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City of Worcester Drainage & Green Infrastructure Master Plan

A Plan to Mitigate Flooding in Worcester

Executive Summary | February 2025

MVP Municipal Vulnerability Preparedness

Weston & Sampson

Contents

Executive Summary cover photo: Green Hill Park – photo by Weston & Sampson

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This project was funded in part by the Massachusetts Executive Office of Energy and Environmental Affairs' Municipal Vulnerability Preparedness (MVP) Grant program, which provides support for cities and towns to plan for climate change and to implement projects to build local resiliency.

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1.0 INTRODUCTION

1.1 Goals of the Master Planning Effort

1.1.1 Overview

The City of Worcester is undertaking proactive planning by developing this Drainage & Green Infrastructure Master Plan (DMP) to assess risks associated with urban flooding and build capacity to adapt to a changing climate. This executive summary presents an overview of existing and anticipated future flooding in Worcester in locations with city owned drainage infrastructure, impacts due to that flooding, development of the plan, and steps to create the model and evaluate green and grey alternatives for flood reduction within selected priority areas.

The DMP limits of work include the drainage infrastructure that is managed by the Department of Public Works & Parks (DPW&P) that are located within the East, West, Central North, and Central North Watersheds (as shown in the figure to the right). The Green Island and Combined Sewer Area, which is in the center of the City, was not included in this analysis and is being studied under a separate project.

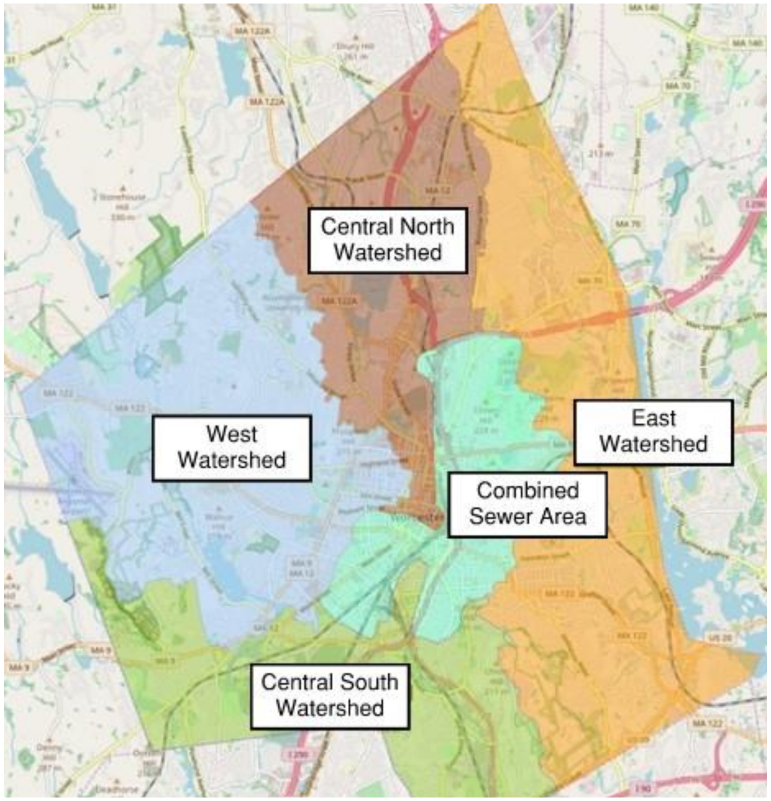

Figure ES-1: Worcester Drainage Watersheds

The City of Worcester has a long history of experiencing flooding in low lying areas across the city, as further discussed in Section 2.2. Most of the city's drain infrastructure was constructed over 50 years ago and was not designed to manage the storms that the city is experiencing now. In addition, over the course of its development, the city has transformed significantly, evolving from a more "natural" landscape into a highly urbanized environment to support industry, manufacturing, and, more recently, higher education, biotechnology, and medicine. Today, Worcester is the second most populous city in New England, home to over 200,000 residents (2020 U.S. Census).

This project is Phase 1 of a multiphase project, and the analysis, model development, and alternatives are limited to city owned drainage infrastructure located outside of the Green Island and Combined Sewer Area, which is in the center of the City. Open water bodies and channels are also excluded from the model currently. Future phases of the drainage model will include incorporating open water bodies and channels, and the combined sewer area.

Figure ES-2: Highland Street on August 19, 2021 – Photo by Weston & Samson

1.1.2 Goals

The goals and objectives of this DMP are to:

- Develop a comprehensive understanding of the municipal drainage system and its constraints in conveying stormwater runoff during peak precipitation events;
- Identify the most vulnerable areas of the city using an infrastructure and social resilience framework; and
- Prioritize actions to move toward a pipeline of near-ready projects that advance flooding resiliency, when funding allows, with a focus on a hybrid approach of nature-based solutions and grey infrastructure enhancements.

1.1.3 Funding for DMP

This DMP was developed starting in mid-2022 and completed in early 2025. Preparation of this plan was identified as a priority through the Municipal Vulnerability Preparedness (MVP) planning process the city underwent during 2019, where the community determined that urban flooding is a high concern natural hazard anticipated to be exacerbated by climate change. Investment in developing a city-wide hydrologic/hydraulic drainage model was needed to evaluate projects effectiveness and make decisions about prioritization. MVP provided a seventy-five (75%) percent grant, and the remainder was the city's match (cash and in-kind).

1.2 Plan Development

1.2.1 Project Partners

Department of Public Works & Parks (DPW&P) – Water & Sewer

Department of Public Works & Parks (DPW&P) – Engineering

Department of Sustainability & Resilience

Executive Office of Economic Development

City of Worcester Residents

1.2.2 Timeline

Scope Development: January 2022 to May 2022

MVP Application Submitted: May 2022

MVP Grant Approval: July 2022

Plan Development:

- Field Investigations: September 2022 to February 2023
- Updates to City's GIS: February 2023 to January 2025
- Hydraulic/Hydrologic Model Development: April 2023 to February 2024
- Gray Infrastructure Alternatives Development: March 2024 to June 2024
- Draft Report: June 2024
- Nature Based Solutions Screening: July 2024 to November 2024
- Draft Final Report: December 2024
- Final Report: February 2025

1.2.3 Drainage Plan Components

Field investigations were conducted to collect information to supplement the City's GIS, and included topside drain manhole inspections, culvert inspections, and outfall inspections.

Figure ES-3: Topside Drain Manhole Inspections

Figure ES-4: Culvert Inspections

Figure ES-5: Outfall Inspections

The hydrologic/hydraulic (H&H) model was developed to assess the city-owned drainage infrastructure located outside of the Green Island and Combined Sewer Area. H&H models can be used to predict the effects of a wide range of precipitation events, ranging from water quality events, which equal approximately 1 inch of precipitation, to an extreme event of 100-year rainfall event. A 100-year rainfall event has a 1/100 (or 1 percent) chance of being equaled or exceed in any given year.

Computer models were run for the 10-year 1-hour and 24-hours storms present day rainfall predictions, and 10-year 24-hour 2070 projected rainfall. The storm selection was done during the scoping phase of the project. The 10-year rainfall event has a 10 percent chance of being equaled or exceeded in any given year.

The model output identifies locations where the flooding occurs under the design storms. The model also provides the predicted volume of flooding that leaves the drainage system.

Following the model runs, Weston & Sampson developed a Flood Viewer, GIS Web Application, so city staff could view and consider multiple factors simultaneously when reviewing next steps. In addition, a selection matrix was prepared to assist City with the selection of priority areas, which compared the model results to historic flooding and other parameters. Following several meetings and analysis of the selection matrix and the Flood GIS Web Application with city staff the team selected the following the priority areas:

- West Sub 5
- West Sub 9
- Central North Sub 10
- Central North Sub 4

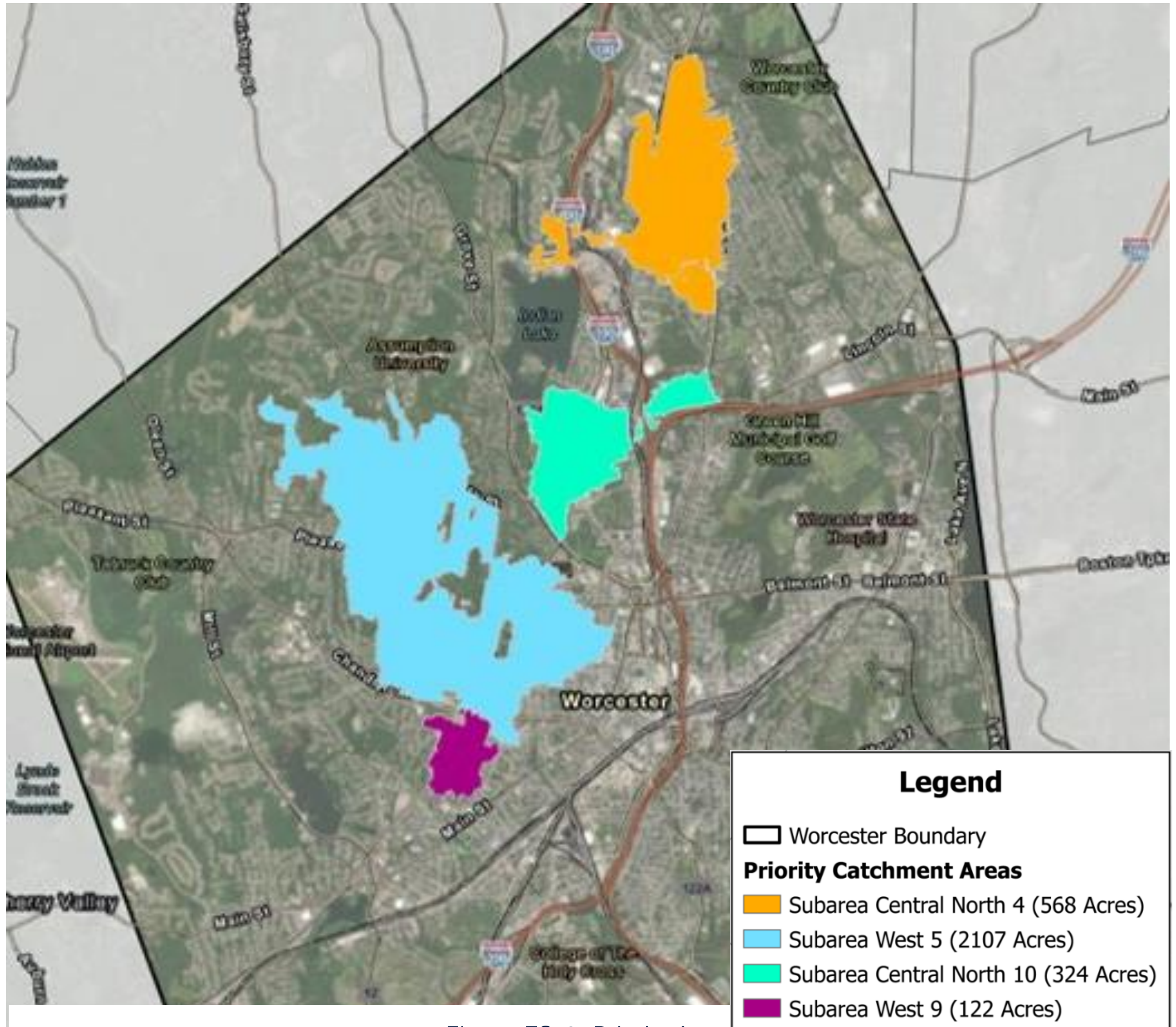

Figure ES-6: Priority Areas

1.2.4 Grey Infrastructure and Nature Based Solutions Included in the Plan

The project team performed alternatives analysis including running the models for the four selected priority areas for the current day 10-year 24-hour and projected 2070 10-year 24-hour rainfall events to determine what size pipes would be needed to contain the peak runoff volume. Pipe replacements ranged from 15-inch to 60-inch diameter for the current day rainfall and 15-inch diameter to 6-foot by 16-foot box culvert for the 2070 rainfall. Due to the presence of existing utilities, it will likely not likely possible to install a 6-foot by 16-foot box culvert in the street. Subsequently, it will be important to try to find solutions that include providing locations for storage where the water is temporarily held back, and then slowly released into the drainage system once the storm has passed or infiltrated into the ground if soil conditions allow.

In addition to grey infrastructure, the project team performed a nature-based solutions (NBS) assessment for the four selected priority areas.

Figure ES-7: Grey Infrastructure and Nature Based Solutions

The work included:

- Review of existing plans, reports of flooding, and available planned capital improvements (sidewalk/ roadway/ parcel development)
- Desktop assessment looks at spatial data, reports of flooding problem areas, and 1D flood model results to identify priority areas to implement NBS
- Sites are reviewed for topography existing drainage infrastructure, and nearby parcel ownership to determine what types of NBS are best suited for the area
- NBS were sized and approximate storage volume was calculated followed by running the model using the 2-year 6-hour storm to quantify flood reduction benefits
- NBS were prioritized based on flood reduction benefits, ease/feasibility of implementation, and co-benefits

2.0 FLOODING IN WORCESTER

2.1 Why Does it Flood in Worcester?

Over the course of the last 150 years, Worcester evolved from a more natural landscape into its current highly urbanized environment. The change has led to the widespread creation of impervious surfaces—such as roadways, rooftops, driveways, and sidewalks—that dramatically alter how stormwater (rain or snowmelt) flows across the land. In natural landscapes, over half of the water infiltrates into the ground. However, in areas with extensive impervious cover, less than 15% of stormwater is absorbed into the soil (see Figure ES-8). The result is a greater volume and faster flow of stormwater, which contributes to localized flooding.

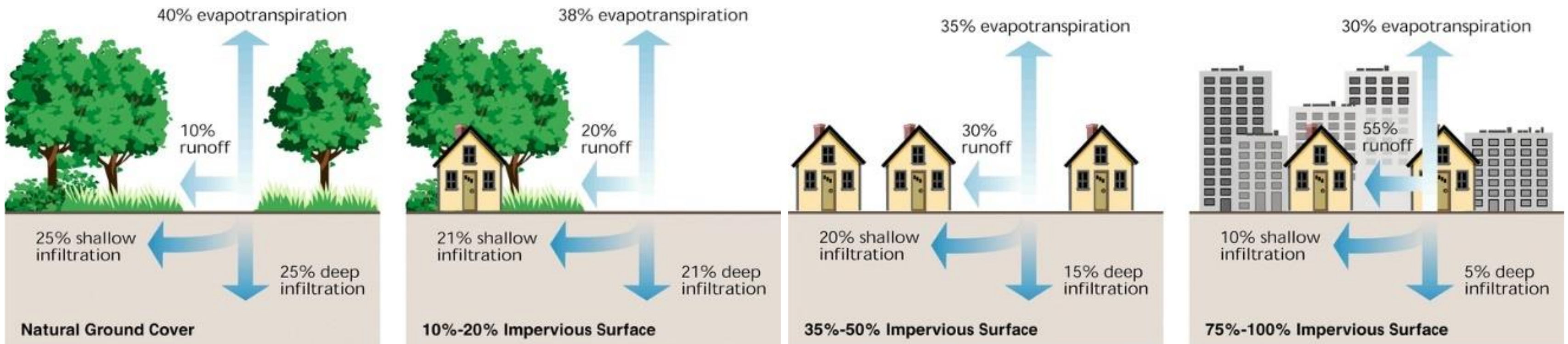

Fig. 3.21 -- Relationship between impervious cover and surface runoff. Impervious cover in a watershed results in increased surface runoff. As little as 10 percent impervious cover in a watershed can result in stream degradation.
In Stream Corridor Restoration: Principles, Processes, and Practices (10/98).
By the Federal Interagency Stream Restoration Working Group (FISRWG) (15 Federal agencies of the U.S.)

Figure ES-8: Impervious surfaces infographic

2.2 Past and Present Reports of Flooding

Worcester has a long history of flooding. Below are some examples of extreme events. Back-to-back hurricanes Connie and Diane caused torrential rainfall resulting to catastrophic flooding in August 1955.

Figure ES-9: Mill Street at Main, showing water backed up during the flood of August 1955. T&G File Photo

Figure ES-10: An open manhole spouts water onto Cambridge Street at McKeon Road in 1955. T&G File Photo

In March 2010, a powerful nor'easter brought three days of rain that dropped almost 10 inches of precipitation on top of rapidly melting snow, causing widespread power outages, downed trees, and localized flooding.

The wettest July on record in Worcester was 2021, when the city received 12.66 inches of rain. In 2023, Worcester's summer was the second wettest on record, with 22.91 inches of rain.

The rainfall recorded from June to September 19, 2023 was 28.52 inches.

As part of the City's Integrated Water Resources Management Plan, a map (Figure ES-9) displaying the concentration of reported flooding events from 2006 to 2016 was developed.

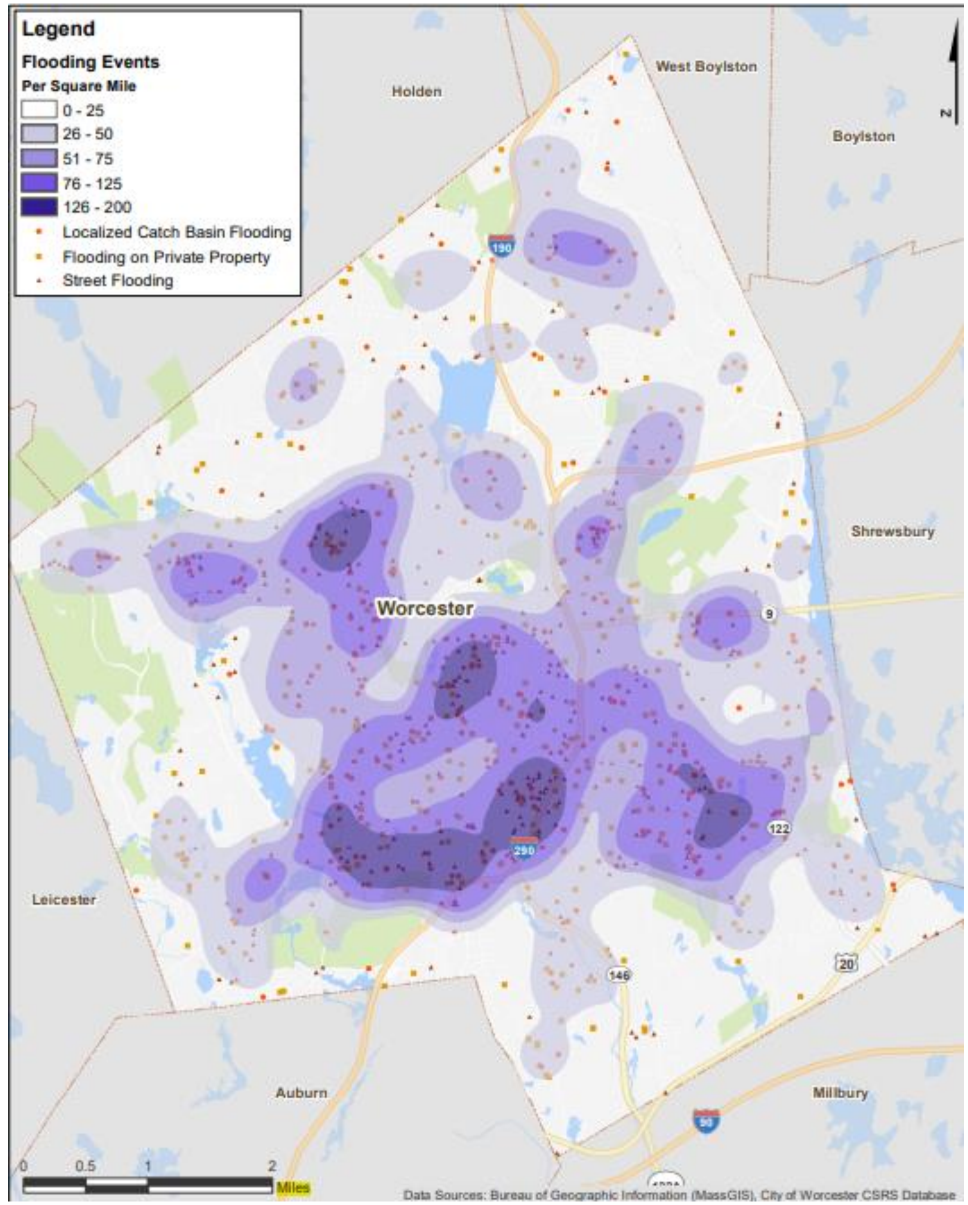

Figure ES-11: Map of Reported Flooding Events from 2006-2016

2.3 Predictions for the Future, including Impacts of Climate Change

As mentioned above, **alternative models were developed** for the present-day NOAA Atlas 14 10-Year 24-Hour rainfall of 4.9 inches and the projected 2070 10-Year 24-Hour rainfall of 6.6 inches.

35%

Within the next 50-years, rainfall totals are **predicted to increase** by 35 percent.

The City currently observes flooding during high intensity short duration rainfall events, which **overwhelm drainage infrastructure** before the water has a chance to enter the system.

"In 2016, the City was in Stage III drought, yet, in the fall of that same year, an intense rain event caused severe flash flooding, **exposing the city's stormwater system vulnerabilities**".

- Worcester 2019 MVP Plan

3.0 MODEL DEVELOPMENT

3.1 Gap Analysis

Weston & Sampson GIS staff reviewed the City's GIS data for the drainage system to identify manholes that were missing information, which included drain manhole rim elevations, and incoming and outgoing pipe sizes, materials, and invert elevations. Weston & Sampson identified 5,200 drain manholes that were missing data.

3.2 Field Data Collection

3.2.1 Topside Drain Manhole Inspections

Weston & Sampson field crews inspected 4,380 manholes to assess existing conditions and collect missing information not currently in GIS. In addition to elevation data, pipe sizes, and material of construction, photos were taken inside the manholes (see example in Figure ES-10) to document current conditions. Approximately 800 manholes could not be located or opened during the field work.

Figure ES-12: Manhole inspection

3.2.2 Stormwater Outfall Inspections

Weston & Sampson field crews inspected 33 stormwater outfalls, which is approximately 10% of a total of 350 system stormwater outfalls throughout the city. Field data collection and inspection included using a zoom camera to collect video and photo images, GPS location, and documentation of system connectivity. The city selected the outfall locations for inspection as part of the DMP. The city's Sewer Operations staff regularly inspect and perform dry and wet weather water quality sampling at the stormwater outfalls as part of the city's Illicit Discharge Detection and Elimination (IDDE) Program.

Figure ES-13: Stormwater Outfall Inspection

Did You Know?

The North Atlantic Aquatic Connectivity Collaboration (NAACC) is a network of individuals from universities, conservation organizations, and state and federal natural resource and transportation departments focused on improving aquatic connectivity across a thirteen-state region, from Maine to West Virginia.

This organization has a procedure and approach to inventory the condition and aquatic passability of stream-road crossings (culverts).

Source: streamcontinuity.org

3.2.3 Culvert Inspections

Weston & Sampson field crews inspected 42 culverts using North Atlantic Aquatic Connectivity Collaborative (NAACC) protocol to complete the assessments. The city provided the culvert locations for inspection as part of the DMP. Weston & Sampson staff entered the data into the NAACC database. Zoom camera inspections were completed at locations where conditions allowed. The culverts that were selected for inspected had spans less than 20 feet. A culvert span refers to the horizontal distance between the inside faces of the sidewalls of a culvert.

Massachusetts Department of Transportation (MassDOT) and city-owned structures with spans greater than 20 feet are categorized as National Bridge Inventory (NBI) structures. MassDOT inspects NBI bridges on an annual basis.

Figure ES-14: Culvert Inspections

3.3 1D Model Development

Weston & Sampson built a computer model using the information collected during the field inspections and the city's drainage GIS. The Personal Computer Storm Water Management Model (PCSWMM) software was used. PCSWMM (is a GIS-integrated modeling software used for simulating and analyzing stormwater, wastewater, and watershed systems. It is built on top of the EPA Storm Water Management Model and is widely used by engineers, hydrologists, and urban planners for flood modeling, stormwater drainage design, and water quality analysis. PCSWMM simulates the rainfall-runoff processes and floodplain interactions, allows spatial analysis and visualization of stormwater networks and flood extents, and supports evaluation of flood mitigation strategies, whether they be grey or green.

Weston & Sampson reviewed the city drainage GIS and provided a quality assurance/quality control (QA/QC), which included identifying system connectivity / protocol issues, and missing data. System connectivity / protocol issues are defined as system data that does not meet modeling software protocol. Typical protocol issues include:

- Ground elevation below node invert elevation
- Downstream conduit invert elevation below node invert elevation
- Upstream conduit invert elevation below node invert elevation
- Downstream crown elevation above node ground elevation
- Upstream crown elevation above node ground elevation
- Inaccurate node / Pipe ID connectivity
- Missing pipe size
- Back pitched pipe
- Outfall rim and invert elevation the same

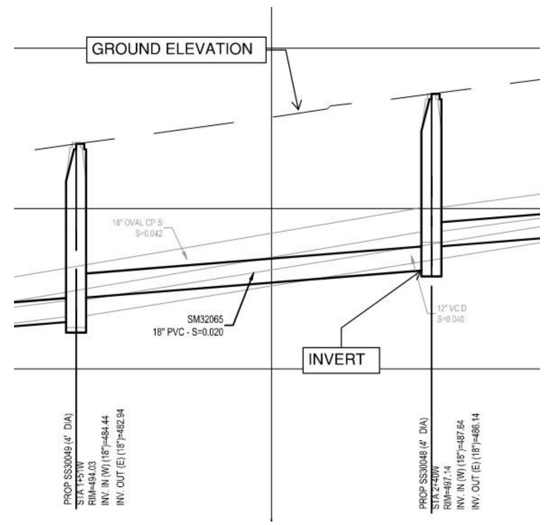

Figure ES-15: Computer Model

Upon final QA/QC review of the city wide PCSWMM model, there were approximately 5,300 model conflicts that required corrections to allow for the model to run. This required Weston & Sampson to apply reasonable engineering judgment adjustments on various data to remove the conflicts. Adjustments included estimating unknown pipe sizes, interpolating inverts to fix back pitch pipes, adjusting rim elevation from the Google Earth resource, and additional field data collection.

3.4 Selection of Storm Events

The rainfall totals for storm event analysis are shown in the Table ES-1 below.

Table ES-1: Rainfall Events Analyzed

Rainfall Type	Duration	Recurrence Interval	Total Rainfall (In)
NOAA Atlas 14	24 Hour	10 Year	4.90
	6 Hour	2 Year	2.14
	1 Hour	10 Year	1.67
2070 Projected Climate Resilient Design Standards Tool	24 Hour	10 Year	6.60
	24 Hour	5 Year	5.60

Existing system model scenarios were completed for the following rainfall events:

- NOAA Atlas 14 10-Year 24-Hour Rainfall (City Wide)
- NOAA Atlas 14 10-Year 1-Hour Rainfall (City Wide)
- Year 2070 Projected 10-Year 24-Hour Rainfall (City Wide)
- Year 2070 Projected 5-Year 24-Hour Rainfall (2 of 4 Priority Areas)

Following discussions with the city, NOAA Atlas 14 10-Year 24-Hour was selected as the design storm for the alternatives analysis. The NOAA Atlas 14 2-Year 6-Hour Rainfall was used for the Nature Based Solutions/Green Infrastructure Screening.

3.5 Predicted Flooding

System flooding totals for the 10-Year 24-Hour NOAA Atlas 14 present day rain event summary and Year 2070 Projected 10-Year 24-Hour Rainfall event summary, shown in the table below, was utilized in the evaluation of selecting the priority areas to be analyzed for alternatives improvement planning. The flooded volumes shown in Table ES-2 represent the flow that leaves the drainage system when the water level in the pipe and drain manhole network reaches the ground level and pops a manhole cover allowing the flow to leave the system and flow overland, creating surface flooding. The flooded volume represents all flooded nodes (typically a manhole or connection) within the watershed at various locations. The impact and depth of surface flooding will be identified under the Phase 2 – 2D Modeling Effort.

Table ES-2: City Watershed Flooding Summary

Watershed	NOAA ATLAS 14 10YR 24HR Total Flooded Volume (Million Gallons)	2070 10YR 24HR Total Flooded Volume (Million Gallons)
West	28.70	76.77
East	11.00	31.13
Central North	15.00	30.75
Central South	10.40	28.43

3.6 Priority Area Selection

Following the model runs, Weston & Sampson developed a Flood Viewer, GIS Web Application, so that city staff could view and consider multiple factors simultaneously, including:

- Observed severity and volume of flooding
- Community Impacts
- Proximity to Environmental Justice Communities

In addition, a selection matrix of fourteen subareas with the highest predicted flood volumes was prepared for the city staff. City staff attended several meetings and reviewed a selection matrix with the flood locations, which allowed them to compare the model results to historic flooding data. The selection of the priority areas is further described in Section 7 of the report.

Four priority subareas out of forty-eight were selected (see Figure ES-14 on right) for an alternatives analysis, and include:

- West Sub 5, which includes Pelham Street Area (Pelham Street, Roxbury Street, Highland Street, and Sever Street), and Chandler Street Area (Brownell Street, Calmia Street, and Chandler Street)
- West Sub 9, which includes Park Ave at Parker Street.
- Central North Sub 10, which includes Grove Street, Indian Lake Parkway, and Alexander Road.
- Central North Sub 4, which is upstream of the Saint Gobain property and is tributary to Weasel Brook.

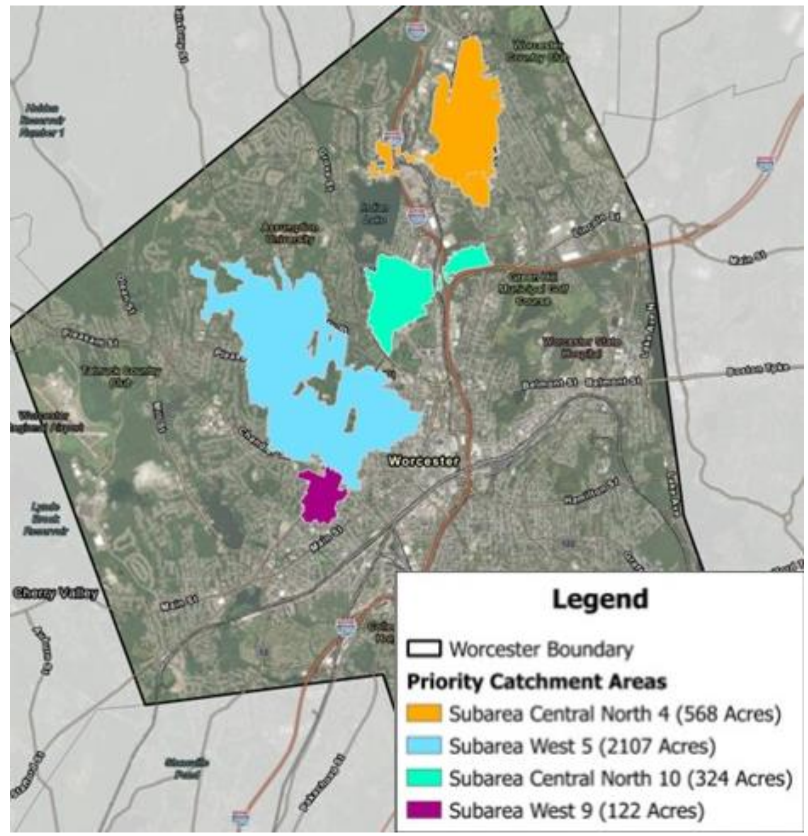

Figure ES-16: Priority Area Locations

4.0 IDENTIFICATION OF POTENTIAL FLOOD MITIGATION PRACTICES

4.1 Grey Flood Mitigation Practices

Alternative models were created for the present-day NOAA Atlas 14 10-Year 24-Hour rainfall of 4.9 inches and the projected 2070 10-Year 24-Hour rainfall of 6.6 inches.

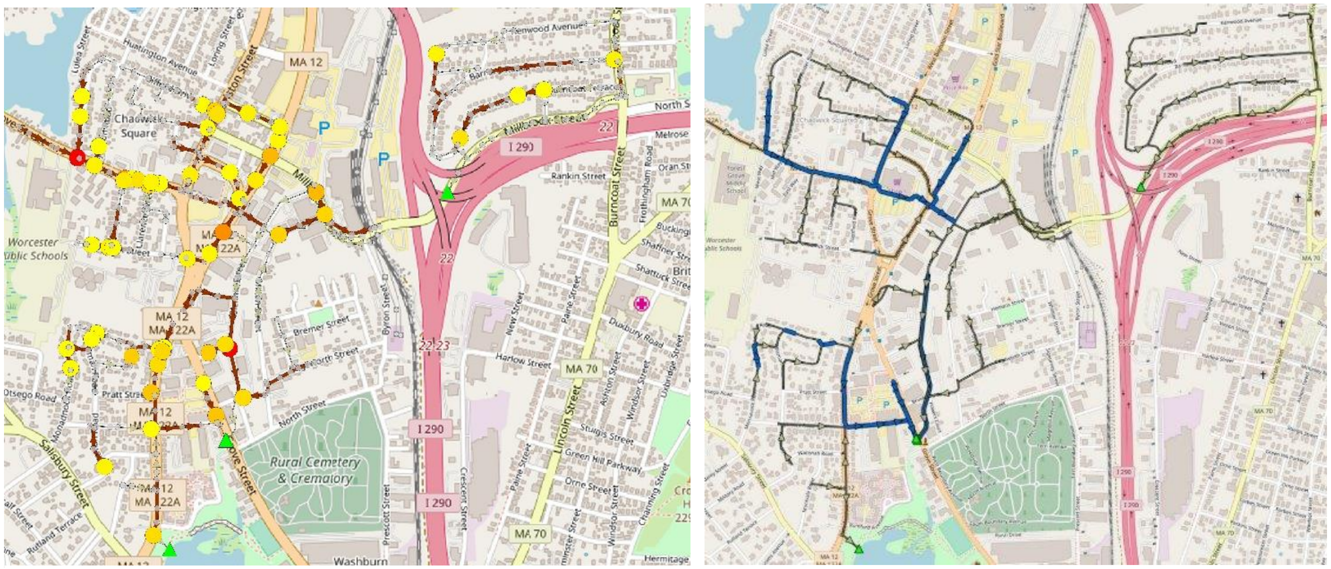

Figure ES-17: Alternate Models

The objective of this initial alternative analysis was not to resize all the pipes that flooded throughout the subarea but to focus on major public travel corridors most affected by the flooding. In all the alternative analysis completed, the capacity needed for upstream tributary flooding volume was included in the design alternative based on the assumption that the upstream flooding will be eliminated in the future. Figure ES-15 on the left identifies all surcharged and flooding nodes within the sub area. Figure ES-15 on the right highlights the pipes that were selected for replacement. The pipes on the right will be sized to provide capacity to carry the entire volume of flooding for the subarea. This approach will ensure the pipes are sized with the capacity to handle the volume from all flooded nodes within the subarea when the upstream pipes are improved. Please note that the lightest yellow flooded nodes on the left represent lowest flooding volumes in the subarea.

A summary of the pipe replacement sizes, lengths, and estimated planning costs is included in Table ES-3 below.

Table ES-3: Summary of Pipe Information

Subarea	Storm Event	Pipe Replacement Description	Estimated Quantity (LF)	Estimated Design and Construction Cost
West SUB 5	NOAA ATLAS 14 10YR 24HR	Reinforced Concrete Pipe Class III (15-inch to 60-inch)	14,490	$75,600,000
		Reinforced Concrete Box Culvert (5-foot by 8-foot to 6-foot by 12-foot)	8,760	
	2070 10YR 24HR	Reinforced Concrete Pipe Class III (15-inch to 66-inch)	18,280	$113,900,000
		Reinforced Concrete Box Culvert (5-foot by 5-foot to 6-foot by 16-foot)	13,640	
West SUB 9	NOAA ATLAS 14 10YR 24HR	Reinforced Concrete Pipe Class III (18-inch to 60-inch)	5,960	$13,800,000
		Reinforced Concrete Box Culvert (5-foot by 6-foot)	1,580	
	2070 10YR 24HR	Reinforced Concrete Pipe Class III (18-inch to 54-inch)	4,620	$24,200,000
		Reinforced Concrete Box Culvert (4-foot by 5-foot to 5-foot by 12-foot)	3,460	
Central North SUB 10	NOAA ATLAS 14 10YR 24HR	Reinforced Concrete Pipe Class III (15-inch to 60-inch)	9,320	$14,300,000
	2070 10YR 24HR	Reinforced Concrete Pipe Class III (15-inch to 60-inch)	7,920	$27,700,000
		Reinforced Concrete Box Culvert (5-foot by 6-foot to 5-foot by 10-foot)	3,570	

Subarea	Storm Event	Pipe Replacement Description	Estimated Quantity (LF)	Estimated Design and Construction Cost
Central North SUB 4	NOAA ATLAS 14 10YR 24HR	Reinforced Concrete Pipe Class III (15-inch to 60-inch)	12,700	$15,500,000
	2070 10YR 24HR	Reinforced Concrete Pipe Class III (15-inch to 66-inch)	14,070	$18,800,000
Total for Four Priority Areas	**NOAA ATLAS 14 10YR 24HR**	**Reinforced Concrete Pipe Class III and Reinforced Concrete Box Culvert**	**52,810**	**$92,380,000**
	2070 10YR 24HR	**Reinforced Concrete Pipe Class III and Reinforced Concrete Box Culvert**	**65,560**	**$184,600,000**

Existing drain pipe sizes in the priority areas range from 10-inch diameter to 6-foot by 11-foot box shaped culverts. The grey infrastructure alternatives analysis shows that pipe sizes ranging from 15-inch diameter to 6-foot by 16-foot box shaped culverts are needed to contain the runoff produced by the design storms. There will likely not be room for some or most of the large diameter and box shaped culverts to be installed under the roadway due to existing utility conflicts. It will be important to try to find city owned property within each subarea to infiltrate and/or store the runoff when possible. This may help reduce the size of the grey infrastructure needed to capture the runoff from the selected design storm.

Phase 2 of the DMP will expand the model to open channels and waterways. This will allow the pipe models to be connected via open channel, waterways and wetlands and will provide a holistic view of the drainage system.

4.2 Nature Based Solutions Opportunities

Weston & Sampson identified opportunities to implement nature-based solutions (NBS) in the four selected areas (Central North 4, Central North 10, West 5, and West 9) as shown in the figure. Opportunities to implement NBS were sited in locations that are both known to experience flooding present day, and are anticipated to experience flooding in the future, informed by the following data sources:

- 10-year 24-hour present day flooded nodes from the Worcester Drainage Master Plan Flood Model (2024, Weston & Sampson)
- Reports of flooding point data (City of Worcester, 2024)
- Flooding complaint map (City of Worcester, 2016)

The types of NBS were selected based on topography, existing site conditions, land use type, and city staff site knowledge. Across the four priority areas, 212 total NBS opportunities were identified. An approximate flood storage volume was calculated for each opportunity based on the type of NBS and then entered into the model to estimate a flood reduction benefit based on the peak runoff reduction in cubic feet per second (cfs) and total flood volume reduction in million gallons (MG) provided by each opportunity. The table on the following page (Nature-Based Solutions Opportunities by Priority Area) summarizes the opportunities identified and the associated estimated storage created by priority area. Model runs were performed for each NBS opportunity and the output provided was the estimated volume of runoff for a present day 2-Year 6-Hour storm.

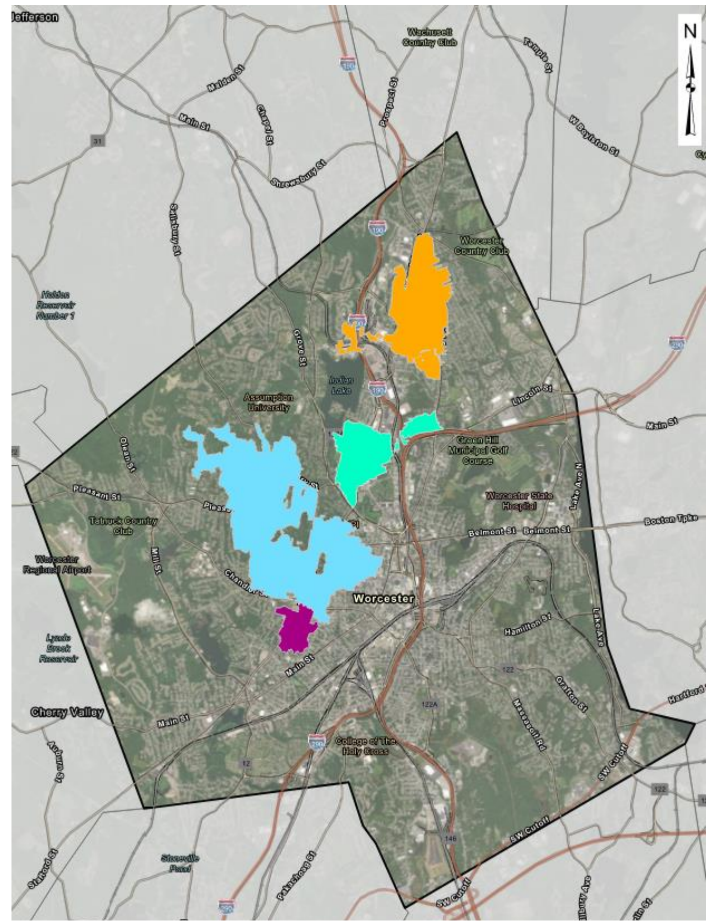

Figure ES-18: Priority Areas for NBS Screening

According to the Massachusetts Municipal Vulnerability Preparedness Program, Nature-Based Solutions (NBS) are climate adaptation measures "focused on the protection, restoration, and/or management of ecological systems to safeguard public health, provide clean air and water, increase natural hazard resilience, and sequester carbon." As Worcester continues to experience increasingly frequent, extreme storm events, drought, and heat, NBS provide more resiliency in response to these variable conditions than traditional stormwater infrastructure.

Examples of NBS include the items listed below.

Bioretention / Rain Gardens

Swales

Tree Box Filters

Figure ES-19: Examples of nature-based solutions. Photos by Weston & Sampson.

It should be noted that subsurface infiltration, on its own, is considered a "grey" solution, not NBS. However, subsurface infiltration can be tied to a surface NBS practice like those shown above and provide additional flood storage.

Table ES-4: Nature-Based Solutions Opportunities by Priority Area

Priority Area	Percent Impervious	Number of NBS Opportunities	Potential NBS Footprint (acres)	Estimated Storage [1] (cubic feet)	Estimated Storage [2] (MG)
Central North Sub 4	49%	63	2.70	168,481	1.26
West Sub 5	36%	94	2.33	149,440	1.12
Central North Sub 10	53%	25	0.58	27,976	0.21
West Sub 9	66%	13	2.16	104,556	0.78
TOTAL	-	**195**	**7.77**	**450,453**	**3.37**

(1) The estimated storage volume was determined by running the model for the present day 2-Year 6-Hour storm.
(2) 1 cubic foot is approximately 7.481 gallons of liquid.

4.2.1 Prioritization Process

The model output data were used to prioritize the opportunities in how effective they are at capturing and retaining stormwater. Specifically, the peak runoff reduction under the present day 2-year 6-hour storm was used for prioritizing the opportunities. This serves as a proxy for peak flow attenuation of the associated estimated storage created by a short-duration rainfall event, which is quite typical of New England summer storms. Traditional drainage systems comprised of grey infrastructure often struggle to capture runoff from events like this due to the volume of water produced in a short period of time.

The model simulates the additional storage provided by each of the identified NBS opportunities and reports a reduction in peak runoff volumes due to this additional storage. NBS opportunities in each priority area were prioritized by their estimated peak runoff reduction along with input and consensus from the City staff.

In a next phase of work, further refinement will be needed to reflect constructability (e.g., soils present on site, depth to groundwater, utility conflicts, etc.), abutter engagement, construction costs vs. designed storage, and maintenance considerations.

It is important to note that public-private partnerships would be beneficial and, in many cases necessary, to accomplish many of the NBS installations. Available space for NBS in a developed area is often on private property as there are limited city-owned or operated space, even with consideration of the right-of-way along roadways. Successful large-scale implementation requires distribution of these practices across a wide land area.

4.2.2 Central North Sub 4 Priority GSI

Priority area Central North Sub 4 is 568 acres, the western portion is commercial along West Boylston Street, and the eastern portion is residential. This priority area also contains Quinsigamond Community College in the center. It is 49% impervious and does not contain any major water bodies, however it is upstream of Indian Lake. In priority area Central North Sub 4, a total of 63 NBS opportunities were identified, summing to approximately 2.70 acres of total surface area, and creating approximately 168,481 cf of total storage.

The 63 identified NBS opportunities were modeled and ranked by reduction in peak runoff, a proxy for flood reduction effectiveness. The top ten ranking opportunities are listed in Table ES-5 below: Top 10 NBS Opportunities in Central North Sub 4. Note that all top 10 NBS opportunities are located on public land.

Table ES-5: Top 10 NBS Opportunities in Central North Sub 4

Unique ID	Type	Location	Unique ID	Type	Location
11	Surface Green Practice + Subsurface Infiltration	Quinsigamond Community College	**25**	Bioretention	Shore Dr @ South Frontage Rd

Unique ID	Type	Location
10	Surface Green Practice + Subsurface Infiltration	Quinsigamond Community College
3	Surface Green Practice + Subsurface Infiltration	Greendale Elementary School
2	Surface Green Practice + Subsurface Infiltration	Burncoat St Preparatory School
8	Surface Green Practice + Subsurface Infiltration	Quinsigamond Community College

Unique ID	Type	Location
69	Bioretention	670 W Boylston St near QCC
50	Bioretention	Quinsigamond Community College
51	Bioretention	Quinsigamond Community College
14	Bioretention	Quinsigamond Community College

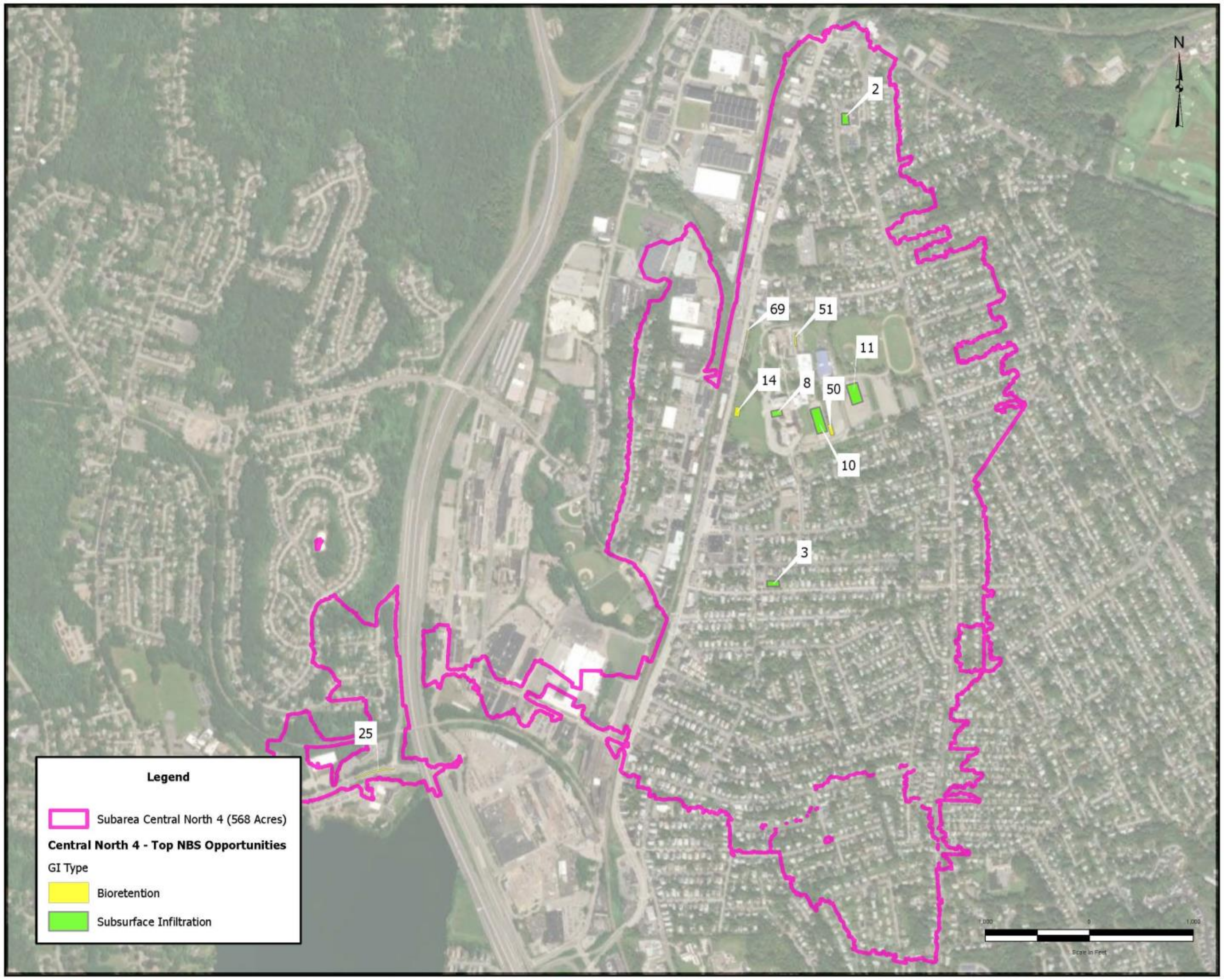

Figure ES-20: Central North Sub 4 - Top NBS Opportunities

4.2.3 Central North Sub 10 Priority GSI

Priority area Central North Sub 10 is 324 acres, the western and eastern portions are residential, and the central portion along West Boylston Street, Park Avenue, and Grove Street is commercial. The priority area is bisected by I-190. It is 53% impervious and does not contain any major water bodies. In priority area Central North Sub 10, a total of 25 NBS opportunities were identified, summing 0.58 acres of total surface area, and creating approximately 27,976 cf of total storage.

The 25 identified NBS opportunities were modeled and ranked by reduction in peak runoff, a proxy for flood reduction effectiveness. The top ten ranking opportunities are listed in Table 9-3: Top 10 NBS Opportunities in Central North Sub 10. Note that all top 10 NBS opportunities are located on public land.

Table ES-6: Top 10 NBS Opportunities in Central North Sub 10

Unique ID	NBS Type	Location
1	Bioretention	Forest Grove Middle School
12	Bioretention	Forest Grove Middle School
3	Bioretention	44 W Boylston Street
2	Bioretention	Forest Grove Middle School
6	Bioretention	Median between Grove St and W Boylston St

Unique ID	NBS Type	Location
28	Bioretention	455 Grove Street
18	Bioretention	41 Park Ave
19	Bioretention	49 Park Ave
25	Bioretention	44 W Boylston St
29	Bioretention	456 Grove Street

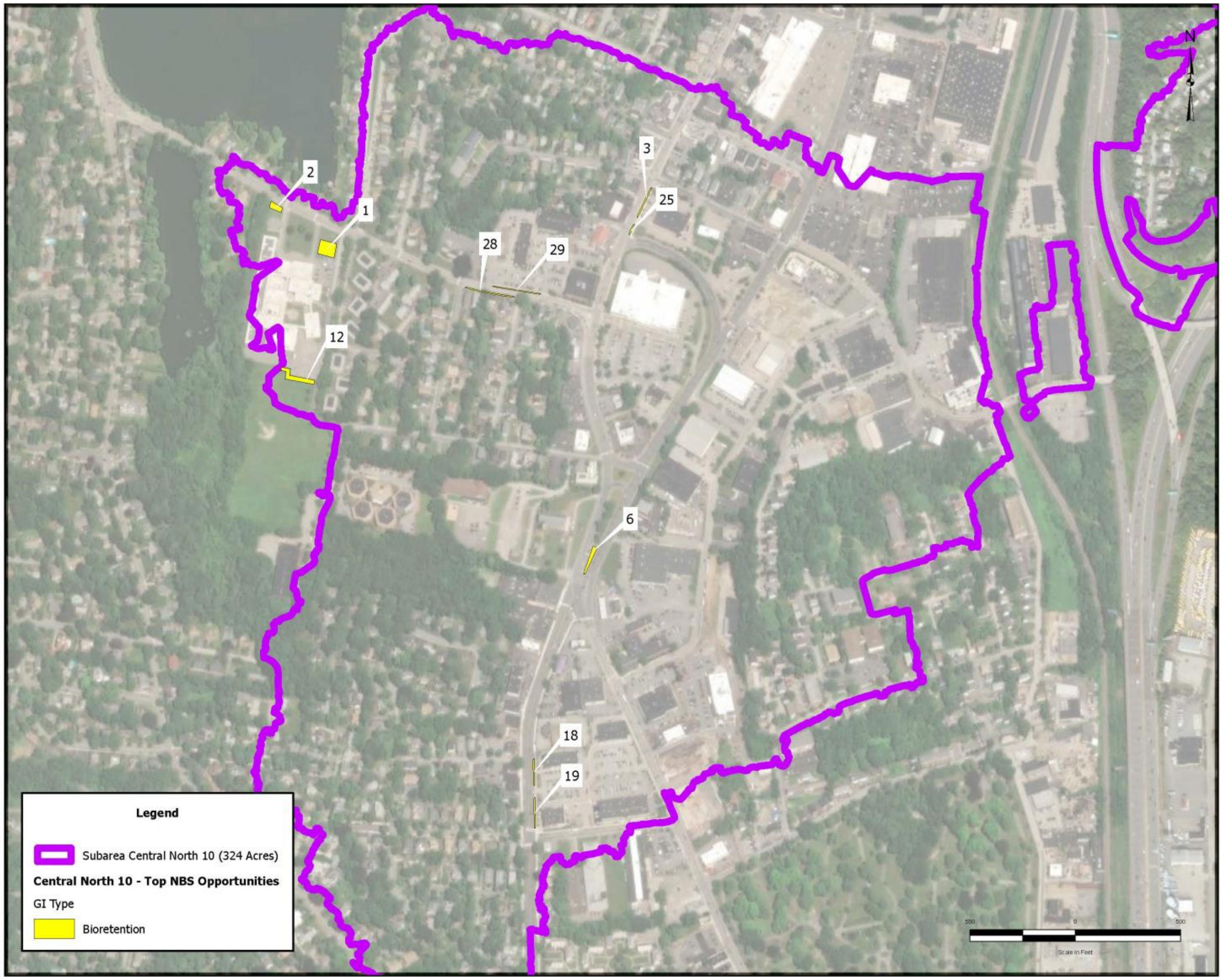

Figure ES-21: Central North Sub 10 - Top NBS Opportunities

4.2.4 West Sub 5 Priority GSI

Priority area West Sub 5 is 1,389 acres and mostly residential. It is 36% impervious, and contains many large open spaces such as Elm Park, Newton Hill, and General Foley Stadium. It does not contain any major water bodies. In priority area West Sub 5, a total of 94 NBS opportunities were identified, summing 2.33 acres of total surface area, and creating approximately 149,440 cf of total storage.

The 94 identified NBS opportunities were modeled and ranked by reduction in peak runoff, a proxy for flood reduction effectiveness. The top ten ranking opportunities are listed in Table 9-4: Top 10 NBS Opportunities in West Sub 5. Note that all top 10 NBS opportunities are located on public land.

Table ES-7: Top 10 NBS Opportunities in West Sub 5

Unique ID	Type	Location
1	Surface Green Practice + Subsurface Infiltration	Flagg St Elementary School
13	Surface Green Practice + Subsurface Infiltration	Foley Athletic Complex
112	Bioretention	Park Ave along Elm Park
33	Surface Green Practice + Subsurface Infiltration	Farber Field
63	Bioretention	Beeching St @ Lenox St
121	Bioretention	Chandler Street @ Foley Athletic Complex

Unique ID	Type	Location
16	Surface Green Practice + Subsurface Infiltration	Elm Park Community School
11	Surface Green Practice + Subsurface Infiltration	Wetherell Park

Unique ID	Type	Location
24	Bioretention	69 Sever St
10	Surface Green Practice + Subsurface Infiltration	Midland St Elementary School

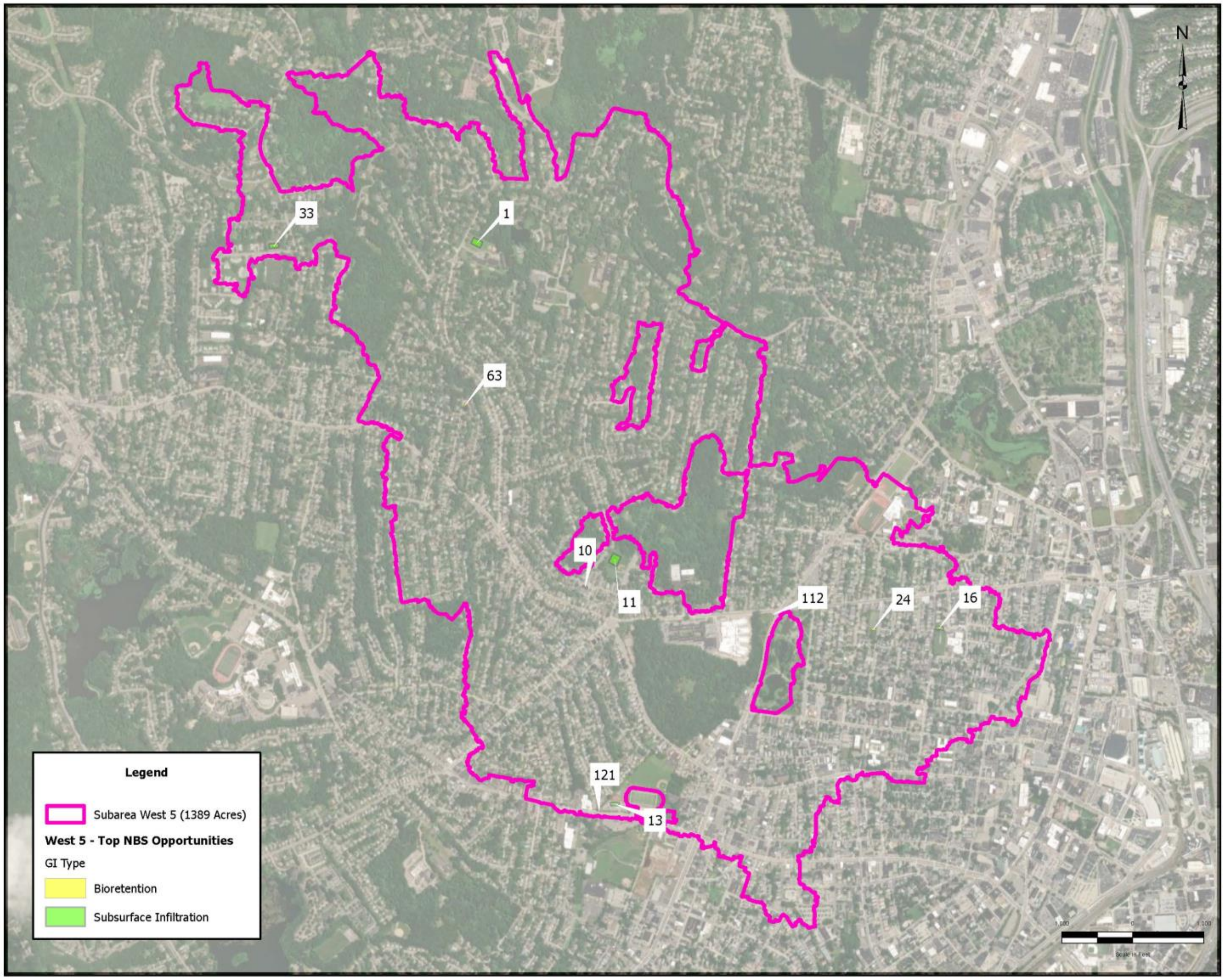

Figure ES-22: West Sub 5 - Top NBS Opportunities

4.2.5 West Sub 9 Priority GSI

Priority area West Sub 9 is 122 acres, the eastern portion is residential, and the central portion along Park Avenue is commercial. It is 66% impervious and contains Beaver Brook Park in the West where Beaver Brook runs through before going underground.

In priority area West Sub 9, a total of 13 NBS opportunities were identified, summing 2.19 acres of total surface area, and creating approximately 104,556 cf of total storage. The 13 identified NBS opportunities were modeled and ranked by reduction in peak runoff, a proxy for flood reduction effectiveness. The top ten ranking opportunities are listed in Table 9-5: Top 10 NBS Opportunities in West Sub 9. Note that all top 10 NBS opportunities are located on public land.

Table ES-8: Top 10 NBS Opportunities in West Sub 9

Unique ID	Type	Location
4	Surface Green Practice + Subsurface Infiltration	Fire Station Engine 4
8	Bioretention	Dewey St @ May St
10	Bioretention	360 Park Ave
6	Bioretention	360 Park Ave
3	Bioretention	Fire Station Engine 4

Unique ID	Type	Location
14	Bioretention	400 Park Ave
11	Bioretention	368 Park Ave
21	Bioretention	Mixter Square – Mason St @ Winfield St
5	Tree box filters	450 Park Ave
13	Bioretention	490 Park Ave

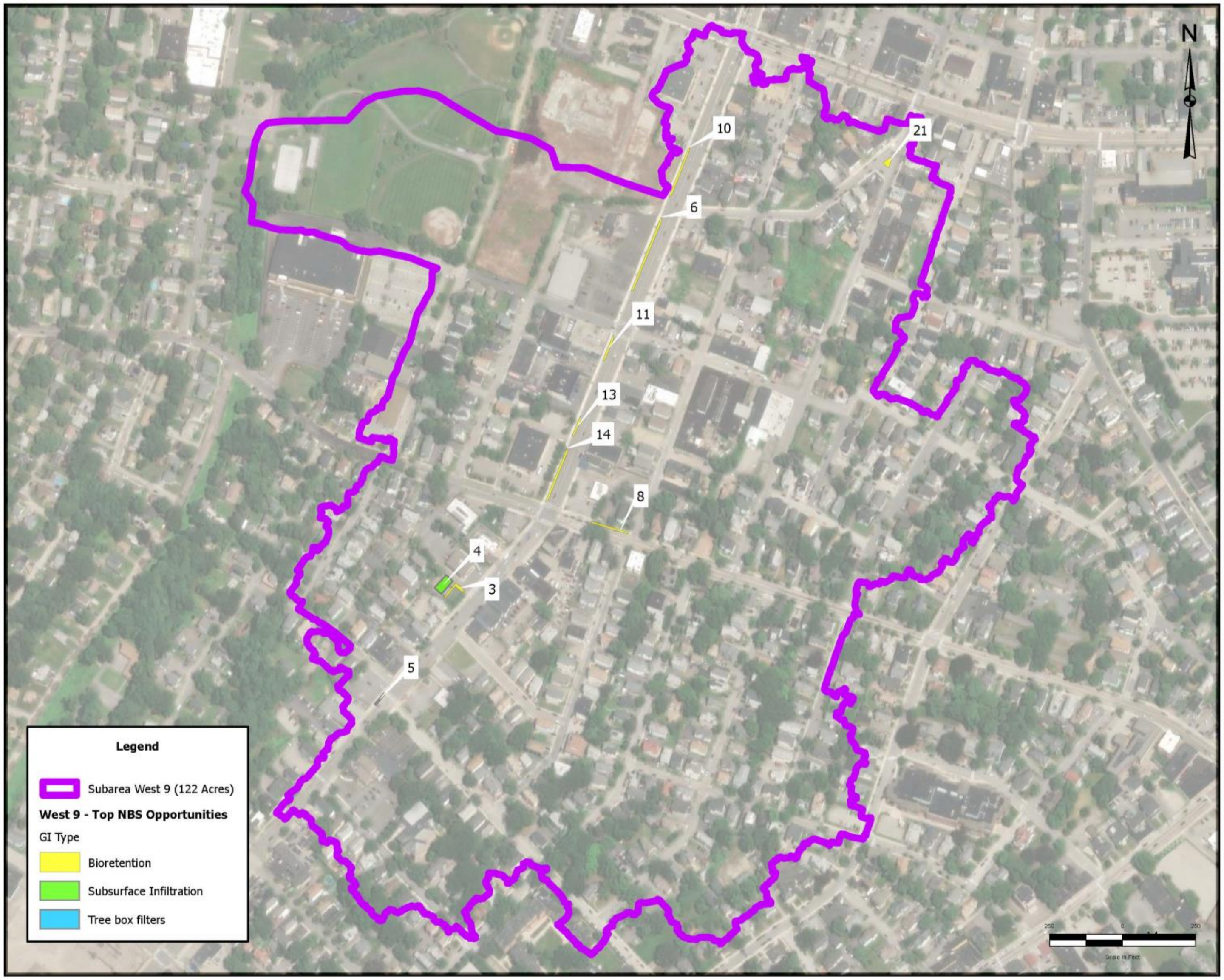

Figure ES-23: West Sub 9 - Top NBS Opportunities

5.0 CONCLUSIONS AND RECOMMENDATIONS

Weston & Sampson developed a H&H model of the existing drainage system for the City of Worcester that evaluates existing (NOAA Atlas 14 10-Year 24-Hour) and future (2070 10-Year 24-Hour) rainfall events and estimates system flooding. The current DMP system evaluation model developed in PCSWMM included the DPW&P managed closed pipe drainage system components outside of the Combined Sewer Area. This modeling effort for the DMP is Phase 1 of H&H modeling required for a complete DMP. The results of the city-wide modeling effort showed extensive stormwater system capacity limitations and projected flooding for the present day 10-Year 24-Hour rainfall event. The increase of the rainfall from present day NOAA Atlas 14 (4.9 inches) to future 2070 projections (6.6 inches) significantly increased the volume of potential flooding that may be experienced in the city. The results of the present-day modeling were corresponding with documented flooding in several city areas.

In Phase 2, the open channels and waterbodies will be assessed and added to the model. In addition, the information from the Combined Sewer Area and Green Island flooding that is being developed under a sperate project will be incorporated into the model.

1. **Calibration & Validation of H&H Model:** The current model has minimal calibration. The next step includes working to develop a field data collection program to provide flow data allowing model adjustments and eventual model calibration on a subarea basis. It is recommended that the City continue the field verification program for at least three months and ideally around 1 year to obtain city-wide model calibration.
2. **Inclusion of Open Channels and Surface Water Bodies:** Phase 2 Modeling is strongly recommended before the process of design and construction of the proposed alternative improvements in the priority areas is initiated. An existing condition model that includes the city's open channel, streams, brooks, and rivers will need to be developed to establish the level of conveyance and flooding conditions.
3. **Development of 2-Dimensional Modeling:** Phase 2 modeling will also include development of a 2-Dimensional model reflecting flooding extents and depths throughout the City.
4. **Integration with the CSO Modeling:** Phase 2 modeling would include flows to the drainage network from any separation analysis or design projects in the Combined Sewer Area currently being developed and or part of a future separation plan or analysis within.
5. **Continued Evaluation of Green/Grey Alternatives:** As part of a future phases, it is recommended that the City consider performing alternative analyses for both grey and NBS for the remaining subcatchment areas when additional model calibration and funding becomes available.

6. **Evolution of Web Application**: For continued improvement of the web application, it is suggested that the City:

- Review the Flooding Complaint Heat Map from 2006 to 2016 and the Flooding Complaints layer from 2017 to 2023 to remove any calls not related to flooding due to system capacity issues such as clogged catch basins and water main breaks.
- Continue with a model calibration program through rain event system data collection and observations to fine tune the model flooding results, flooded node table, and update the web application.