | 54-120" | $7.1 |
| SR_PA5-02 | 570 | 42-48" | $1.1 |
| SR_PA5-03 | 458 | 42-48" | $1.0 |
| SR_PA5-04 | 978 | 108-120" | $5.2 |
| SR_PA5-05 | 1,382 | 96-108" | $6.6 |
| SR_PA5-06 | 526 | 42-96" | $2.8 |
| SR_PA5-07 | 129 | 120" | $0.7 |
| SR_PA5-08 | 760 | 108-120" | $4.1 |
| SR_PA5-09 | 808 | 120" | $5.4 |
| SR_PA5-10 | 97 | 30" | $0.2 |
| SR_PA5-11 | 93 | 42-54" | $0.2 |
| SR_PA5-12 | 882 | 42-60" | $1.7 |
| SR_PA6-01 | 1,304 | 120" | $7.7 |
| SR_PA6-02 | 948 | 42-54" | $1.9 |
| SR_PA6-03 | 738 | 42" | $1.2 |
| SR_PA6-04 | 162 | 30-36" | $0.3 |
| SR_PA6-05 | 203 | 42-48" | $0.4 |
| SR_PA7-01 | 1,047 | 42-54" | $1.9 |
| SR_PA7-02 | 1,286 | 42-54" | $2.1 |
| SR_PA7-03 | 136 | 42" | $0.2 |

## LEGEND

Conveyance Concepts Label:
(in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

Data:
- Problem Areas
- Conveyance Concept Pipes
- Challenging Conveyance Expansion

Basemap:
- Watershed
- County Boundary
- Buildings
- Hydrology

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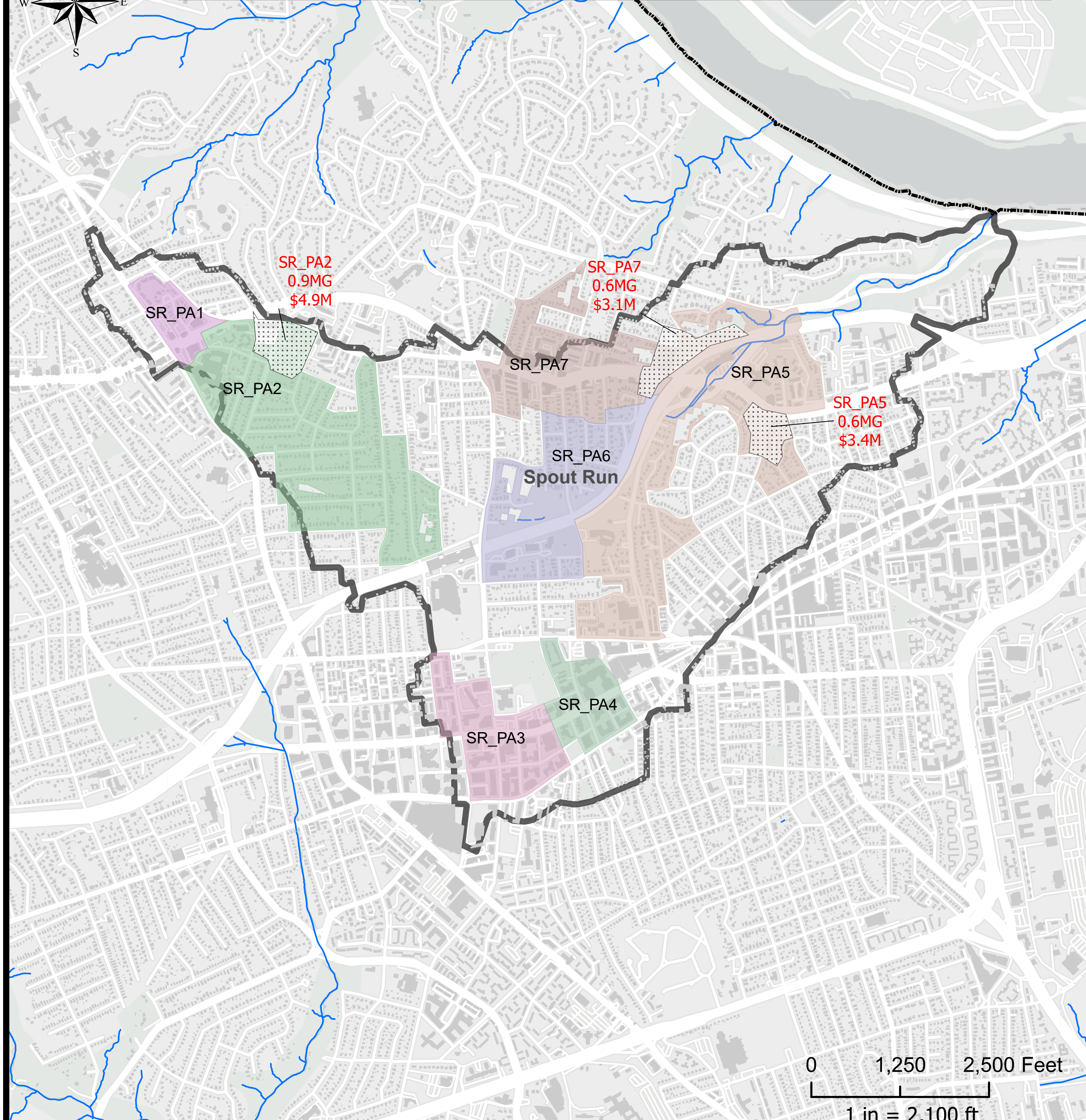
**Conveyance Concepts: Spout Run**

# Individual Storage Concepts with Size and Estimated Capital Cost




| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| SR_PA2 | 0.9 | Mixed | 4.9 |
| SR_PA7 | 0.6 | Mixed | 3.1 |
| SR_PA5 | 0.6 | Mixed | 3.4 |

## LEGEND

Storage Concepts Label:
(in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

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**Storage Concepts: Spout Run**

# Torreyson Run

## Baseline and Projected 2070 Inundation Conditions for 10-year storm

## Baseline and Projected 2070 Inundation Conditions for 100-year storm

## 10-year event Inundation with Proposed Conveyance or Storage Concepts

## Individual Conveyance or Storage Concepts with Size and Estimated Capital Cost

Note: The County recently completed construction of 4 MG Cardinal School Vault, which was included in the baseline scenario.

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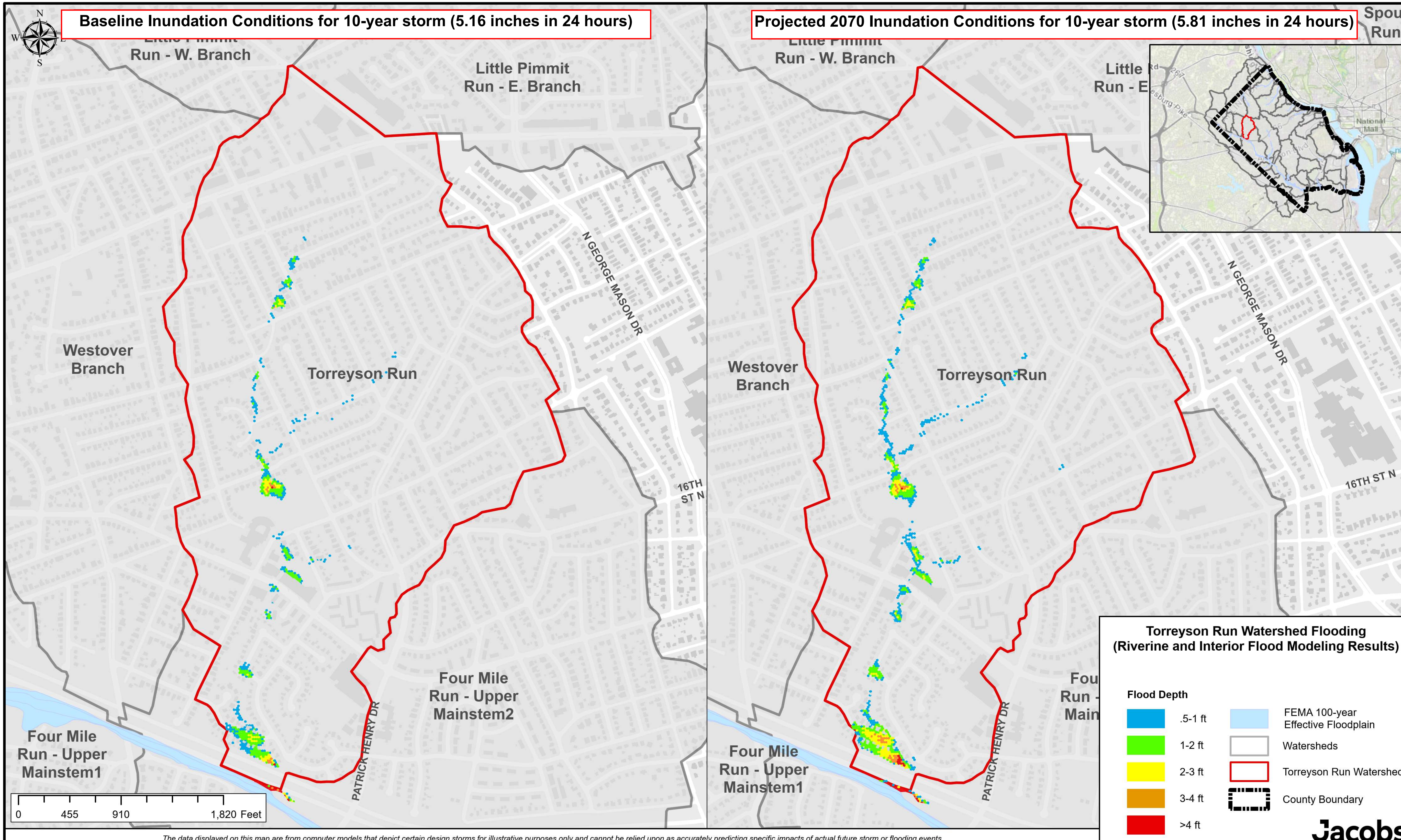
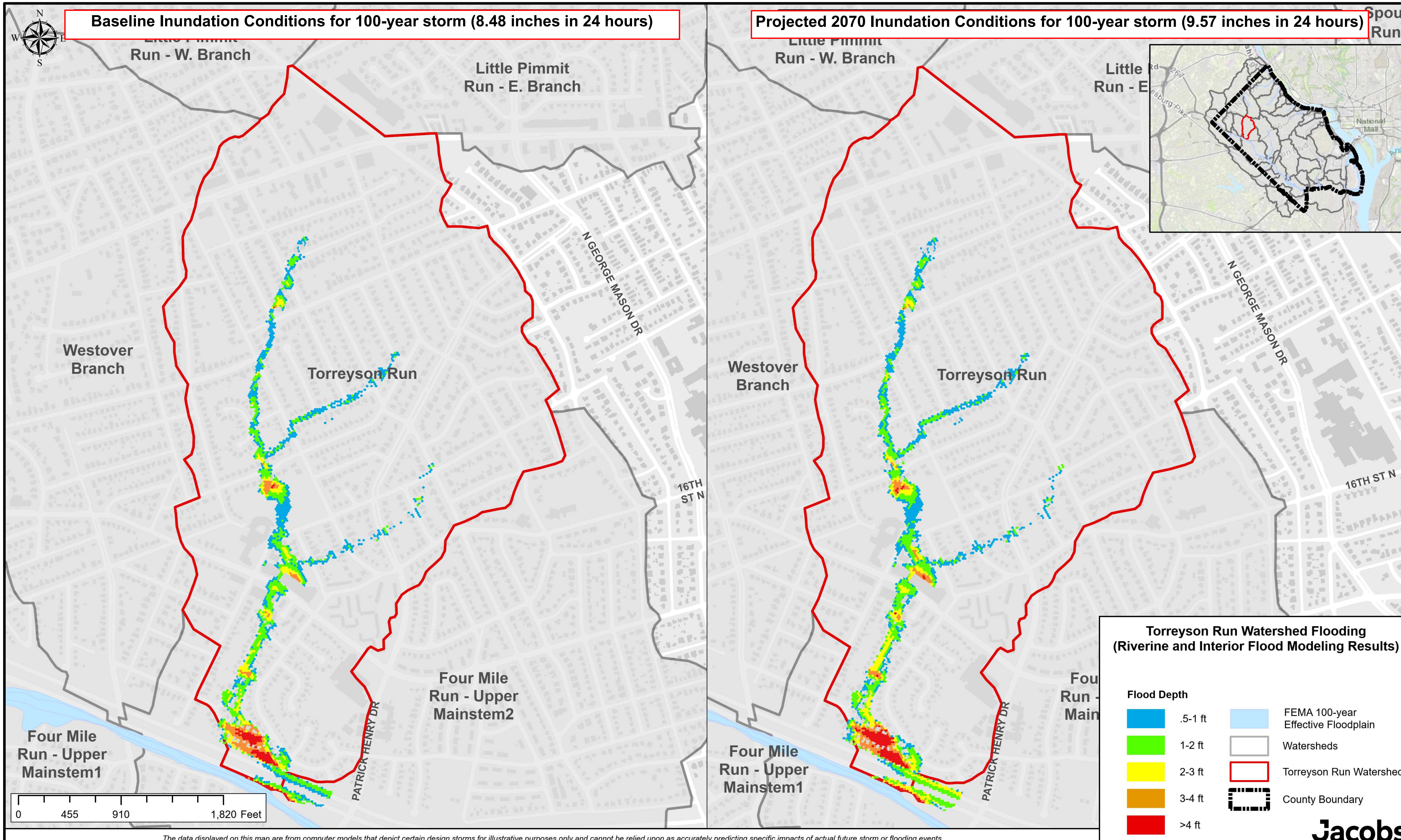
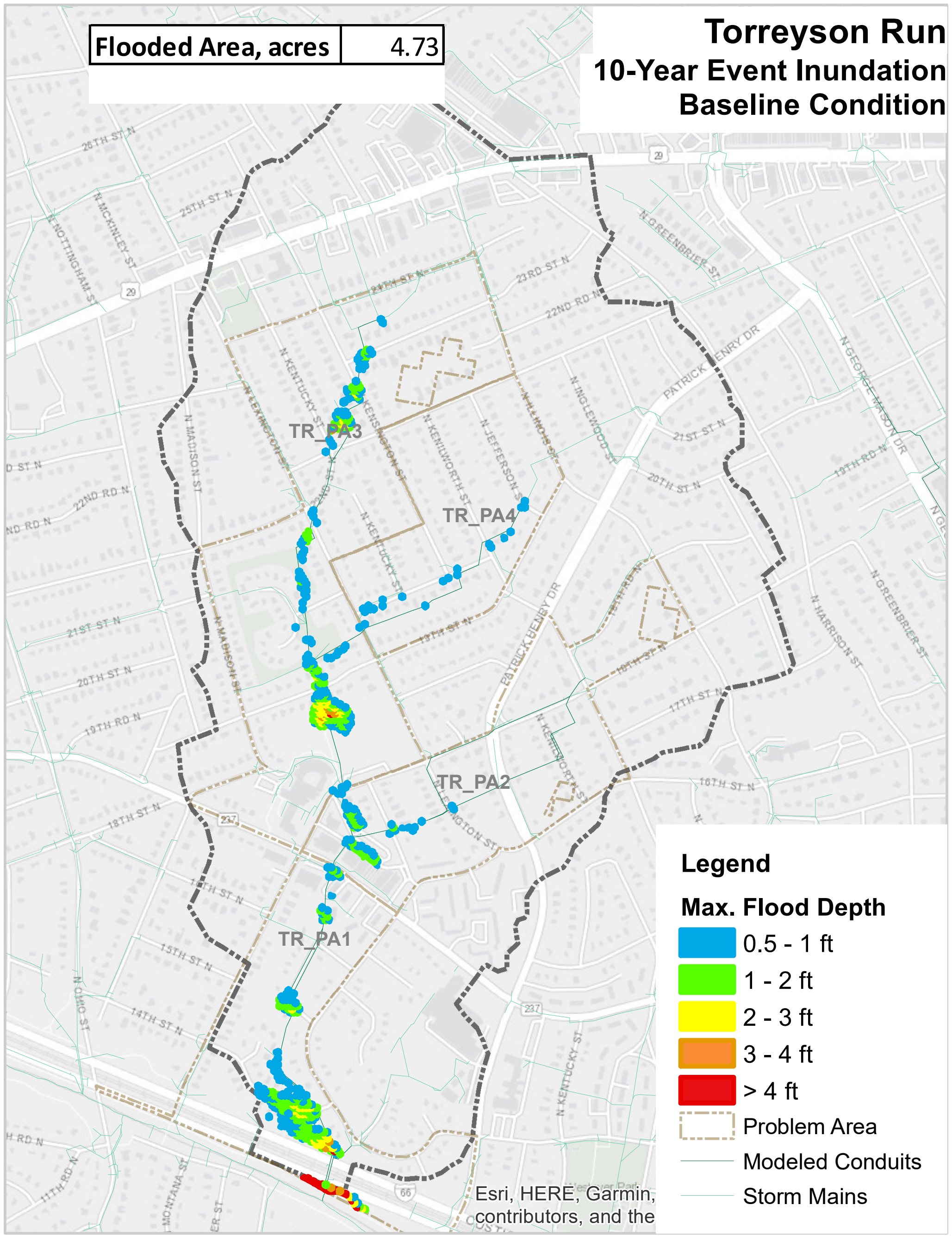


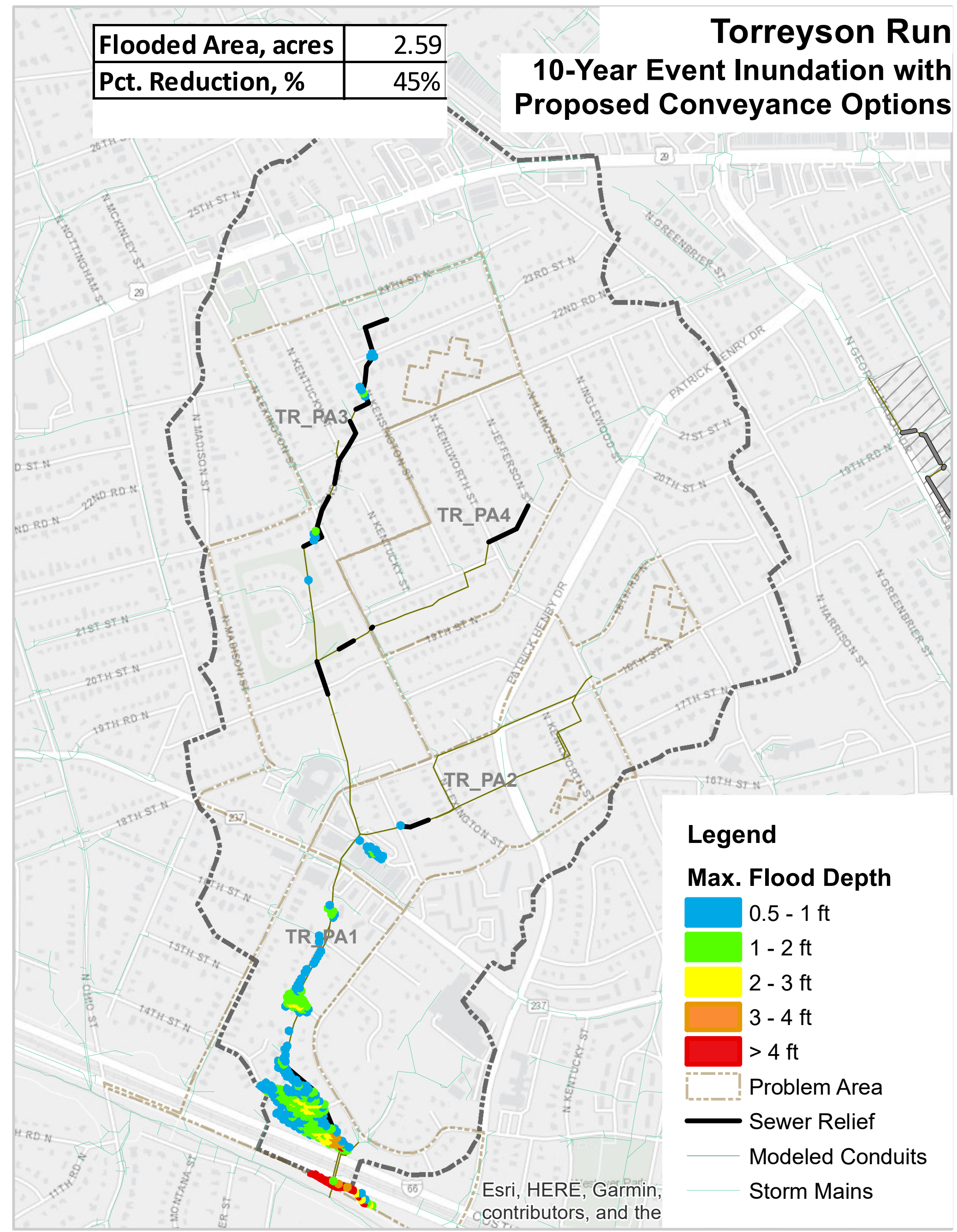

Note: The County recently completed construction of 4 MG Cardinal School Vault, which was included in the baseline scenario.

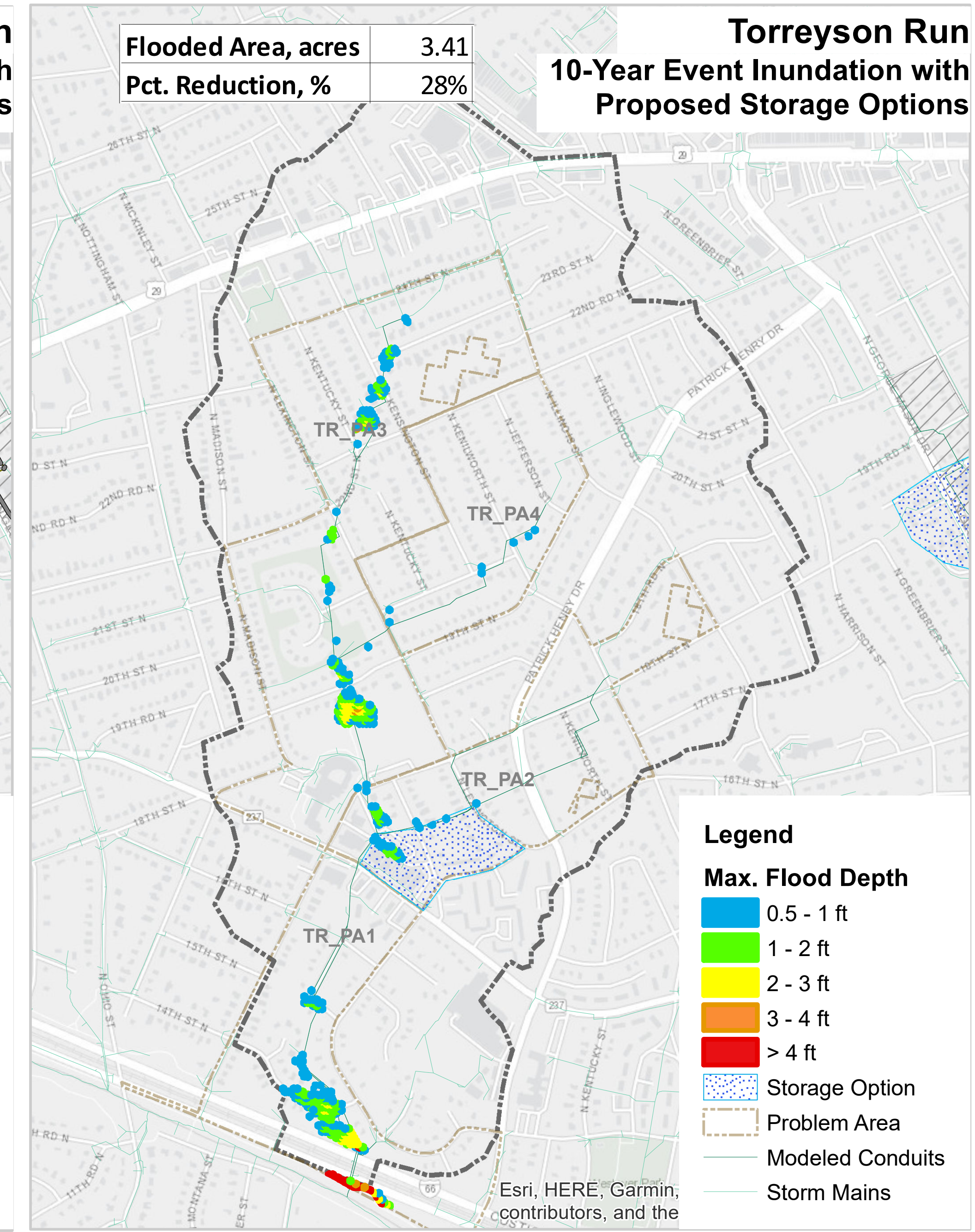



Note: The County recently completed construction of 4 MG Cardinal School Vault, which was included in the baseline scenario.

# Baseline, Conveyance Solutions and Storage Solutions

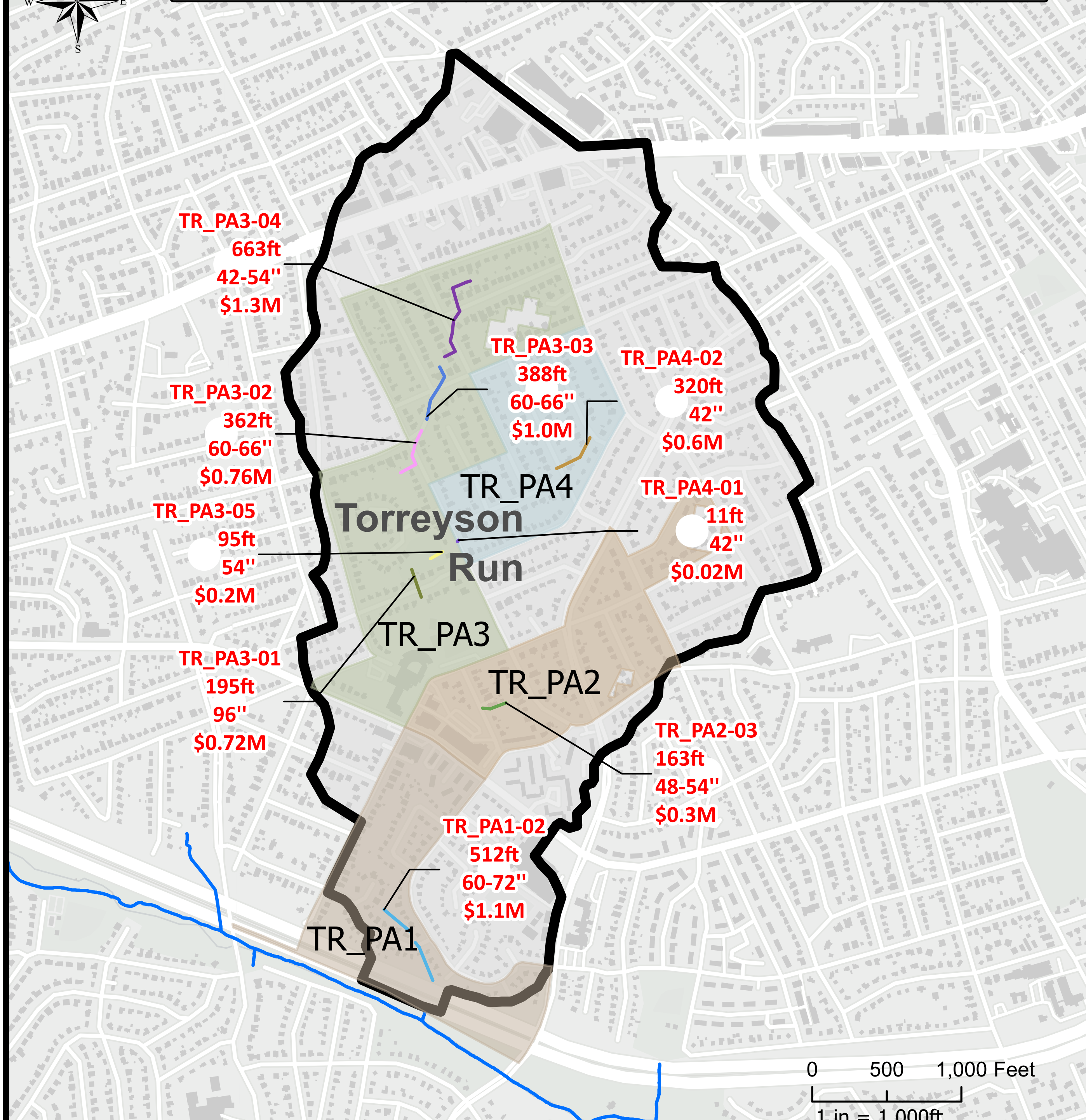



Note: The County recently completed construction of 4 MG Cardinal School Vault, which was included in the baseline scenario.

# Individual Conveyance Concepts with Size and Estimated Capital Cost




| Concept ID | Total Length, feet | Pipe Diameter, Inches | Capital Cost, $millions |
|---|---|---|---|
| TR_PA1-02 | 512 | 60-72" | $1.1 |
| TR_PA2-03 | 163 | 48-54" | $0.3 |
| TR_PA3-01 | 195 | 96" | $0.7 |
| TR_PA3-02 | 362 | 60-66" | $0.8 |
| TR_PA3-03 | 388 | 60-66" | $1.0 |
| TR_PA3-04 | 663 | 42-54" | $1.3 |
| TR_PA3-05 | 95 | 54" | $0.2 |
| TR_PA4-01 | 11 | 42" | $0.02 |
| TR_PA4-02 | 320 | 42" | $0.6 |

Note: The County recently completed construction of 4 MG Cardinal School Vault, which was included in the baseline scenario.

## LEGEND

Conveyance Concepts Label:
(in the order shown)
Concept ID
Pipe Length, feet
Pipe Diameter, inches
Capital Cost, $millions

Basemap:
Watershed
County Boundary
Buildings

Data:
Problem Areas
Conveyance Concept Pipes

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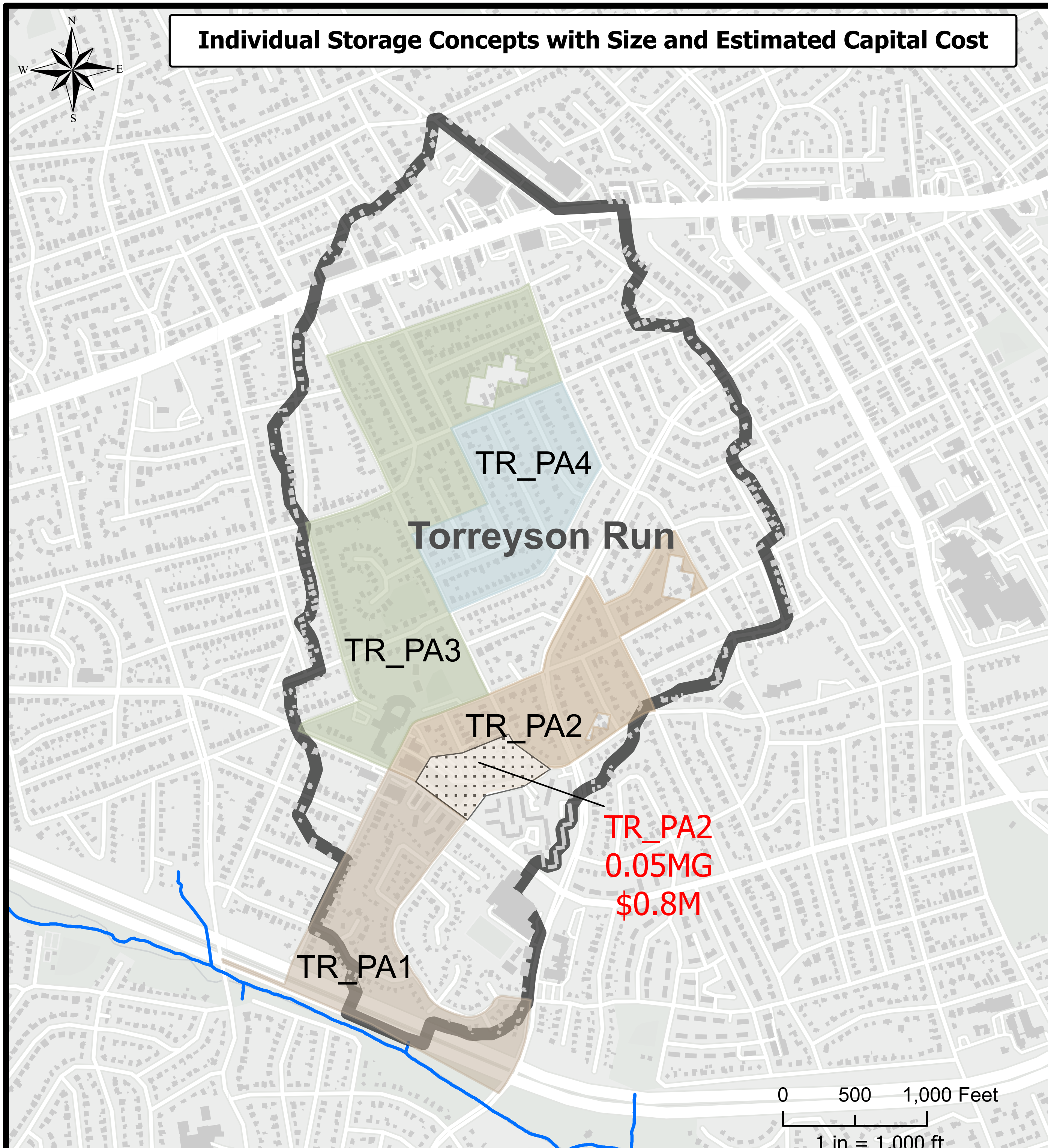
**Conveyance Concepts: Torreyson Run**

# Individual Storage Concepts with Size and Estimated Capital Cost




| Concept ID | Storage Volume, million gallons | Ownership | Capital Cost, $millions |
|---|---|---|---|
| TR_PA2 | 0.05 | Mixed | 0.8 |

Note: The County recently completed construction of 4 MG Cardinal School Vault, which was included in the baseline scenario.

## LEGEND

Storage Concepts Label:
(in the order shown)
Concept ID
Storage Volume, million gallons
Capital Cost, $millions

Data:
Problem Areas
General Area for Storage Concept

Basemap:
Watershed
County Boundary
Buildings
Hydrology

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**Storage Concepts: Torreyson Run**

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Jacobs

Jacobs Engineering Group Inc.
1100 N Glebe Road, Suite 500
Arlington, VA 22201