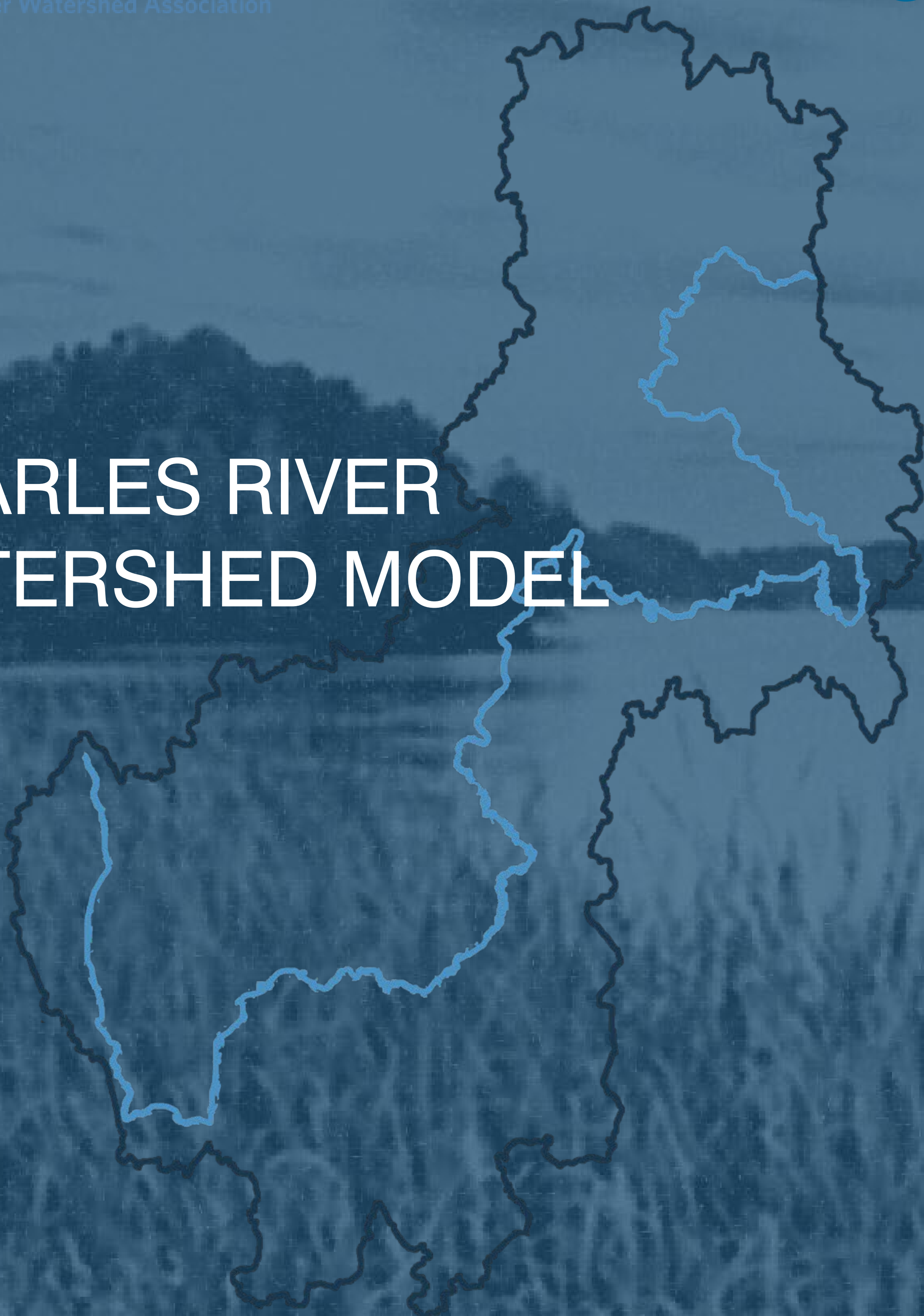
Charles River Watershed Association

CHARLES RIVER WATERSHED MODEL



Charles River Watershed Association

Acknowledgements

This regional effort would not have been possible without the efforts of many people working diligently over the project period. The Charles River Climate Compact would like to recognize the Town of Natick, and Marianne Iarossi and Jillian Wilson-Martin in particular, for serving as the fiscal agent for this program. Marianne and Jillian managed project contracting as well as grant reporting and reimbursements, and this initiative would not have been possible without them. We would also like to acknowledge the team at Charles River Watershed Association including Julie Wood, Iris Seto, Dira Johanif, and Nishaila Porter for their efforts on the project supporting both the technical work and public engagement and keeping the project on track. We would also like to acknowledge the talented team at Weston & Sampon who developed the Charles River Flood Model in record time. In particular we thank Indrani Ghosh, PhD, who in addition to bringing extensive technical skills, know how, and experience, also served as an excellent project spokesperson to the project team and the public. Steve Roy also served as a project manager, bringing insights to the work and keeping the project on track. Finally, we thank their entire technical team: Andrew Walker, Robin Seidel, Deanna Lambert, Rupsa Roy, Lindsey Adams, and Eliza Jobin-Davis; we appreciate your late nights/early mornings and cold weather field outings! We would also like to acknowledge the team from CREW who worked extremely hard to make public engagement a successful element of this project despite the ongoing challenges of the COVID-19 pandemic. CREW brought a unique perspective and skill set to the project that made it more successful than it would have been without them. Thank you Ethan McDonough, Anna Simon, and Grace Morrissey. This project would also not have been possible without the active participation of municipal staff from project team communities, thank you for your timely collection of data and information, regular meeting attendance and feedback, financial support, and continued support for this effort despite the very tight timeline. Finally, this project would not have been possible without funding from the Municipal Vulnerability Preparedness (MVP) Action grant program. Thank you for your support of the project both financial and otherwise!

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EXECUTIVE SUMMARY

The Town of Natick, in partnership with fourteen other communities and the Charles River Watershed Association (CRWA) teamed up to develop the Charles River Flood Model. Weston and Sampson was engaged as the project technical lead to design and build the model. Communities Responding to Extreme Weather (C.R.E.W.) was engaged to assist with community engagement, especially to residents of environmental justice communities and community-based organizations that work with climate vulnerable populations.

Existing models, data, and reports from the watershed communities, the Massachusetts Water Resources Authority (MWRA), and the Department of Conservation and Recreation (DCR) were utilized as a baseline for the model. The project Technical Team, made up of Weston & Sampson and CRWA, built upon previous efforts to the maximum extent practicable by engaging project partners and utilizing previous studies and models to compensate for the tight project timeline and budget restraints, and to not duplicate prior work conducted in the watershed.

The model was developed for the watershed area draining to the Watertown Dam and comprises of over 270 square miles. This represents the upper/middle Charles River watershed and will complement extensive flood modeling work that has already been done for the lower Charles River watershed. The Charles River Flood Model represents the impacts of flooding across the watershed from various types and sizes of rainstorms under both present and future climate scenarios, and can also be used to test the efficacy of various flood mitigation measures. Considerable public input was also sought to inform the modeling scenarios run during the project.

The team modeled ten different 24-hour duration rainstorms:

- Three present day storms: 2-yr or 50% chance of occurring annually,10-yr or 10% chance of occurring annually, and 100-yr or 1% chance of occurring annually;
- Six corresponding future storm scenarios: 2-yr, 10-yr and 100-yr design storm events projected for mid-century (2030/2050), and the 2-yr, 10-yr, and 100-yr design storm events projected by late in the century (2070/2090)
- One extreme rain event of 11.7 inches in 24 hours, which was used in a similar modeling effort in the neighboring Mystic River watershed

Future rain events can impact between 1,200 and 1,900 additional acres of watershed that are not flooded

Table ES 1 Change in flooding between present and 2070.

		Acres of flooding (ac)	Runoff Volume (MG)
2-yr Storm	Present	3,490	3,053
	2070	4,719	4,264
	Increase from Present	*+1,229 (+35%)*	*+1,211 (+40%)*
10-yr Storm	Present	7,243	7,368
	2070	8,928	10,651
	Increase from Present	*+1,685 (+23%)*	*+3,283 (+45%)*
100-yr Storm	Present	11,067	17,321
	2070	12,500	25,568
	Increase from Present	*+1,433 (+13%)*	*+8,247 (+48%)*
Mystic 100-yr Storm	2070	13,001	30,794
	Increase from Present	*+1,934 (+18%)*	*+16,473 (+95%)*
March 2010 Storm (8.99 inches)		10,446	20,831

under current conditions, depending on the type of the storm. Additionally, many areas that currently experience modest or nuisance flooding are likely to experience more severe flooding as a result of larger and more frequent storms (Figure ES.1). This increased flooding could also impact additional critical facilities and infrastructure and climate vulnerable residents.

The team also assessed the impacts of six different flood mitigation strategies described below. Each strategy employs nature-based solutions (NBS), which are 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. The goal and impacts of each of these strategies are presented in Table ES.2. Incorporating NBS in local planning and design projects produces long-term solutions that benefit human and natural systems.

The Charles River Flood Model demonstrates that implementing these changes on the ground will reduce the impacts of climate change driven flooding. However, to fully mitigate the impacts of climate change, or to offer additional protection to people and property, more aggressive flood mitigation measures will be needed. It will take considerable investment and on the ground changes, beyond what may be considered feasible today to truly mitigate projected flooding impacts. None of the scenarios modeled in the study were able to fully mitigate the projected impacts of climate change. With this understanding, it is expected that future flood resiliency planning and implementation across the region will need to adopt bold and aggressive actions to mitigate projected climate change impacts. Model results also highlight the potentially devastating impacts of unabated development across the watershed. If just half of the potentially developable open spaces are developed, it can impact thousands of acres that are not currently flooded and exacerbate existing flooding. Communities must begin to review, develop, practice, and explore opportunities to build density that allow them to protect existing open spaces, which are clearly providing critical flood protection today.

The report and the accompanying appendices describe the project work in detail. Additional information and links to the online maps are available on the project webpage:
www.crwa.org/watershed-model.html. This project was funded by the Massachusetts Executive Office of Energy and Environmental Affair's Municipal Vulnerability Preparedness (MVP) program and the project team is grateful for their support.

Table ES 2 Nature based solutions considered

	Green Stormwater Infrastructure	Reduce Impervious Cover	Land Conservation	Increase Tree Canopy
Goal	• Store 2" storm runoff from up to 50% of all impervious cover town-wide with GI • 20% of priority land area designated for GSI • Storage on large (>5 acres) public properties	Reduce impervious cover in the watershed by 10%	Conserve only highest priority unprotected and undeveloped land, allow rest to be developed	Increase tree canopy by 25%
Impacts	Protects **>500 acres from flooding and reduces up to 300 million gallons of runoff** in the present day 10-yr storm Protects **>400 acres from flooding and reduces up to 270 million gallons of runoff** in the 2070 10-yr storm	Protects **>100 acres from flooding and reduces up to 70 million gallons of runoff** in the present day and 2070 10-yr storm	Add **>2,000 acres of flooding and generates 646 million gallons of runoff** if ***not*** conserved in the present day 10-yr storm Add **>1,700 acres of flooding and generates 740 million gallons of runoff** if ***not*** conserved in the 2070 10-yr storm	*For a single subwatershed:* Protects **3 acres of flooding and reduces up to 26 million gallons of runoff** in the present day 10-yr storm Protects **7 acres of flooding and reduces up to 29 million gallons of runoff** in the 2070 10-yr storm

1

INTRODUCTION

1.1 PROJECT BACKGROUND

The Charles River Watershed is already experiencing the impacts of climate change. Heavy precipitation and flooding are among the top hazards that create significant damage in the towns located within the watershed. There has been a significant increase in the intensity and frequency of precipitation over the past 50 years. In the northeastern United States, precipitation during heavy events has increased by more than 70% between 1958 and 2010.[1] Studies have shown that a rain event with a six-hour duration and a 10% annual chance of occurring has increased by 0.15 inches between 1961 and 2015. A rain event with a 24-hour duration and a 1% annual chance of occurring has increased by 1.9 inches between 1961 and 2015 (Fig. 1.1). Changes in precipitation can cause several impacts locally, including flooding, property damage, and increased pollution in waterbodies. There are two types of flooding experienced in the watershed area: riverine flooding and stormwater infrastructure flooding. Both are expected to worsen with climate change. Riverine flooding naturally occurs when waterbodies overtop their banks. This is natural and expected during large rain events such as the 100-year and 500-year flood..

Stormwater is rain or snowmelt that soaks into the soil and recharges groundwater, drains into a waterbody, or is channeled through a series of piped infrastructure until being released into a nearby waterbody. Therefore, stormwater infrastructure flooding occurs when the piped system becomes overwhelmed or when water is too quickly released into waterbodies rather than retained onsite causing waterbodies to overtop. Increased rates of streamflow from stormwater may also cause streambank erosion. Stormwater flooding can be caused by high amounts of impervious surfaces, insufficient stormwater collection, detention, and drainage, or retaining walls and culverts in poor condition.

The condition of waterbodies and of the stormwater infrastructure can play an important role in flooding. When sediment builds up in water bodies or pipes or when vegetative debris collects in water bodies or catchbasins, the functionality of the stream deteriorates and can contribute to localized stormwater flooding.

The Charles River Watershed Association (CRWA) launched the Charles River Climate Compact (CRCC) in 2019, to bring together communities in the Charles River watershed to work on climate adaptation by taking a watershed view of adaptation strategies. The CRCC identified developing a watershed scale flood model as a high priority project. Many low-lying neighborhoods in the watershed are within the 100-year and 500-year floodplains. However, flooding may occur even during the 10-year event due to inadequate capacity of stormwater systems and past development practices that significantly alter the natural hydrologic cycle. It is crucial to develop a watershed wide flood model to better understand flood risks and evaluate resiliency opportunities to address the expected impacts of climate change.

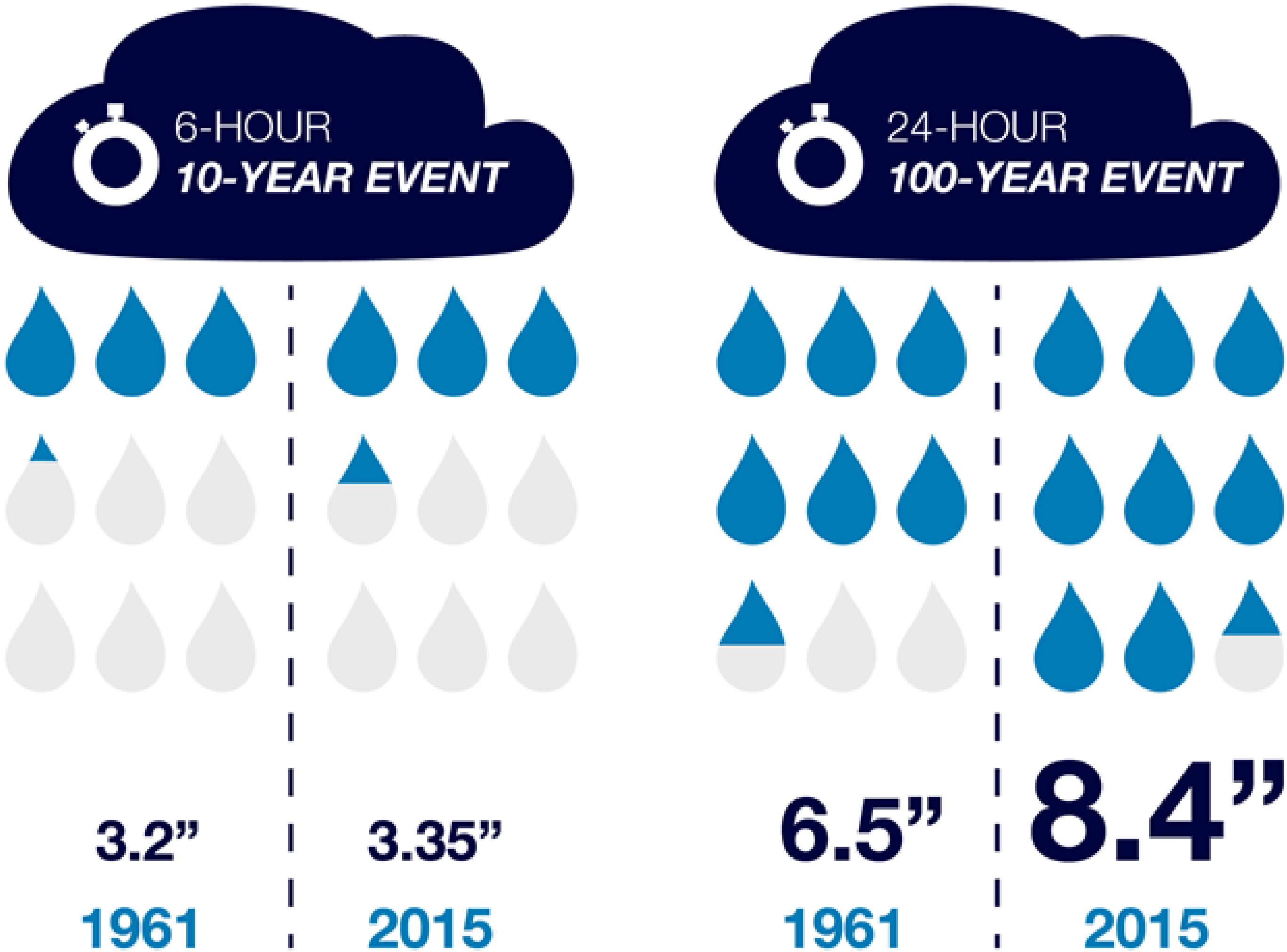


FIGURE 1.1 Historic changes in preceipitation [Source: NOAA TP-40 (1961) and NOAA Atlas Volumer 10 (2015).

1.2 Goal of the Project

The Charles River Climate Compact (CRCC) is collaborating to develop a Charles River watershed flood model. This project is funded by the Massachusetts Executive Office of Energy and Environmental Affairs (EEA) Municipal Vulnerability Program (MVP). This initiative will produce both much needed technical information about where and when precipitation driven flood-risks in the watershed are expected to be exacerbated by climate change and bring consistency across the watershed communities regarding planning and governing for expected climate impacts, thus promoting a more comprehensive and synergistic approach. The watershed model can be used to forecast expected flooding scenarios and test watershed scale adaptation strategies, serving as a tool to assist municipal staff in protecting their citizens, especially vulnerable populations, and to engage residents and businesses in enhancing climate preparedness and resilience.

1.3 Charles River Watershed Overview

A watershed is a land area where precipitation and snowmelt collect and drains into a water body, taking a path directed by topography of the land. Charles River, the longest stream entirely within the Commonwealth of Massachusetts winds through Eastern Massachusetts, stretching 80 miles (Fig. 1.2).

CRWA would like to acknowledge that here in Massachusetts, we are on sacred land that was stolen and holds history of violence and slavery. We recognize the Massachusetts, Nipmuc, and Wampanoag peoples as the traditional stewards of this land (Fig. 1.3). We honor the legacy life, knowledge, and skills stolen due to violence and colonization.

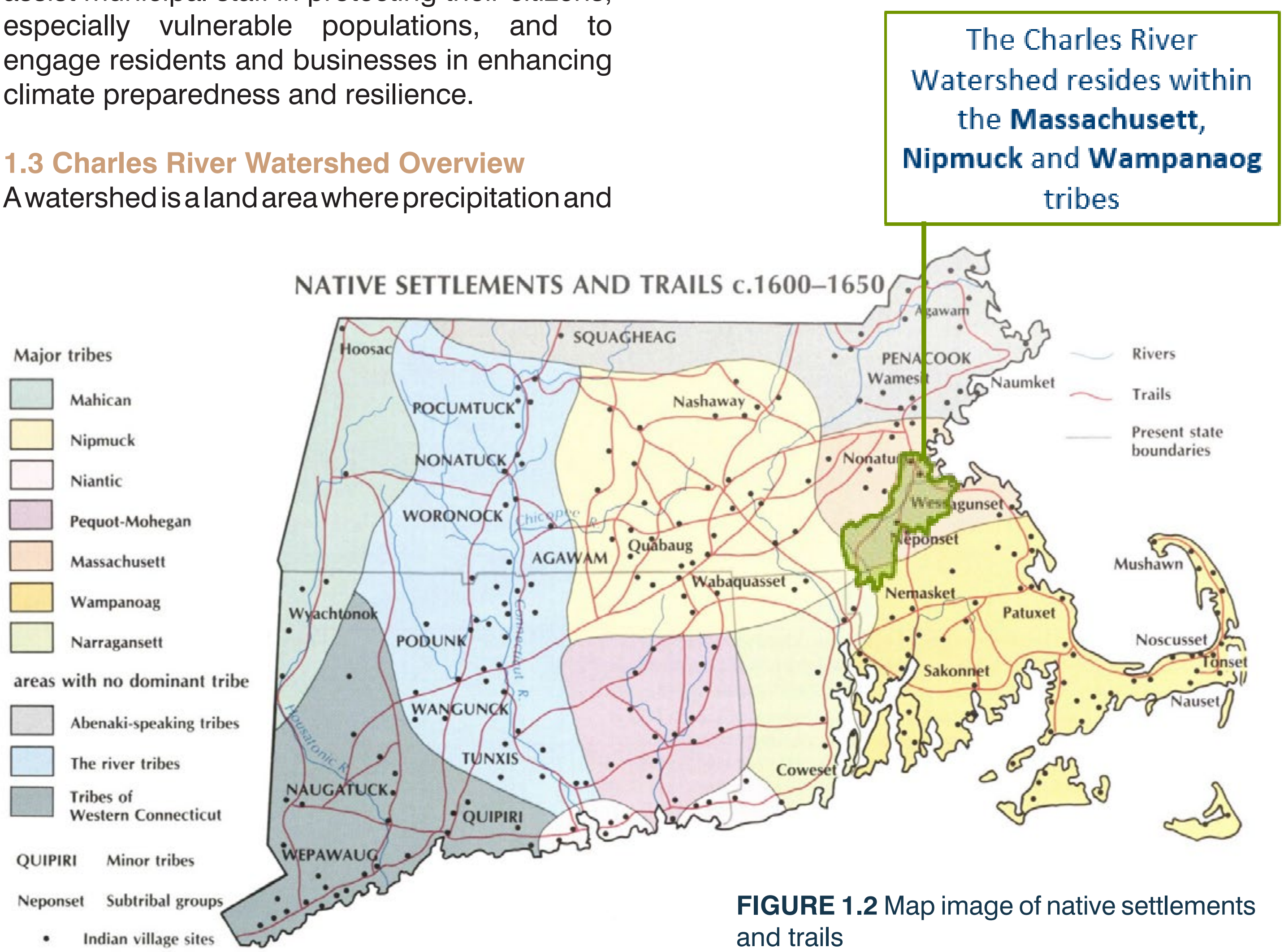


FIGURE 1.2 Map image of native settlements and trails

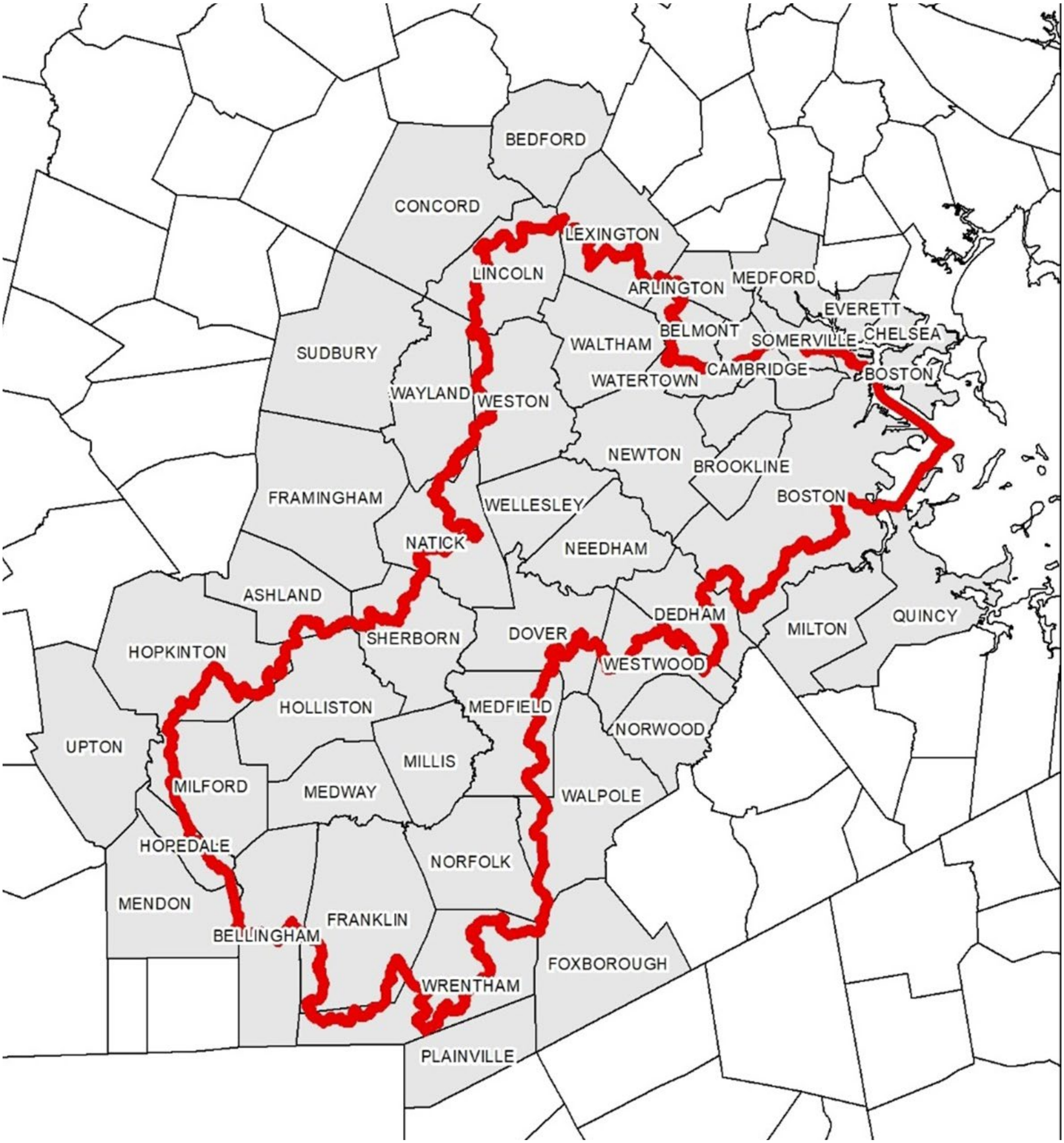


FIGURE 1.3 Project area within Charles River Watershed in red. Map showing Town boundaries.

The watershed area consists of about 310 square miles, with 29 miles of vertical stretch, and 28 miles of horizontal stretch affecting nearly 1 million people spread across 35 municipalities (Arlington, Ashland, Bellingham, Belmont, Boston, Brookline, Cambridge, Dedham, Dover, Foxborough, Franklin, Holliston, Hopedale, Hopkinton, Lexington, Lincoln, Medfield, Medway, Mendon, Milford, Millis, Natick, Needham, Newton, Norfolk, Sherborn, Somerville, Walpole, Waltham, Watertown, Wayland, Wellesley, Weston, Westwood, and Wrentham) in the Boston metropolitan region. The Charles River is a slow flowing river (302 cu ft/second) which makes it home to various species that are unique to a slow flow watershed. The watershed areas offer various recreational activities including but not limited to running/walking, hiking, cycling, kayaking, sailing, rowing/crew, etc. There are multiple playgrounds built along the river for kids' recreation. This project addresses areas in the Upper and Middle watersheds upstream of Watertown Dam. Lower watershed area is not included in the scope of this project as extensive and detailed modeling already exists for this portion of the watershed.

1.4 Modelling Overview

Flooding impacts is evaluated at the watershed scale which will be exacerbated due to changing precipitation patterns in the future. Since rain does not observe jurisdictional boundaries, the best strategy for addressing flooding is at the watershed scale. For example, an extreme precipitation event in Wellesley (located upstream), might cause flooding in Newton (located downstream) (Fig. 1.4). To understand future flooding impacts, a computer-based hydrologic/hydraulic (H/H) flood model called an H/H Model is an extremely helpful tool (Fig. 1.5). The process includes collecting and combining the drainage data from each town into one GIS map and dataset. Then the sizes and elevations of culverts, dams, and underground pipes acquired through record drawings and field measurements, are fed into the model. Finally, future climate projections are added to the model and future risk of flooding is estimated in watershed area based on the capacity of current infrastructure (pipes, culverts, and dams) to hold

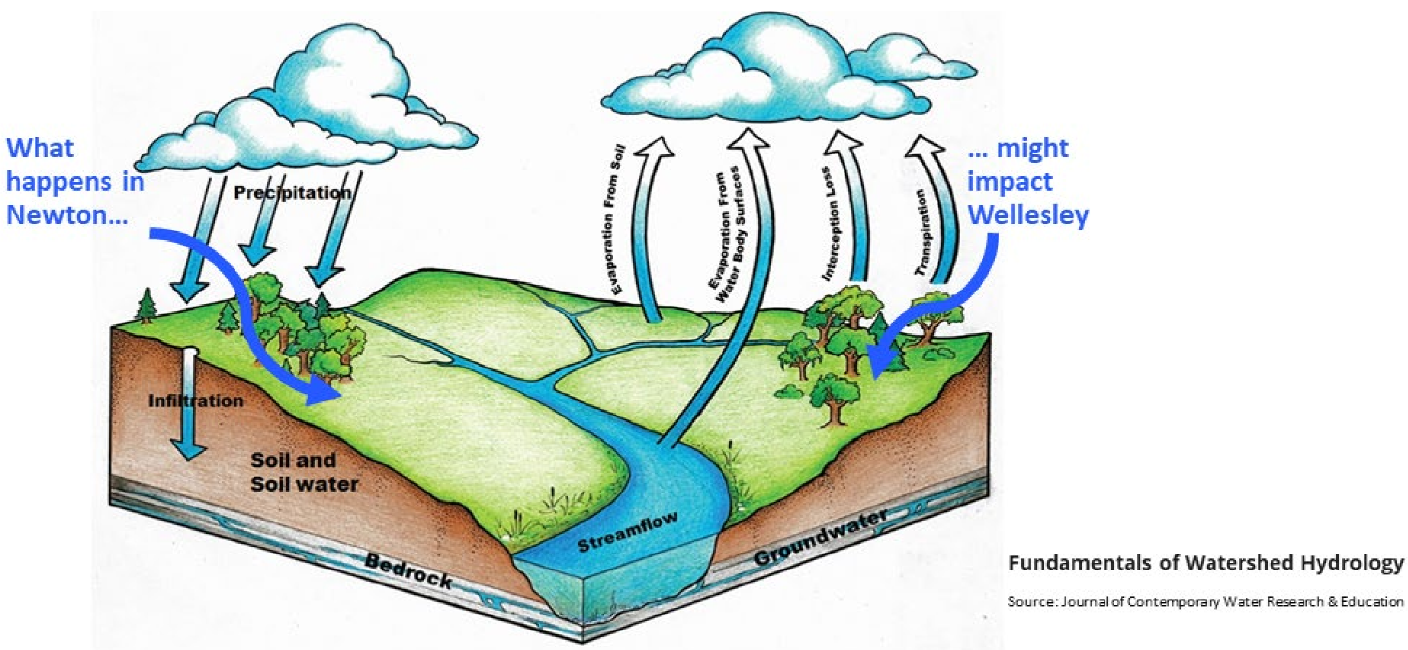


FIGURE 1.4 Importance of watershed wide model.

stormwater runoff.

This model-based approach provides multiple benefits:

- a more accurate representation of surface flooding risks
- a better understanding of flood extents, depth, volume, and duration, across the watershed
- an easier approach to evaluate and visualize flood reduction benefits

Cities and towns in the watershed will be able to utilize model results to make informed decision to prioritize the high-risk flood projects to protect public health and critical infrastructure. The model can help assess the efficacy of nature based green infrastructure solutions and other flood mitigation strategies, such as upstream flood storage, tree canopy, land conservation / land use changes, floodplain reconnection, dam removal, and wetland restoration. Flood mitigation strategies evaluated in this project are a combination of watershed wide strategies and site-specific strategies.

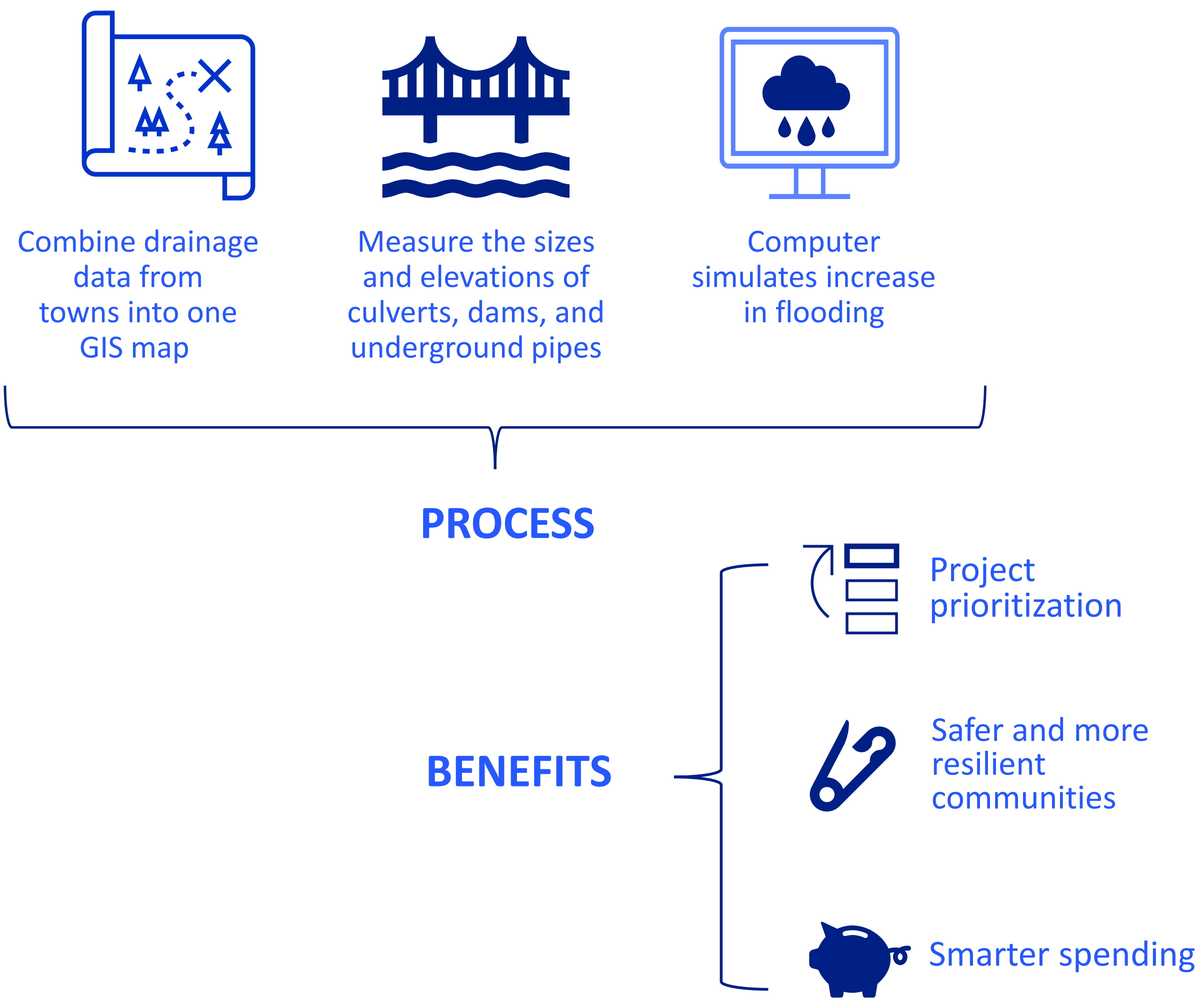


FIGURE 1.5 Illustration showing technical aspects of H/H modeling.

2

WATERSHED MODEL DEVELOPMENT

2.1 INTRODUCTION AND MODEL DESIGN

With data and input from the entire project team, project technical lead Weston & Sampson developed a stormwater model to identify likely flood-prone areas under a range of design events in a baseline climate, increases in flooding impacts during those same events under future climate scenarios, and to evaluate the potential benefit of various green infrastructure and/or development scenarios.

The model was developed with the latest version of the USEPA's Storm Water Management Model (SWMM) using the PCSWMM modeling platform. Results from the model simulation was then used to evaluate the extents and depth of flooding in the Upper and Middle watersheds, as well as estimate the total runoff volume and peak discharge rate occurring at multiple locations throughout the watershed. The model was developed to include both one dimensional (1D) component to represent the watershed, channels, and stormwater infrastructure and a two-dimensional (2D) mesh to represent surface flooding and flood conveyance in the various floodplains found throughout the watershed. Section 2 summarizes the development of that 1D/2D stormwater model and model results are discussed in Sections 3 and 5.

2.1.1 Model Geography

The model covers the upper/middle Charles River watershed, defined as the drainage area to the Watertown Dam and referred to as "the watershed" for the purposes of this report. The area draining to the Watertown Dam is approximately 169,273 acres or 265 square miles. Detailed stormwater system models already exist for Boston, Cambridge, and Somerville that constitute the lower watershed, and therefore those areas were excluded from this project. There are portions of Watertown and Newton that drain directly to the Charles River below the Watertown dam, which are not included in the detailed Boston/Cambridge model. These areas will be incorporated into the model and results will be displayed with all other project modeling results; however, they are outside the immediate scope of this project and are not summarized in this report.

2.2 ONE-DIMENSIONAL FRAMEWORK

Like all SWMM-based stormwater models, the backbone of the Charles River model is a 1D framework of successive junctions and conduits. Junctions provide the elevation of the bottom of river channels or manholes and the "rim" elevation at which flooding begins to occur. Conduits define the shape, size, material, and slope of natural river/stream channels, of bridge crossings or culverts, of dam spillways, and of storm drains. This 1D backbone of junctions and conduits is fed runoff from various subcatchments that together make up the land surface of the watershed. Some junctions may also be converted to storage nodes to represent ponds, reservoirs, and wetlands that temporarily store and attenuate some of that runoff. Fig. 2.1 provides an overview of the 1D framework of the modeled watershed. Development of each 1D model component – subcatchments, junctions, conduits, and storage nodes – is described briefly below.

2.2.1 Subcatchments

Subcatchments represent the land's response to various rainfall events. That watershed was subdivided into a series of 705 subcatchments based on the watershed's topography and the location of tributaries, wetlands, and ponds as

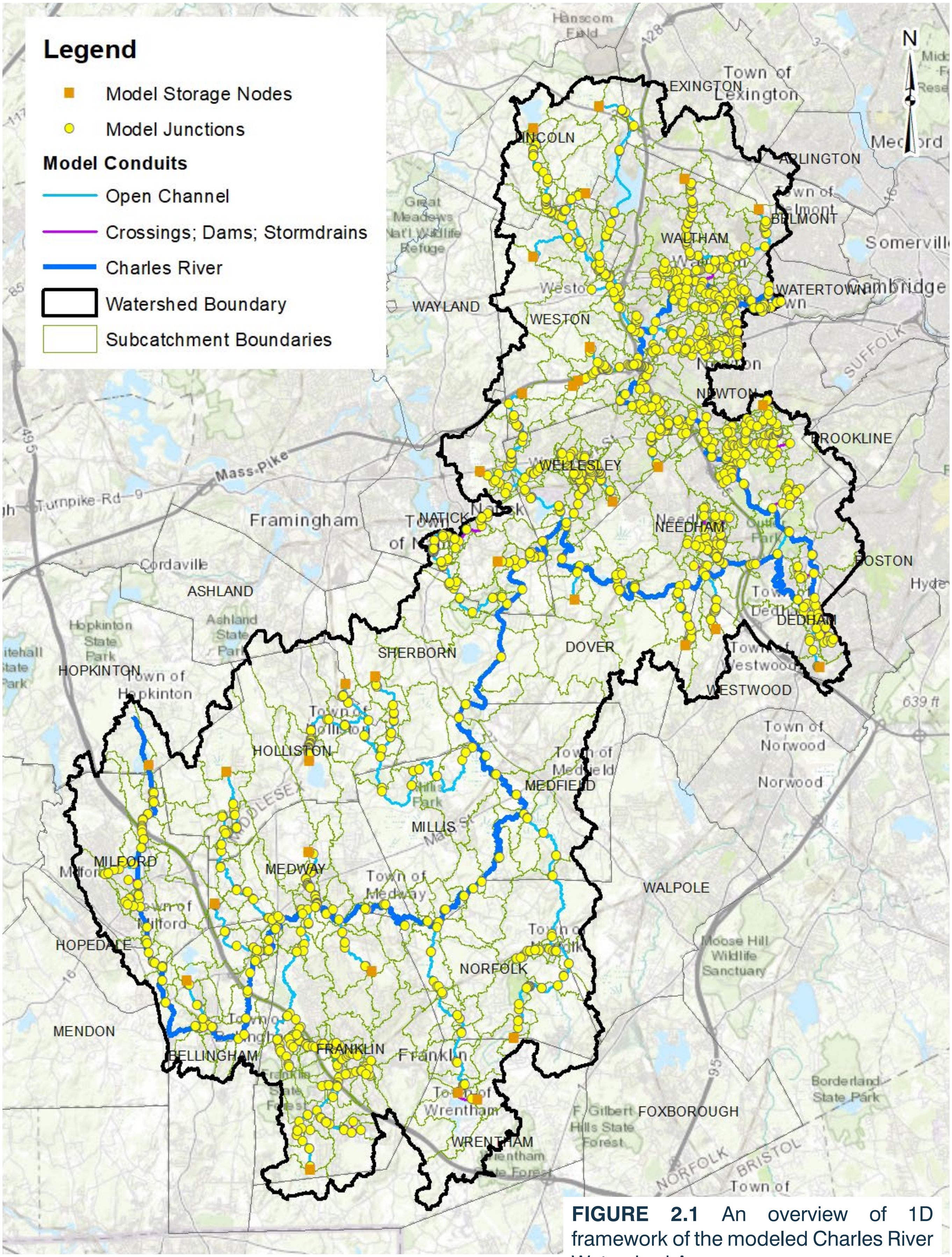


FIGURE 2.1 An overview of 1D framework of the modeled Charles River Watershed Area.

well as storm drains, dams, bridges, culverts, and flood prone areas. Delineation of subcatchment boundaries was based primarily on the latest LiDAR ground elevation datasets available in the watershed using a suite of tools in the Spatial Analyst toolkit in ArcGIS. The delineations were then hand-checked to confirm their accuracy. The size of subcatchments incorporated into this model range from several thousand acres in relatively rural areas on tributaries to the Charles River to less than one acre in highly developed areas tributary to the catch basins within a single intersection. Table 2.1 provides an overview of the number of subcatchments based on their sizes.

In PCSWMM, runoff is generated separately for the pervious and impervious portions of a subcatchment. Impervious surfaces are generally assumed to convert 100% of rainfall to runoff with minimal opportunities for infiltration into the ground or storage in small depressions. . Approximately 35.5% of the modeled Charles River watershed consists of impervious surfaces like roofs, roadways, and parking lots. Percent impervious cover per subcatchment is summarized in Table 2.2 and shown graphically in Figure 2.2.

In contrast, pervious areas were modeled using the unit hydrograph (a.k.a. Curve Number) method, which calculates the fraction of rainfall converted to runoff as a function of land cover type and underlying soil types.

TABLE 2.1 Number of subcatchments by area

Subcatchment Area (acres)	Number of Subcatchments
0-1	24
1-10	142
10-100	270
100-1,000	226
1,000-5,100	43

2.2.2 Junctions

The runoff generated by subcatchments is modeled as being discharged to one of the model's junctions. In general, junctions represent a singular location within the natural or piped stormwater system and contain information about the channel or manhole bottom and the "rim" elevation at which flooding occurs. In practice, these junctions are used to represent manholes where two or more storm drains enter, confluences of two or more rivers and streams, areas of interest where specific flood level outputs may be required, and the upstream and downstream faces of bridges, dams, and other structures that cross a river/stream.

TABLE 2.2 Percentage of impervious cover and percentage of watershed area per subcatchment.

Percent Impervious Area	Number of Subcatchments	Percent of Watershed
0-10%	129	18%
10-20%	119	17%
20-30%	126	18%
30-40%	112	16%
40-50%	71	10%
50-60%	51	7%
60-70%	44	6%
70-80%	29	4%
80-90%	21	3%
90-100%	3	0%

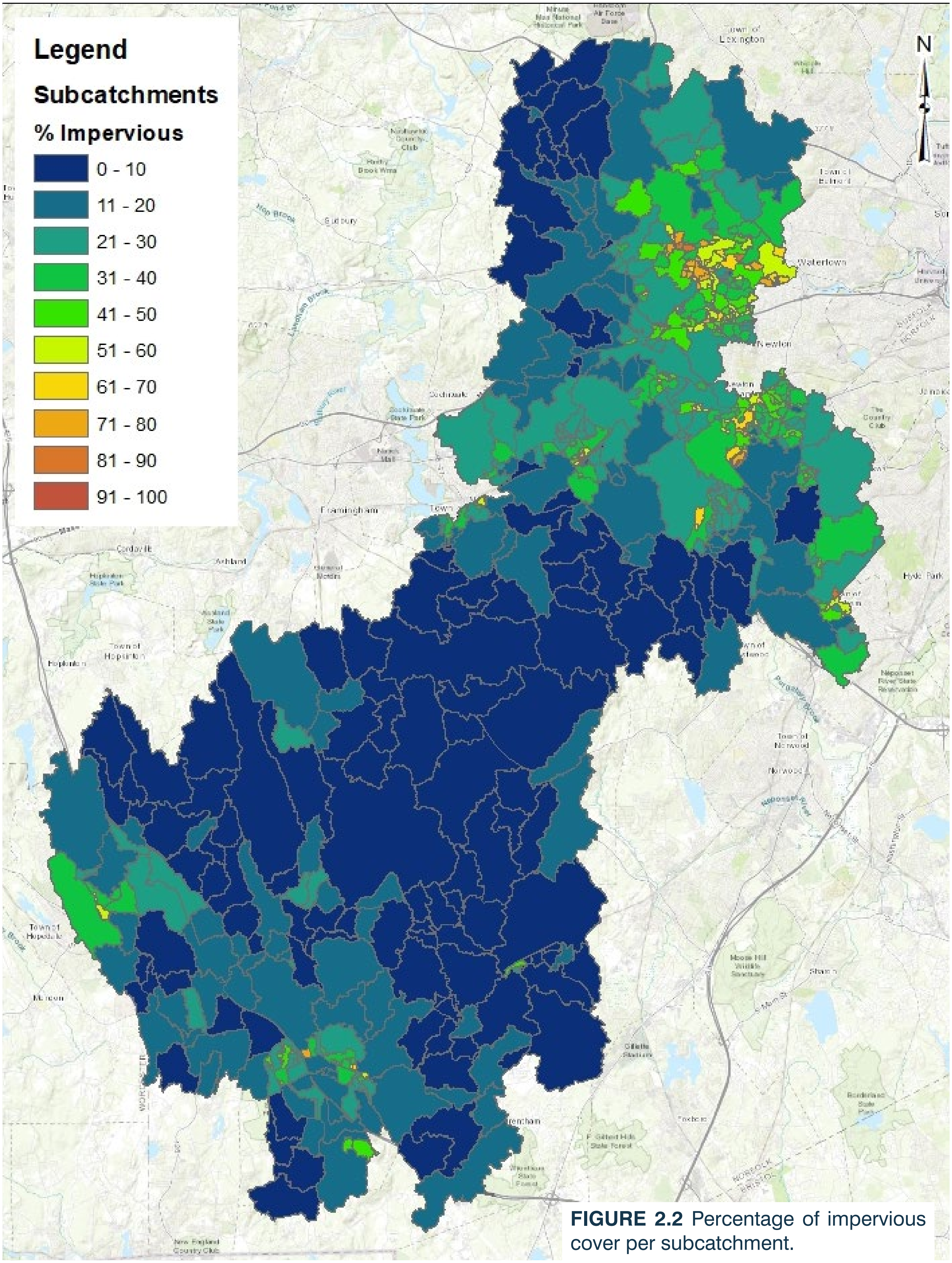


FIGURE 2.2 Percentage of impervious cover per subcatchment.

This model includes 1,471 junctions. Initially, invert and rim elevations for natural channels were generally derived from the most recent Federal Emergency Management Agency's (FEMA) Flood Insurance Studies (FIS) (2015 for Norfolk County and 2016 for Middlesex County), supplemented with LiDAR ground elevation data. Invert and rim elevations at manholes and catch basins were generally obtained from the stormwater infrastructure GIS data provided by project partner communities, which was supplemented by LiDAR as needed. Where insufficient elevation data was available or where the accuracy of elevation data was in question, the project team conducted field investigations to obtain more accurate data, as discussed in Section 2.3.

2.2.3 Conduits

This model also includes 1,551 modeled conduits that represent the approximate shape of the natural channel between junctions and that define the dimensions of culverts, dam outlets, and stormwater infrastructure. The conduits representing rivers and streams were modeled as open top rectangles where the top widths were estimated from aerial imagery and depths were estimated from FEMA FIS. Conduits representing culverts/bridges, dam outlets, and stormwater infrastructure were modeled based on project partner-provided GIS or from field measurements, described in Section 2.3. Table 2.3 summarizes the total number of each type of conduit.

Stormwater drainage data was collected from 14 of the 15 project partner communities and two additional communities located in the headwater's region (Milford and Bellingham), through a SharePoint site that allowed project partners to submit stormwater infrastructure data. Weston & Sampson also utilized recent stormwater infrastructure data from Waltham that was received as part of another stormwater flood mitigation project. All data was reviewed as it was submitted and tracked in a spreadsheet to identify data gaps. The GIS files of stormwater infrastructure were determined to be most critical in the early stages of the model. Modeled drains included those that were greater than or equal 24 inches in diameter that discharge to the Charles River watershed or its primary tributaries. Storm drains that were less than 24 inches in diameter or that conveyed flow

TABLE 2.3 Conduit counts in the watershed based on type

Conduit Type	Number of Conduits
Channel	635
Crossing (Bridge/Culvert)	384
Dam	74
Storm Drain	414
Bridge/Dam Overtopping	44

TABLE 2.4 Length of storm drains (in linear feet) incorporated into the model per town.

Town	Linear Feet of Pipe
Arlington	0
Dedham	4,347
Franklin	6,467
Holliston	0
Medway	0
Millis	0
Natick	5,566
Needham	9,507
Newton	27,326
Norfolk	372
Sherborn	0
Watertown	1,676
Wellesley	6,071
Weston	0
Wrentham	0
Milford	2,761
Waltham	13,685

away from the watershed were not included in the model. Table 2.4 summarizes the length of storm drains incorporated into the model by town. Towns with 0 linear feet did not have drains greater than 24 inches included in the model.

2.2.4 Storage

The majority of floodplain storage within the modeled Charles River watershed was incorporated with a 2D mesh as described in Section 2.4. However, in the case of some ponds and wetlands, located along the edges of the watershed and with no significant development or infrastructure along their shores, their capacity to store and attenuate runoff was incorporated by converting basic junctions to storage nodes.

Stage-surface area curves were developed for 32 individual waterbodies scattered throughout the modeled watershed, the location of these wetlands and ponds are shown in Fig. 2.1 in Section 2.2. Stage-surface area curves were developed from the latest LiDAR ground elevation datasets at 1-foot intervals, extending from the normal water level to approximately five feet above the lowest point at which significant overland flooding to downstream areas might be expected to occur. The outlet structures for each of the 32 storage volumes were modeled directly based on approximations from aerial imagery and using the findings of the field investigations, including culvert and control structure invert elevations and dimensions.

2.3 Data Collection and Field Investigation

The Technical Team, Weston & Sampson and CRWA was tasked with collecting and reviewing available data regarding stream and stream crossing elevations and dimensions, as well as the drainage systems in each of the towns that fall within the watershed. As described above, this information was primarily derived from publicly available sources like LiDAR, aerial imagery, and FEMA Flood Insurance Studies or from project partner-provided stormwater infrastructure GIS. However, following initial model development in this manner, the Technical Team identified several hundred elevations or measurements of dam outlets or bridges and culverts that were not adequately understood. In total, 442 data gaps were identified from field investigations as summarized in Table 2.5. Additional details related to the data received from the communities and the gaps identified from reviewing existing data sources are summarized in Appendix A.0.

Two teams, each with a representative from wo teams, each with a representative from Weston

TABLE 2.5 Type of gaps in data and total data gaps based on total number of sites visited.

Data Gap Type	Number of Sites Visited
Crossing	298
Dam	25
Junction	119
Total	**442**

FIGURE 2.3 Photo showing a field team member measuring the diameter of a culvert.

& Sampson, and a representative from the Charles River Watershed Association, spent a total of six days collecting data.

The ArcGIS Collector mobile phone application was utilized to record notes, measurements, and take photographs (example in Fig. 2.3). Elevation data was collected for junctions with data gaps. Dimensions for culverts, bridges, and dam outlets were collected for conduits with noted data gaps. Fig. 2.4 is a screenshot from the ArcGIS Collector app utilized during the field work, which shows an overview of the data collected in the field. Data gathered in the field in this manner was used to complete development of the model's 1D framework

2.4 TWO-DIMENSIONAL FRAMEWORK

Following completion of the 1D framework, Weston & Sampson developed and overlayed a 2D mesh on top of it. The 2D mesh serves two functions: 1) capture the instream and near-stream storage located in the channels and floodplains of the Charles River and its named tributaries, and 2) reflect the capacity of those floodplains to convey flood flows downstream.

In general, 2D models are computationally intensive, so it is important to optimize the level of detail reflected in the 2D mesh with the goals of the model and associated project. This optimization was accomplished first by limiting the surface area represented with the mesh. The boundary of the 2D zone incorporated

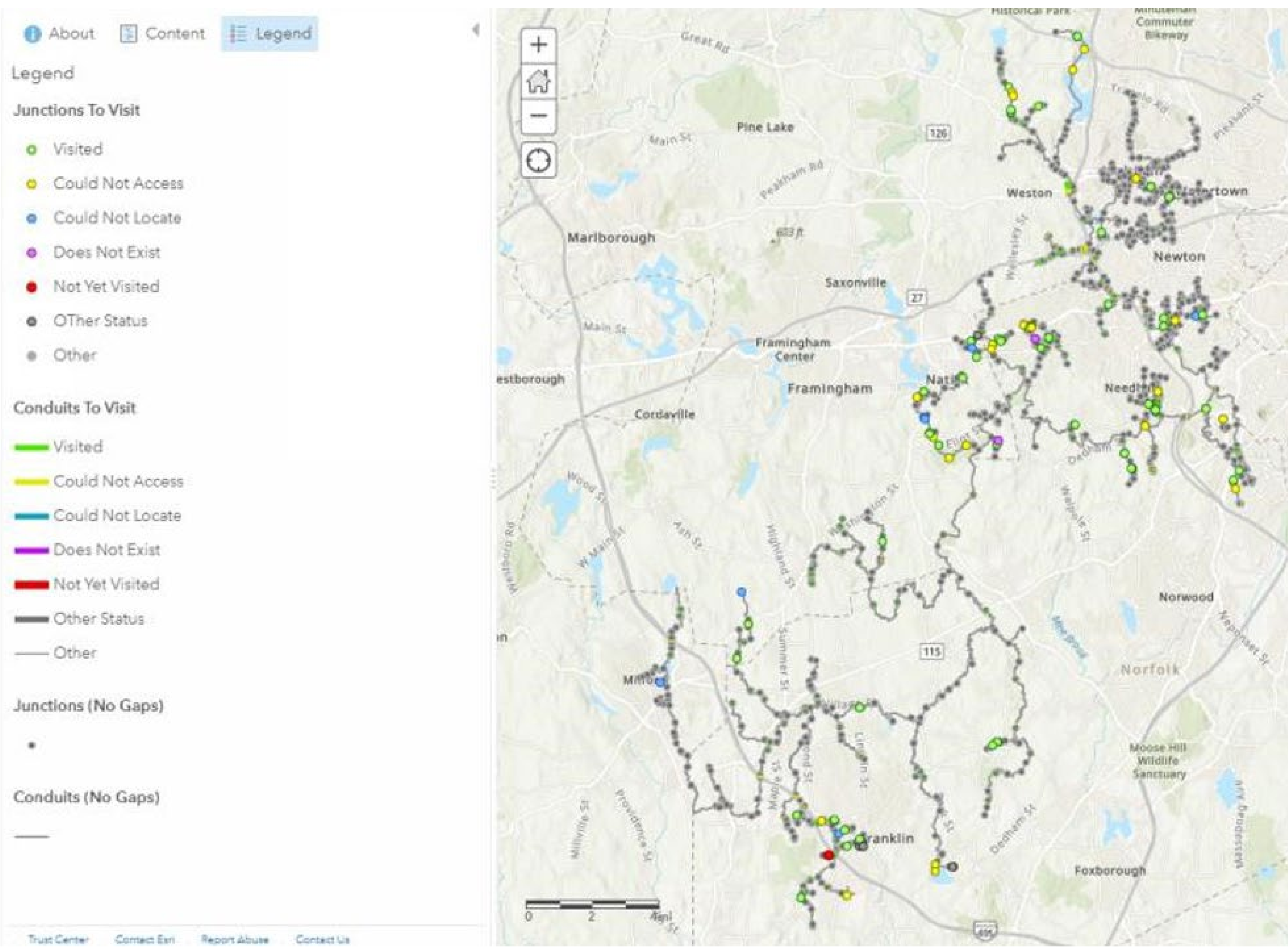


FIGURE 2.4 Example from ArcGIS Online used during field investigation. Overview of collected field data.

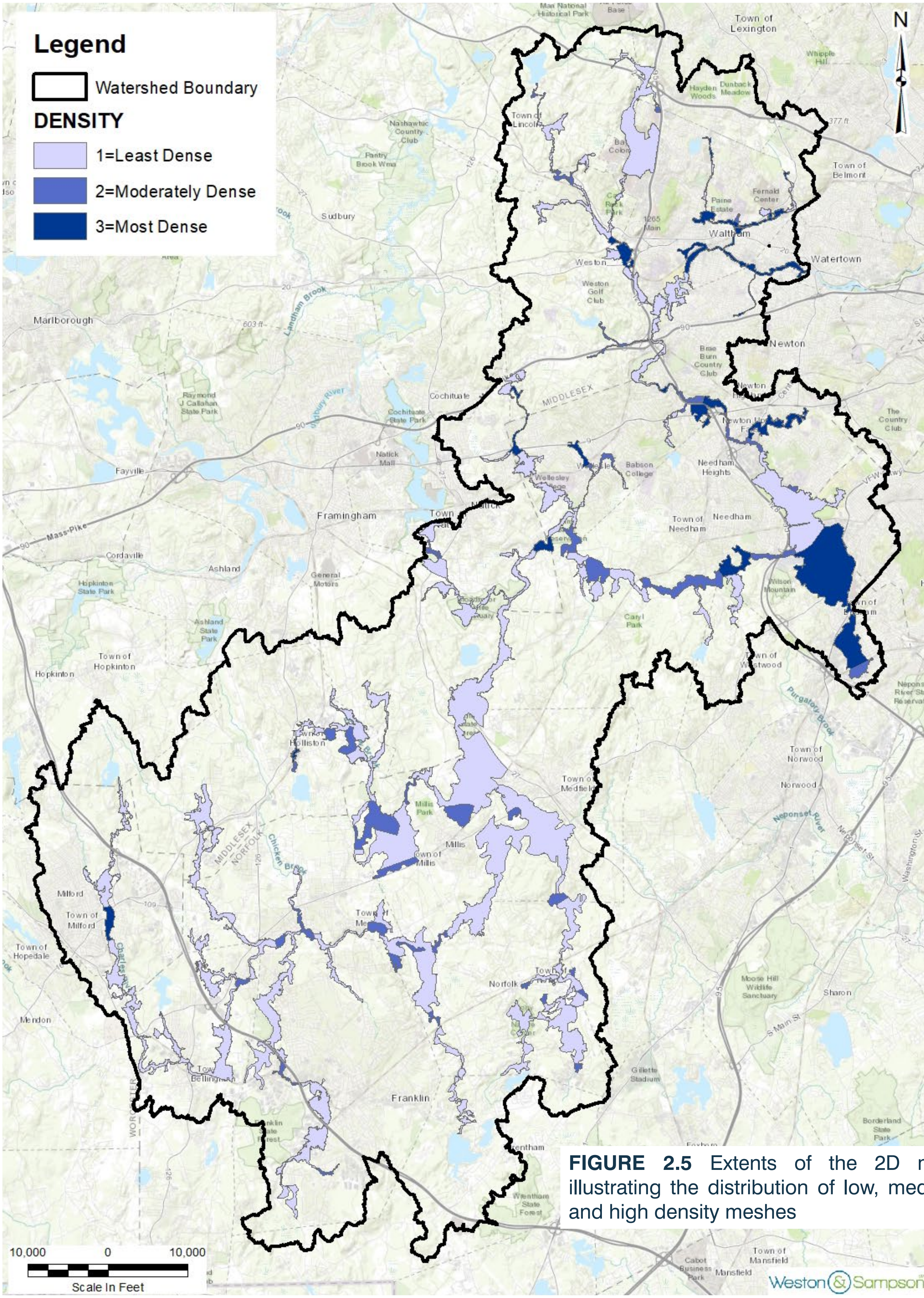


FIGURE 2.5 Extents of the 2D mesh illustrating the distribution of low, medium, and high density meshes

into the model was first approximated by the FEMA 500-year floodplain. That boundary was further extended to include upland areas where significant storm drain systems were included in the model's 1D framework. However, some areas located within the FEMA 500-year floodplain, which were specifically the undeveloped areas surrounding the 32 ponds and wetlands that were modeled as simple storage nodes, as discussed in Section 2.2.4, were removed from the 2D zone.

The optimization for detailed output for a watershed wide model with reasonable computation times was further accomplished by using a variable density of 2D cells. For undeveloped areas along the Charles River and its tributaries that provide significant flood storage but where impacts to buildings or bridges are unlikely, 2D cells were defined with relatively low density. In these areas, the floodplain's storage capacity is adequately modeled, but there is relatively low detail available in the model output regarding flood depths or specific extents. Floodplain areas with a small number of buildings were modeled with more moderate density. Floodplain areas with significant development or several bridge crossings in quick succession were modeled with relatively high density of 2D cells. Fig. 2.5 shows the extents of the 2D mesh and illustrates the distribution of low, medium, and high density meshes.

2.5 MODEL CALIBRATION & VERIFICATION

To ensure the reliability of the Charles River Flood model and its usefulness as a planning or prioritization tool, Weston & Sampson calibrated the model – modifying a variety of input parameters to maximize agreement between simulated and historically observed flood flows. The calibration event selected for this model occurred over the period March 2010, during which 8.99 inches of rain fell over 58.5 hours, with a peak intensity of 0.68 in/hour, onto a relatively pre-saturated ground due to a combination of snowmelt and smaller rain events in the preceding days and weeks.

Known as the March 2010 event, this event produced extremely high flows throughout the watershed. In fact, for more than one USGS gage, they represent the flows of record. Calibration efforts focused on reproducing historically observed streamflow at five USGS gages – 01104480 on Stony Brook and Medway (01103280), Dover (01103500), Wellesley (01104200), and Waltham (01104500) on the Charles River (Fig. 2.6).

Through an iterative process, model parameters were continuously revised to maximize agreement between the total flood volume and peak discharge rate that was observed at each of the five calibration gage locations. The types of model inputs that were calibrated include but are not limited to: increasing subcatchment Curve Numbers, reducing subcatchment storage, and increasing channel roughness coefficients. Standard practice is to continue the calibration process until target and simulated results are within 20% with an ideal deviation of less than 10%. After many iterations, adequate agreement was achieved, as summarized in Table 2.6 and Figures 2.7 through 2.11.

TABLE 2.6 Calibration results (percent difference)

Location	Stony Brook	Medway	Dover	Wellesley	Waltham
Flood Volume	-87%*	-22%	-6%	4%	-15%
Peak Discharge	-21%	1%	-3%	11%	-6%

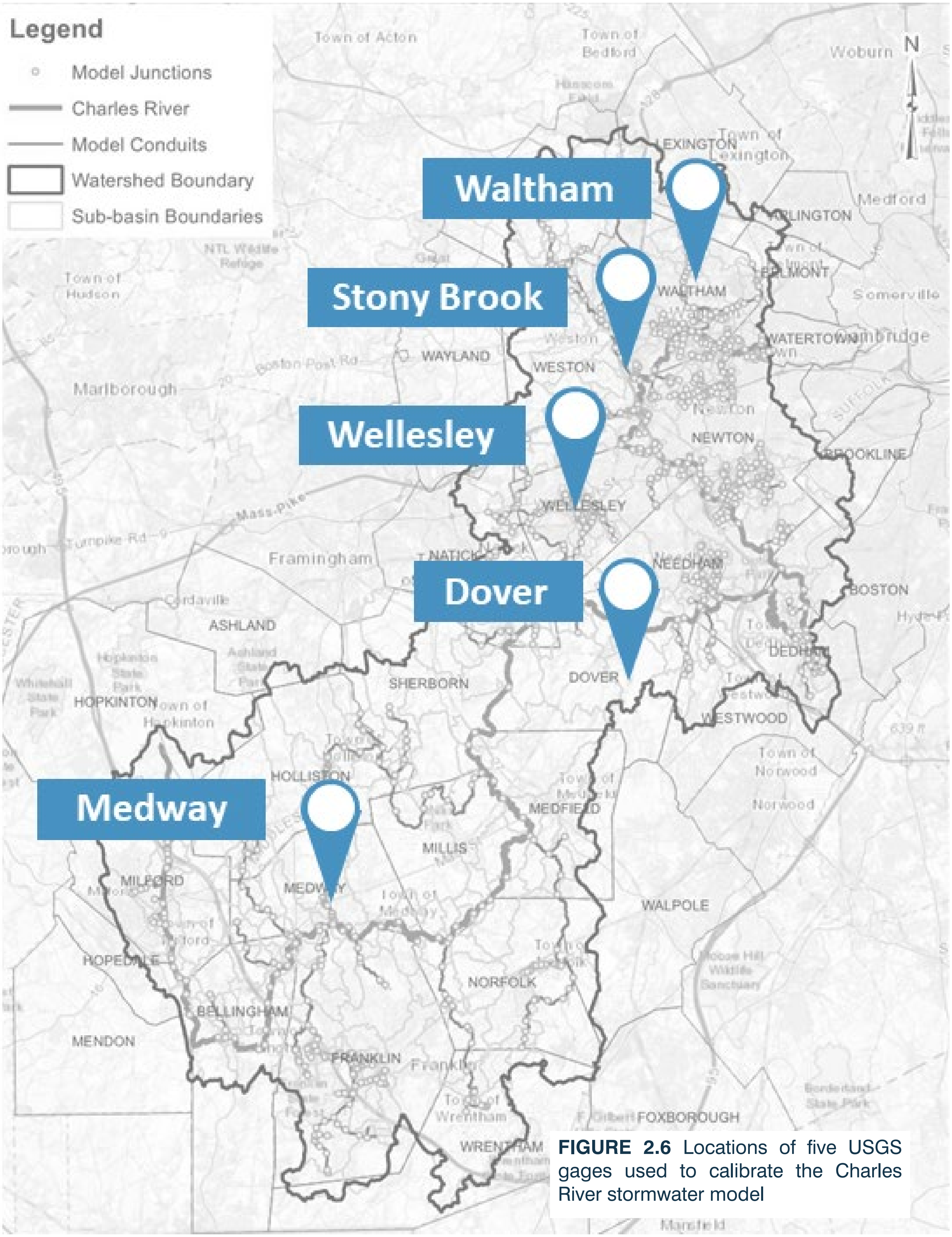


FIGURE 2.6 Locations of five USGS gages used to calibrate the Charles River stormwater model

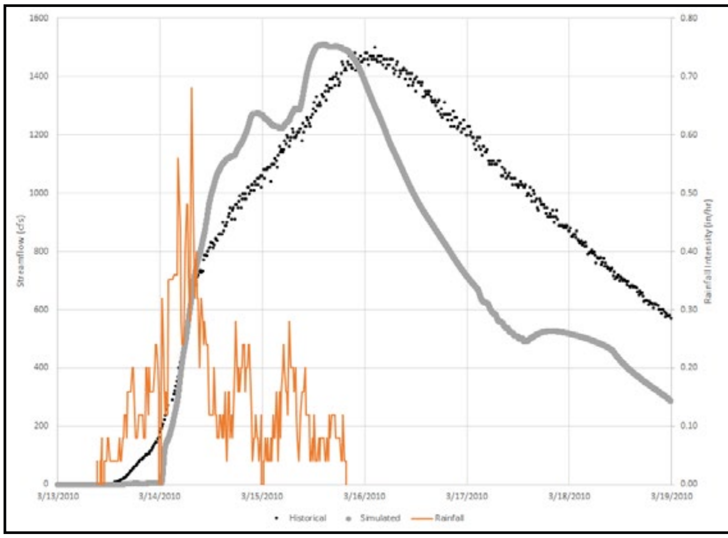


FIGURE 2.7 Calibration results for 01103280 Charles River at Medway

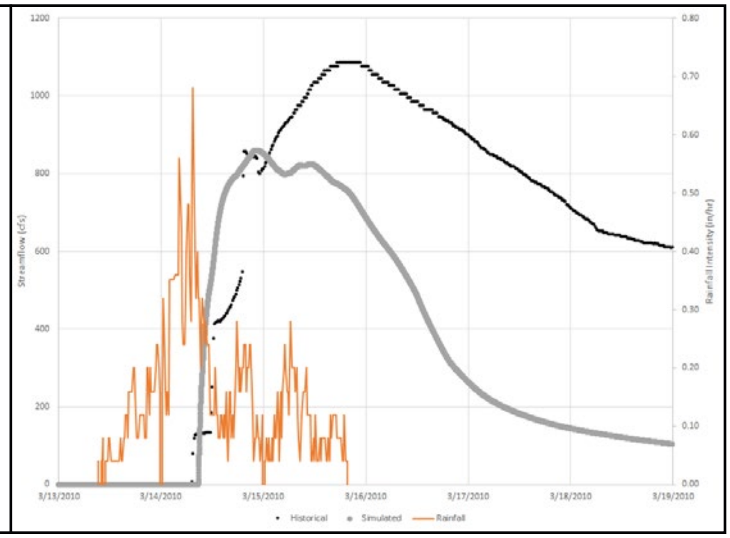


FIGURE 2.8 Calibration results for 01104800 Stony Brook

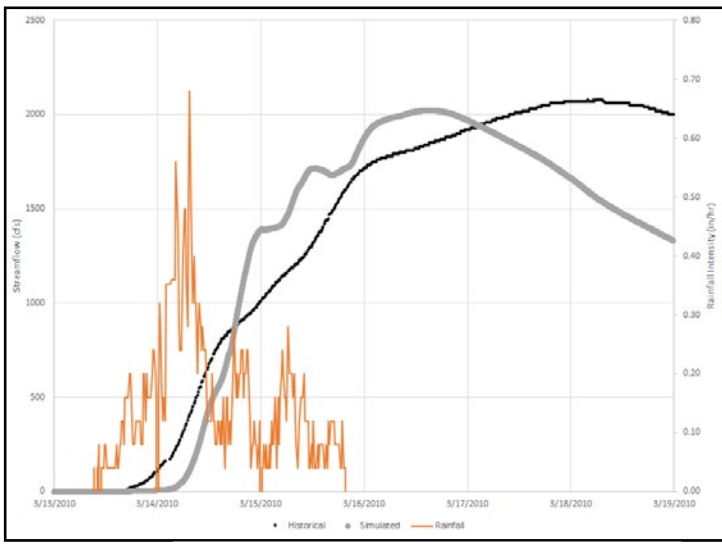


FIGURE 2.9 Calibration results for 01103500 Charles River at Dover

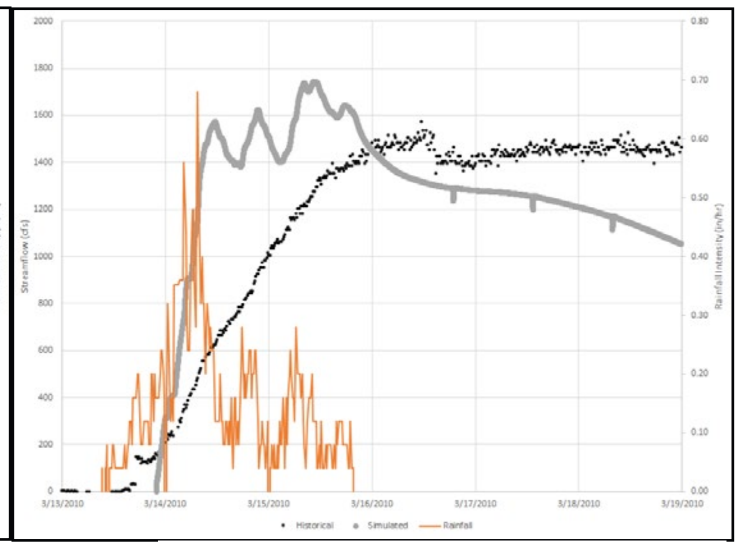


FIGURE 2.10 Calibration results for 01104200 Charles River at Wellesley

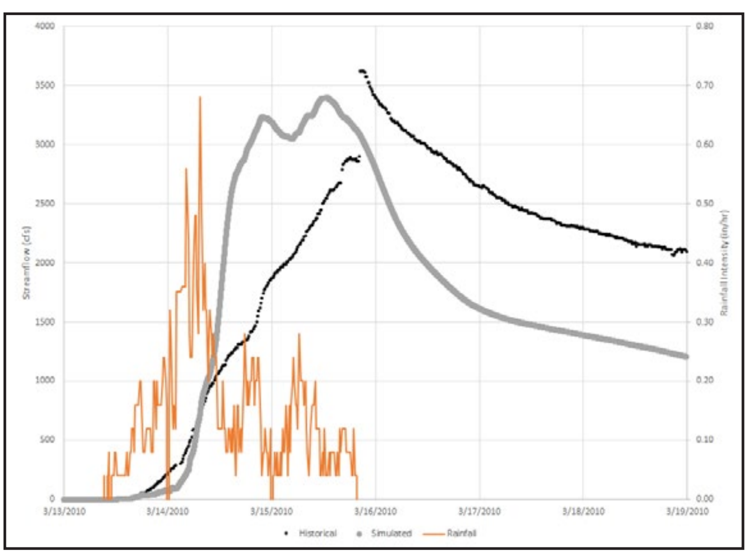


FIGURE 2.11 Calibration results for 01104500 Charles River at Waltham

In general, the Charles River Flood Model is well calibrated. Its ability to simulate peak discharge rates at multiple locations within the watershed is particularly strong, with deviations of 1, -3, 11, and -6% at the Medway, Dover, Wellesley, and Waltham gages, respectively. Total runoff volumes are also reasonably well matched with deviations of –22, -6, 4, and –15%, respectively, at those same four gages.

Deviations at the Stony Brook gage are more significant with peak discharge and total volume deviations of –21 and -87%, respectively. The magnitudes of these discrepancies, particularly the total volume of flood flows, are, in part, due to operations at Cambridge Reservoir and/or Stony Brook Reservoir during the March 2010 event that were not fully reproduced. The Waltham gage on the Charles River, located a short distance downstream, is well calibrated, suggesting these discrepancies in the Stony Brook sub-basin are localized in nature. Model results within the Stony Brook sub-basin are also still generally useful with the possible exception of the short reach of brook between Stony Brook Reservoir and the Charles River.

Following successful calibration, the Charles River Flood Model was then subjected to verification to ensure that the changes made to model input parameters during the calibration process can produce reasonable appropriate results under a different set of loading conditions. In this case, the model was verified against an event that occurred on April 16, 2018, during which 2.96 inches of rain fell in just under 20 hours, based on precipitation data recorded by the USGS Stony Brook gage. This event is roughly equivalent to a baseline climate 2-year storm. Results of the verification simulation are shown in Figures 2.12 through 2.14

The verification simulation rather accurately reproduced the rising limb and peak of the runoff hydrograph that was historically observed at the Charles River gage in Waltham (01104500) at

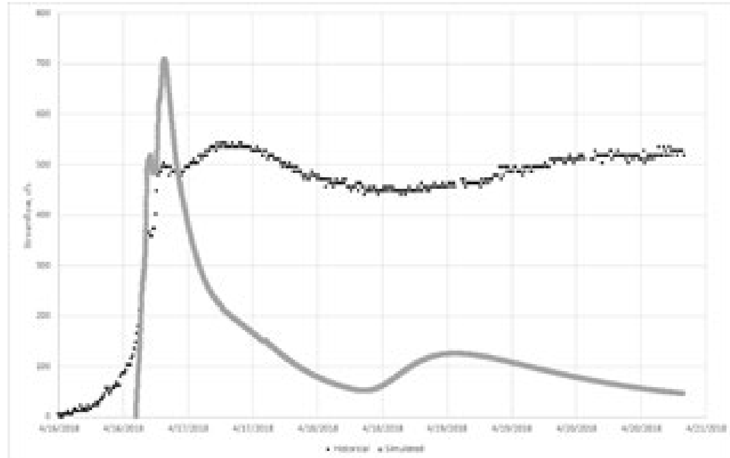


FIGURE 2.12 Verification results for 01103280 Charles River at Medway

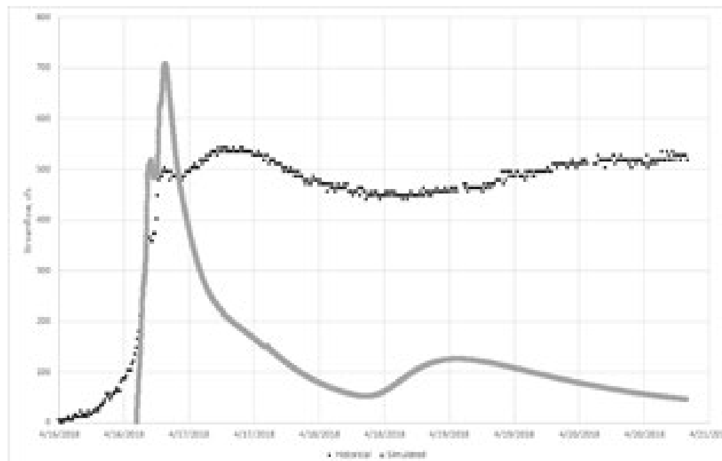


FIGURE 2.13 Verification results for 01104200 Charles River at Wellesley

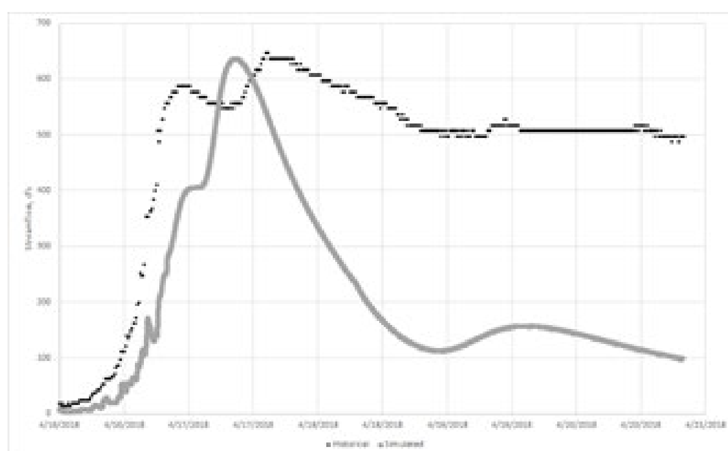


FIGURE 2.14 Verification results for 01104500 Charles River at Waltham

the downstream end of the watershed. The peak value is within 1% and the slope of the rising limb of the storm is quite similar to historical observations. It is clear, however, that the model is not generating enough runoff during this relatively small event or that that runoff is being captured and attenuated by too great a degree by instream and near stream storage.

A similar pattern is found at the Charles River gage in Wellesley (01104200) near the middle of the watershed, where the rising limb of the hydrographs are well matched, the simulated peak discharge is actually somewhat higher, 18%, than what was historically observed, but there is a significant discrepancy in the total runoff volume in the Charles River following the peak of the resulting flood event. The same observations are generally true at the Charles River gage in Medway (01103280) in the upper reaches of the watershed, although in that area, the simulated peak discharge does not rise quite as high as historically observations, and is, in fact, approximately 26% lower, in contrast to the other verification gage locations.

Although the model is not simulating historical flood volumes during the April 16, 2018 verification event, the model does a reasonable job of simulating peak discharge rates, and therefore, likely, peak water surface elevation. This suggests that the inundation extents and associated impacts predicted by the model for this event are relatively accurate, particularly in the downstream sections of the watershed. Combined with the calibration results, since the simulated peak discharge rates and total flood volumes in the Charles River watershed matched historical March 2010 values at multiple locations in the upper, middle, and lower reaches of the watershed, it indicates that this model is well-suited to simulate flooding impacts throughout the watershed during a wide range of storm events.

FLOOD RISK MODELING

3.1 BASELINE CLIMATE SCENARIOS

Weston & Sampson modeled design events under both baseline and future climate conditions. Design rainfall depths for a baseline climate were derived from NOAA's Atlas 14: Precipitation-Frequency Atlas of the United States for Stormwater Management (NOAA 14). NOAA 14 values represent the industry-standard design rainfall depths for events under a late-1900s/early 2000s (baseline) climate condition. The design storms are analyzed for the 2-,10-, 25-, 100-, and 500-year recurrence intervals. NOAA Atlas 14 design rainfall depths associated with these events are presented in Table 3.1 and represents the watershed area-weighted average values, which were estimated by weighting the NOAA 14 values for each community based on the percentage area of the community that falls within the Charles River watershed.

3.2 FUTURE CLIMATE SCENARIO

To determine future design storm depths, Weston & Sampson relied on a methodology developed for the State of Massachusetts as part of their ResilientMA initiative, specifically "Draft guidance on future precipitation estimates from the Resilient MA Action Team (RMAT) project by EEA, 2020",[2] which has been integrated This guidance was based on a detailed technical analysis conducted by Weston & Sampson of design storm projections for 9 locations across Massachusetts, using an ensemble of climate models of the RCP 8.5 emission scenario (the greenhouse gas emission scenario that EEA has selected to use). That analysis determined that except for projects in Hampden County, design rainfall depths for "more frequent" events like the 2- and 10-year events are expected to increase by approximately 20% by late century i.e., 2070/2090 (Table 3.2), and design storm depths for the less frequent storms like the 100-year event is expected to increase by approximately 27%.

TABLE 3.1 Present day design rainfall depths for the 24-hr duration design storms for the Upper and Middle Charles River Watershed

Recurrence Interval	NOAA Atlas 14 (Watershed Average), inches
2-yr	3.34
10-yr	5.20
25-yr	6.37
100-yr	8.17
500-yr	11.12

TABLE 3.2 Recommended percent increase estimates from RMAT Climate Resilience Design Standards and Guidelines beta Tool

Location	Design Storm	Mid-Century (2030/2050)	Late Century (2070/2090)
Massachusetts (all counties except Hampden)	More Frequent Design Storm (2-year, 5-year, 10-year, 25-year, and 50-year return periods)	8%	20%
	100-year Design Storm	11%	27%
	Extreme Design Storm (200-year and 500-year return periods)	15%	36%

Therefore, future design rainfall depths were determined by multiplying NOAA Atlas14 values by 1.08 for mid-century events by 2030/2050, and by 1.2 for late century events by 2070/2090 for "more frequent" (2-year, 5-year, 10-year, 25-year return period)design storms. Future design rainfall depths for the 100-year design storm was determined by multiplying NOAA Atlas14 value by 1.11 for the mid-century events by 2030/2050 and by 1.27 for late-century events by 2070/2090. Future design rainfall depths for the 100-year design storm was determined by multiplying NOAA Atlas14 value by 1.15 for the mid-century events by 2030/2050 and by 1.36 for late-century events by 2070/2090. It is important to mention here that simulations of 500-year storm conditions, baseline or future, were not conducted for the project area. Instead, a more extreme storm of 11.7 inches in 24 hours, which corresponds to the 2070 100-year storm for the Mystic River watershed was used as the "extreme" event scenario. Calculated values for mid-century (2030/2050) and late-century (2070/2090) climate scenario and their baseline climate counterparts are presented in Table 3.3 and presented visually in Figure 3.1.

Based on the analyzed data, it appears that today's 100-yr storm (1% annual chance of occurrence) is likely to be a 25-yr (4% annual chance of occurrence) storm by 2070. Similarly, today's 25-yr storm (4% annual chance of occurrence) is likely to be a 10-yr storm (10% annual chance of occurrence) by 2070.

Climate scenarios modeled in the project were selected based on input from both the project team and the general public. Input was obtained through online surveys developed and circulated by CRWA and Communities Responding to Extreme Weather. This process is described in Section 4. In general, members of the public were more interested in seeing results from near-term scenarios (2030/2050) while the project team demonstrated a preference for longer planning horizon scenarios (2070/2100). Communities that span multiple watersheds, particularly those partially in the Mystic watershed, also stated a preference for some consistency in storm scenarios between the two watershed modeling initiatives. As described below, a mix of storms and time horizons were selected.

3.3 MODEL RESULTS

3.3.1 Watershed-Wide

Using the calibrated Charles River stormwater model and the present (baseline) day and future climate design precipitation depths identified above, Weston & Sampson simulated ten storm events, including:

- Present day 2-, 10-, and 100-year events (3)
- 2030 2-, 10-, and 100-year events (3)
- 2070 2-, 10-, and 100-year events (3) and
- The Mystic 2070 100-year event (1)

TABLE 3.3 Proposed design rainfall depths for future storm scenarios in the Charles River Watershed Model

Recurrence Interval	Present (Watershed Average), inches	2030/2050 (using RMAT percent increase estimates), inches	2070/2090 (using RMAT percent increase estimates), inches
2-yr	3.34	3.60	4.00
10-yr	5.20	5.62	6.25
25-yr	6.37	6.88	7.64
100-yr	8.17	9.07	10.37
500-yr	11.12	12.79	15.12

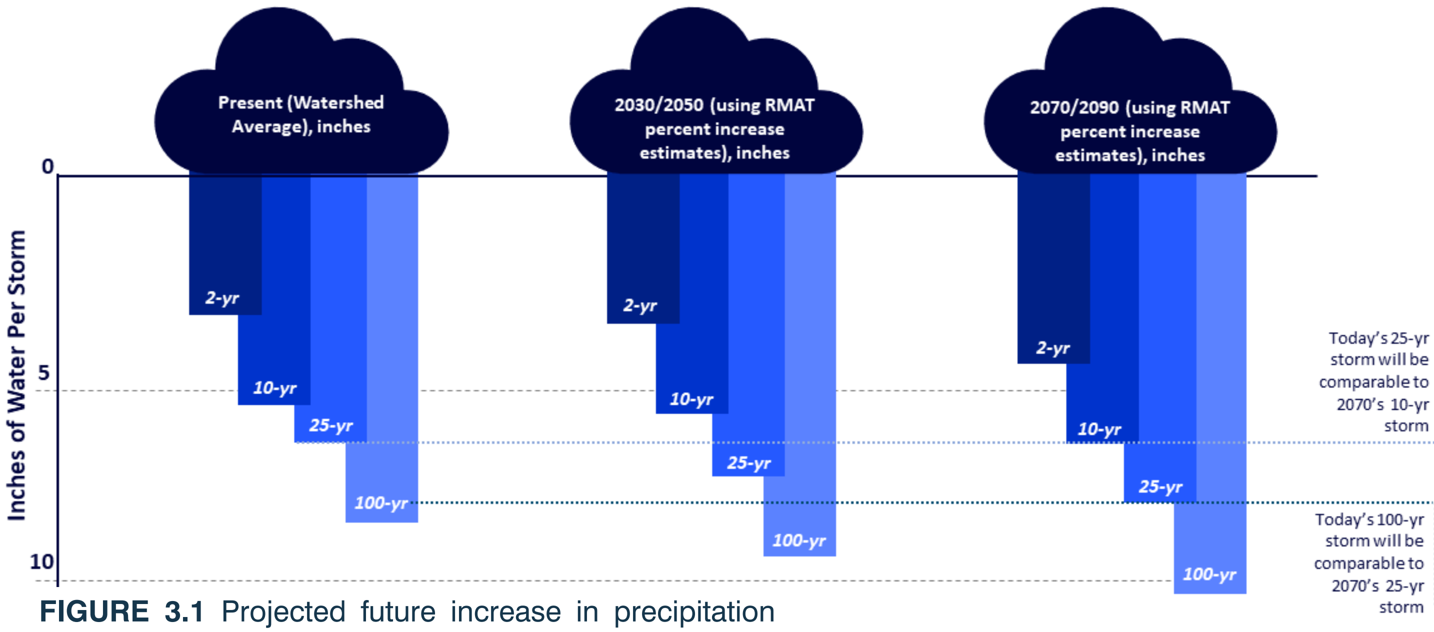


FIGURE 3.1 Projected future increase in precipitation scenarios in the Charles River Watershed Model

Storm events were assumed to take place over a 24-hour period with peak intensity occurring at the middle of the event per the SCS Type III rainfall distribution curve. In some small basins, precipitation is represented at 6-minute or small intervals; however, given the size of the Charles River watershed, precipitation was defined at 15-minute intervals. While precipitation was assumed to fall over a 24-hour period, the model simulations were run for a simulation period of five days to allow time for runoff generated in the upper reaches of the watershed to accumulate and travel downstream. Figures 3.2, through 3.5 demonstrate example areas within the watershed where flooding is increased by late-century for the different design storms compared to present day.

Based on the 1D model framework and the overlying 2D mesh, the Charles River stormwater flood model is capable of estimating peak and total runoff from more than 700 subcatchments within the watershed; peak and total runoff in nearly 200 miles of the Charles River and its tributaries and nearly 50 miles of storm drain; of estimating peak water levels and flood depths at more than 450 dams and bridge crossings; and of estimating flood levels, depths, and extents throughout nearly 19,000 acres of floodplain.

To understand how flooding impacts may evolve under future climate scenarios, Weston & Sampson compared some of these outputs for future climate simulations against simulations of corresponding present day design events. In general, comparisons of present day and future climate conditions were made by considering the total inundated area, the number of critical infrastructure (e.g., schools, fire departments, police departments, etc.) expected to be inundated, total runoff volume, and peak discharge. Watershed-wide estimates of inundated area, impacted critical infrastructure, and total runoff volume are summarized below in Tables 3.4, 3.5, and 3.6, respectively, for all ten events.

3.3.1 Sub-Basin Specific

There is considerable variation in flooding impacts throughout the watershed. To understand the distribution of flood impacts at different locations, results were evaluated for each of 33 sub-basins, one for each of 26 named tributaries and seven along the main stem of the Charles River itself. These 33 sub-basins are shown in Fig. 3.6 and were based on aggregating the 705 subcatchments that

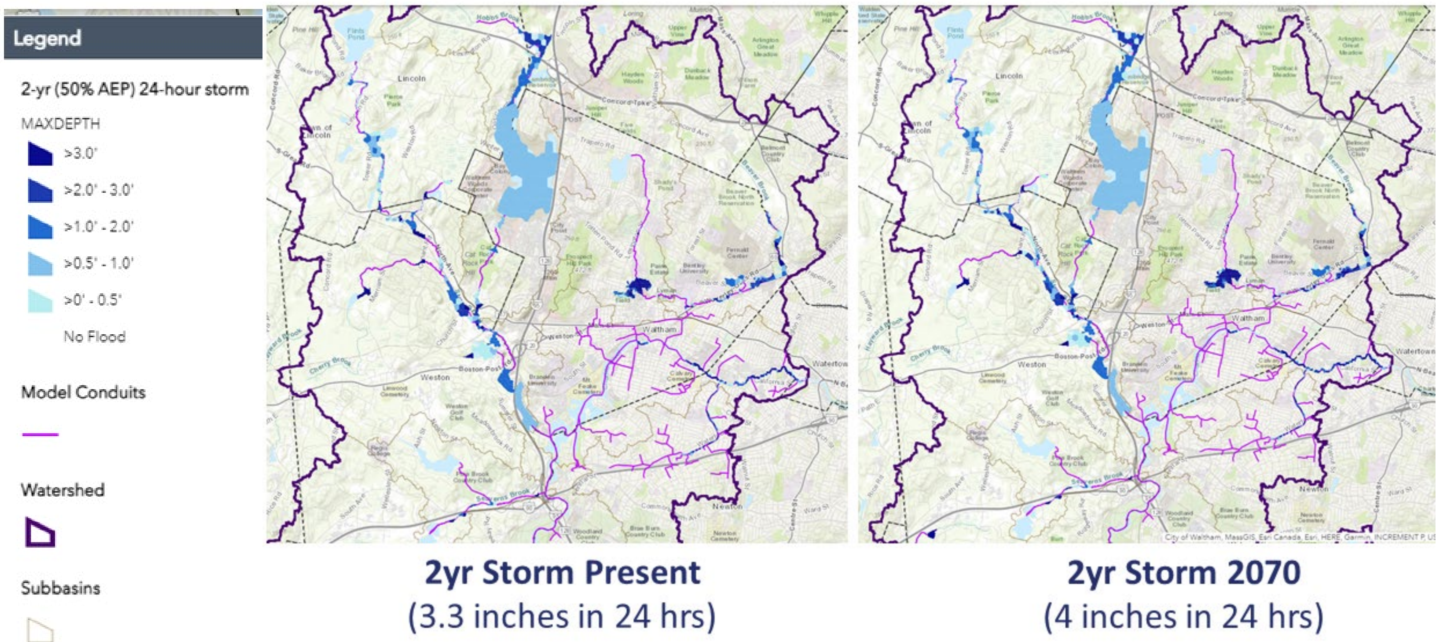


FIGURE 3.2 2-year storm present day (left); 2-year storm 2070 (right)

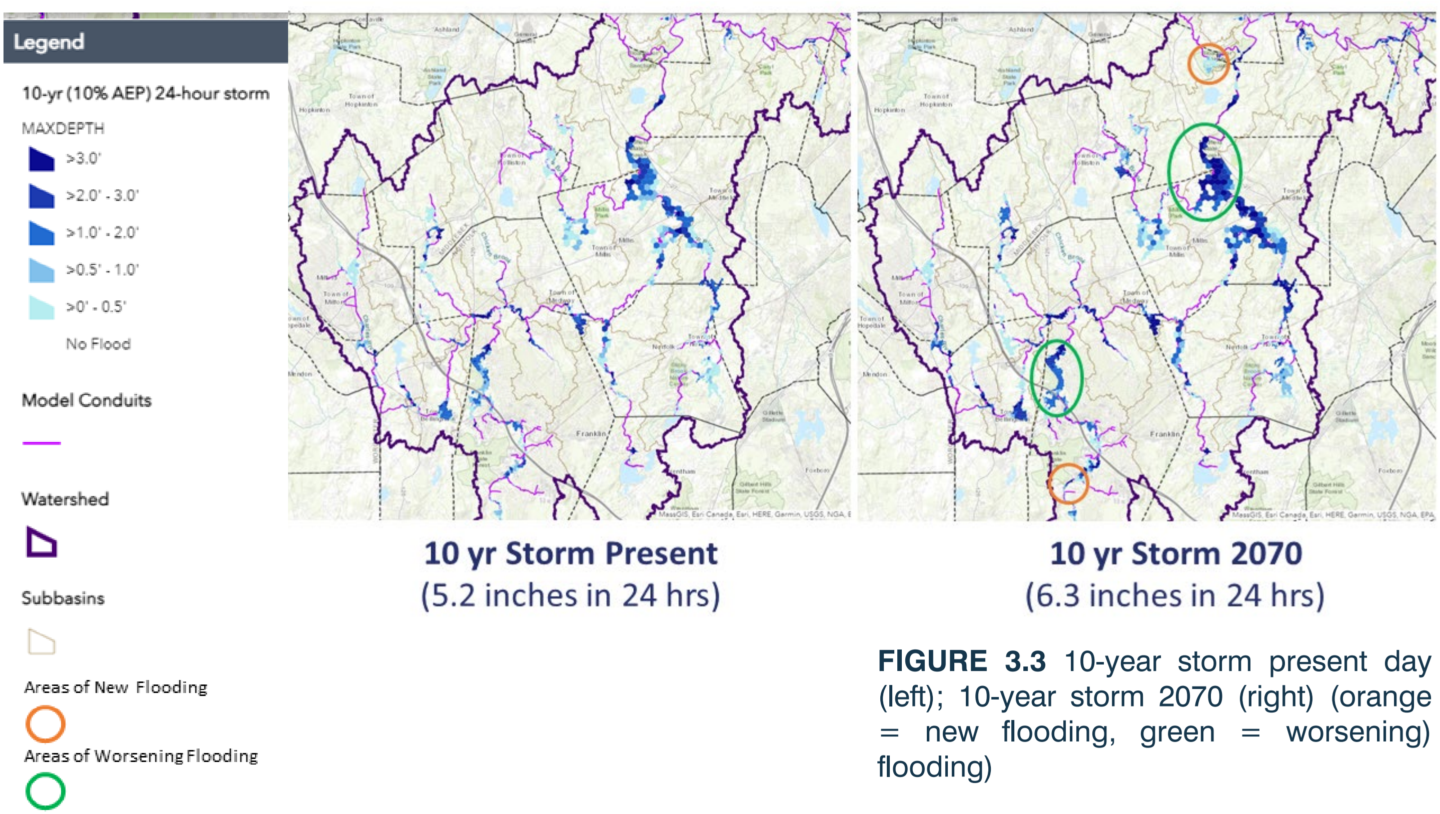
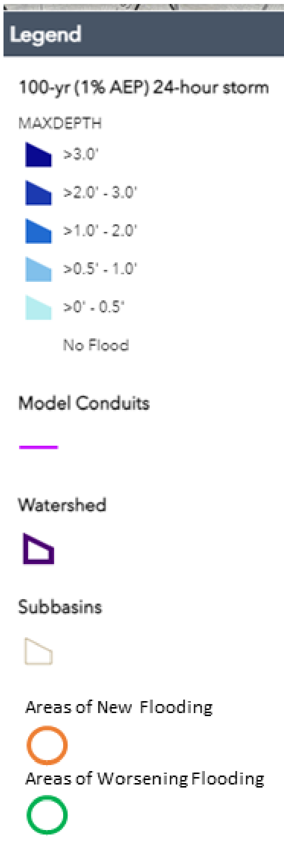
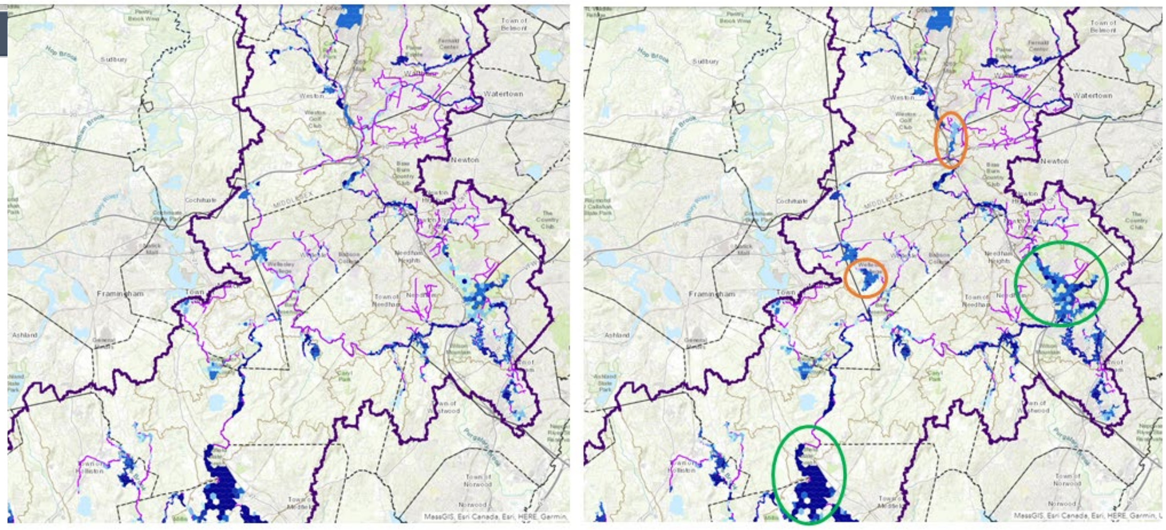


FIGURE 3.3 10-year storm present day (left); 10-year storm 2070 (right) (orange = new flooding, green = worsening) flooding)

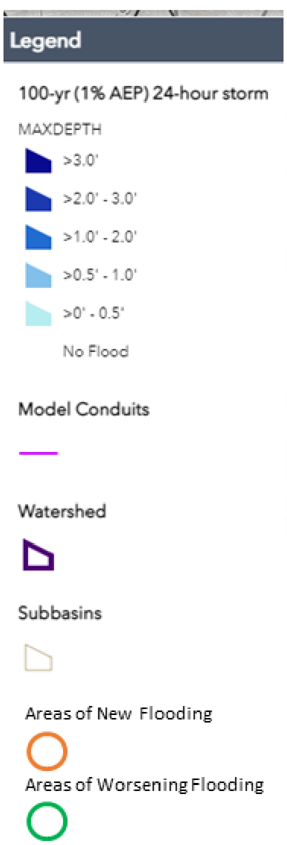


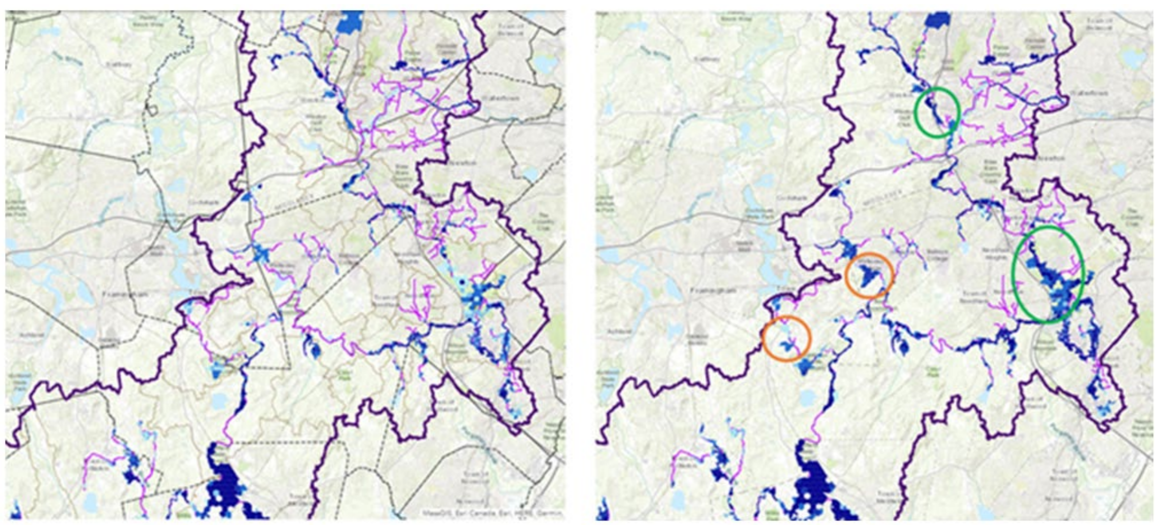


100 yr Storm Present
(8.2 inches in 24 hrs)

100 yr Storm 2070
(10.4 inches in 24 hrs)

FIGURE 3.4 100-year storm present day (left); 100-year storm 2070 (right) (orange = new flooding, green = worsening) flooding)





100 yr Storm Present
(8.2 inches in 24 hrs)

100 yr Storm 2070
(11.7 inches in 24 hrs)

FIGURE 3.5 1100-year storm present day in 24 hrs (left); more extreme storm in 24 hrs (right). green = worsening) flooding)

TABLE 3.4 Total inundated area (acres) by Design Storm Event

Climate Scenario	Design Event (Recurrence Interval)		
	2-year	10-year	100-year
Baseline	3,490	7,243	11,067
2030	3,896	7,955	11,636
% Change above Baseline	12%	10%	5%
2070	4,719	8,928	12,500
% Change above Baseline	35%	23%	13%
Mystic 2070	N/A	N/A	13,001

TABLE 3.5 Impacted critical infrastructure by Design Storm Event

Climate Scenario	Design Event (Recurrence Interval)		
	2-year	10-year	100-year
Baseline	33	53	66
2030	37	56	66
% Change above Baseline	+4	+3	---
2070	42	56	72
% Change above Baseline	+9	+3	+6
Mystic 2070	N/A	N/A	73

TABLE 3.6 Total runoff (MG) by Design Storm Event

Climate Scenario	Design Event (Recurrence Interval)		
	2-year	10-year	100-year
Baseline	3,053	7,368	17,321
2030	3,487	8,642	20,646
% Change above Baseline	+14	17%	19%
2070	4,264	10,651	25,568
% Change above Baseline	40%	45%	48%
Mystic 2070	N/A	N/A	30,794

Critical Facilities Considered

Colleges & Universities
Prisons
DEP Ground Water Discharge Permits
Fire Stations
Police Stations
Acute Care Hospitals
Non-acute Care Hospitals
Long Term Care Facilities
Schools
Town & City Halls
Public Water Supplies

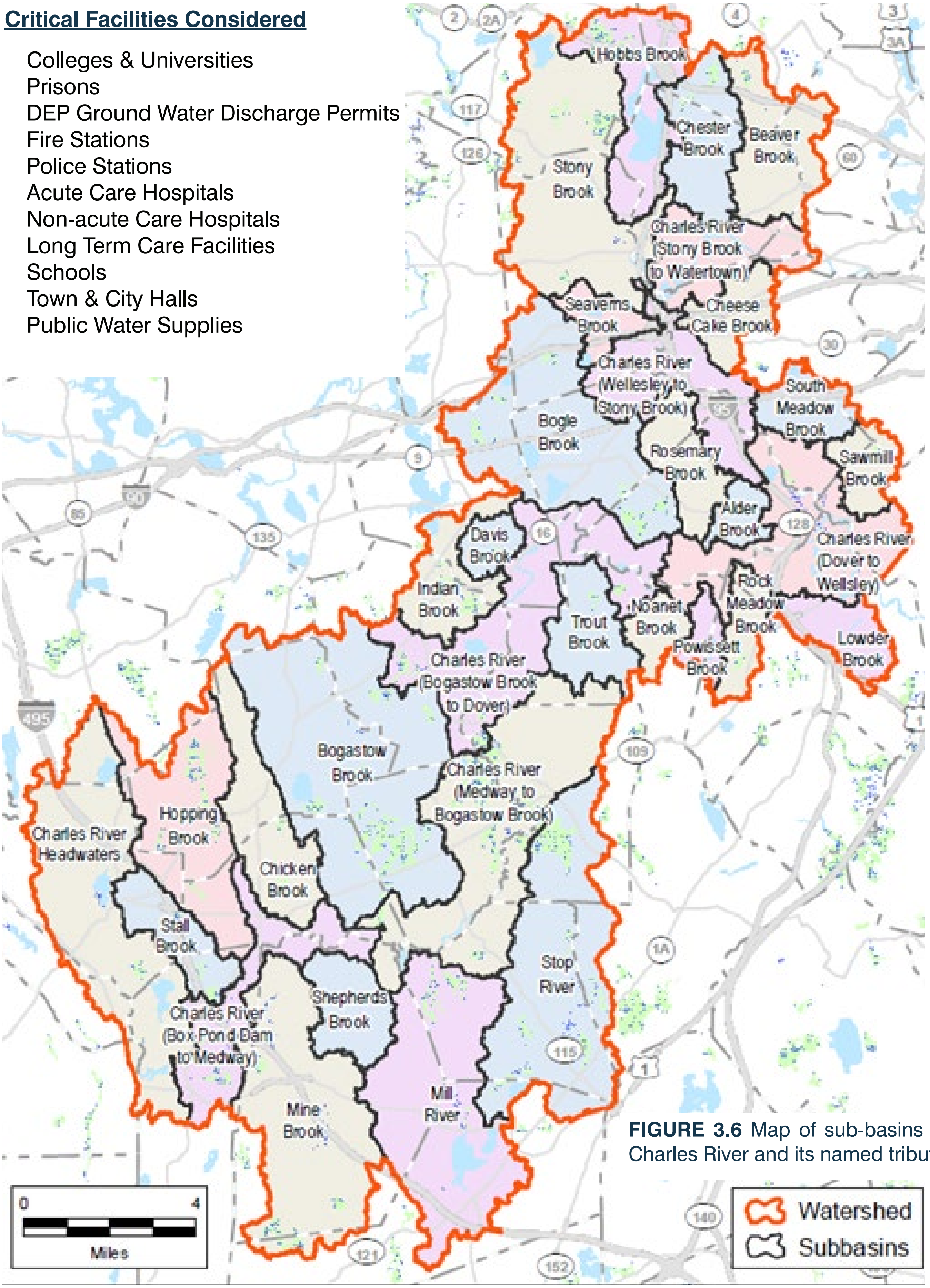


FIGURE 3.6 Map of sub-basins of the Charles River and its named tributaries.

were used for dividing the watershed for model development.

Table 3.7 summarizes the expected flooding and associated impacts to critical infrastructure for the present day (baseline) and 2070 10-year events for each of the 33 sub-basins.

There is considerable variability throughout the watershed in the anticipated increase in flood-prone area from baseline to 2070 during the 10-year event. As noted above, on average, flood prone areas in the watershed are expected to increase by 23% increase for the 10-year storm by 2070. However, several sub-basins, such as Alder, Hobbs, Powissett, Rosemary, and Shepherds Brooks, are all expected to experience minimal increases in flooding extents. In contrast, sub-basins like Indian, Stall, and Trout Brooks are expected to experience more than 100% increases in their flood-prone areas for the 10-year storm by 2070. In three sub-basins – Bogle Brook, Charles River (Wellesley to Stony Brook), and Hopping Brook – the increase in flood-prone areas are expected to impact additional critical infrastructure.

Fig. 3.7 and Fig. 3.8 present the anticipated percent increase in total runoff and peak discharge, respectively by 2070 for the 10-year storm compared to present day 10-year storm for these same 33 sub-basins.

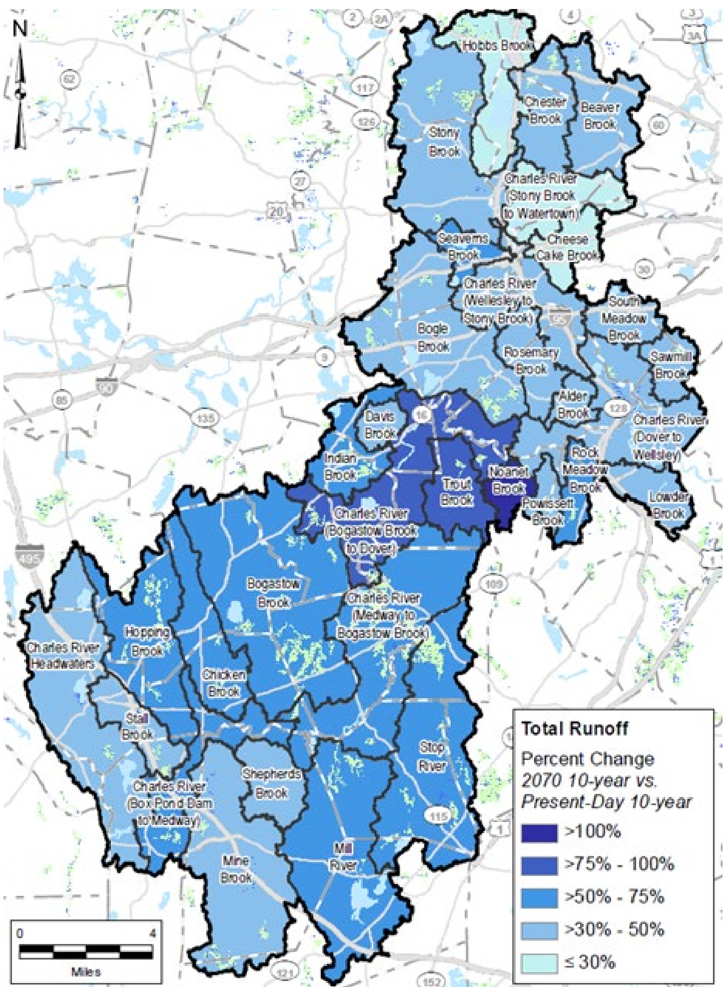


FIGURE 3.7 Map of the percent increase in total runoff volume during the 2070 10-year event versus the baseline 10-year event, by sub-basin.

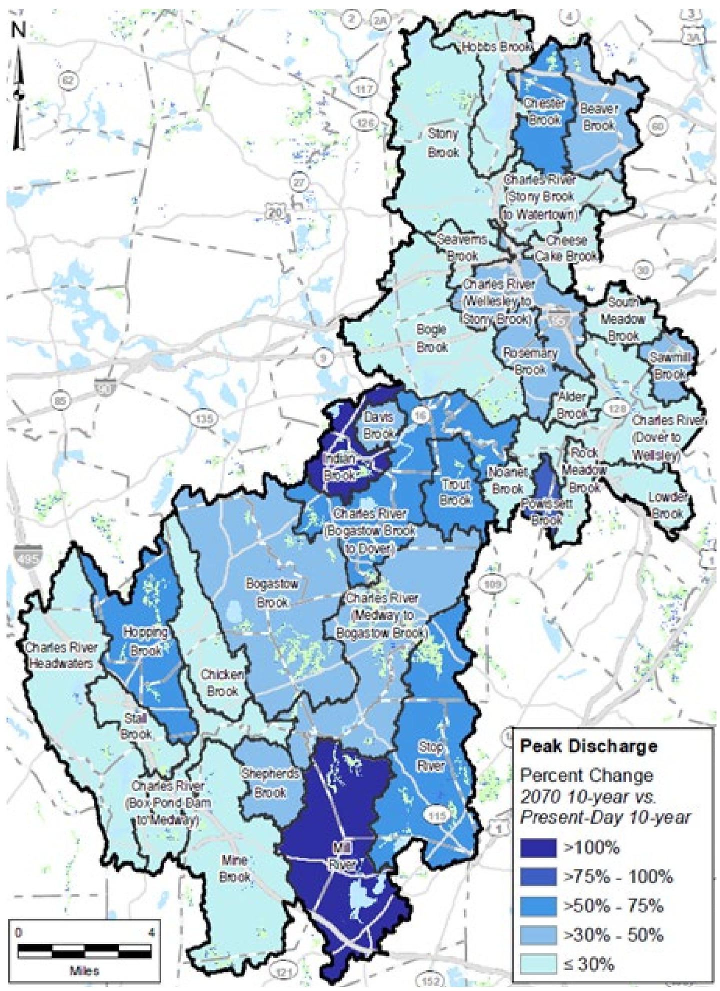


FIGURE 3.8 Map of the percent increase in peak discharge rate during the 2070 10-year event versus the baseline 10-year event, by sub-basin.

TABLE 3.7 Summary of inundation extents and impacted critical infrastructure for baseline and 2070 10-year events, by sub-basin.

Sub-Basin	Inundated Area (acres)			Critical Infrastructure Inundated		
	Baseline 10-year	2070 10-year	% Change	Baseline 10-year	2070 10-year	Change
Alder Brook	6	6	0%	0	0	0
Beaver Brook	96	116	21%	4	4	0
Bogastow Brook	509	715	40%	1	1	0
Bogle Brook	278	295	6%	2	3	+1
Charles River - Bogastow Brook to Dover	260	340	31%	2	2	0
Charles River: Box Pond Dam to Medway	279	408	46%	2	2	0
Charles River: Dover to Wellesley	530	805	52%	3	3	0
Charles River: Medway to Bogastow Brook	1261	1386	10%	5	5	0
Charles River: Stony Brook to Watertown	61	73	20%	3	3	0
Charles River: Wellesley to Stony Brook	136	175	29%	2	3	+1
Charles River Headwaters	304	328	8%	8	8	0
Cheese Cake Brook	15	16	6%	0	0	0
Chester Brook	58	67	16%	2	2	0
Chicken Brook	16	24	53%	1	1	0
Davis Brook	18	19	7%	0	0	0
Hobbs Brook	624	624	0%	2	2	0
Hopping Brook	245	310	27%	1	2	+1
Indian Brook	43	137	215%	0	0	0
Lowder Brook	144	155	8%	0	0	0
Mill River	246	271	10%	1	1	0
Mine Brook	637	763	20%	3	3	0
Noanet Brook	0	0	0%	0	0	0
Powissett Brook	40	40	0%	0	0	0
Rock Meadow Brook	25	32	30%	2	2	0
Rosemary Brook	44	44	0%	2	2	0
Sawmill Brook	39	39	0%	0	0	0
Seaverns Brook	13	17	37%	1	1	0
Shepherds Brook	46	46	0%	0	0	0
South Meadow Brook	50	52	5%	0	0	0
Stall Brook	61	149	145%	0	0	0
Stony Brook	420	453	8%	5	5	0
Stop River	696	930	34%	1	1	0
Trout Brook	46	92	100%	0	0	0

As with total inundated area, there is also considerable variability across the watershed in the anticipated increase in runoff volume and peak discharge rates during the 10-year event under baseline and 2070 climate conditions. However, the intra-watershed variability for percent increase in runoff volume is somewhat less severe compared to variability for percent increase in flood-prone areas. As noted above, on average, there is a 45% increase in total runoff volume generated across the whole watershed. However, increases range from a low of 24% in Hobbs Brook to a high of 137% in Noanet Brook.

Increases to peak discharge rates also vary considerably. In some sub-basins, like Alder Brook, the Charles River Headwaters, Rock Meadow Brook, and Stall Brook, those increases are relatively small due to the substantial untapped flood storage capacity of ponds and wetlands. In other sub-basins with little untapped flood storage, like Indian Brook (+107%), Mill River (+121%), and Powisset Brook (+79%), peak discharge by 2070 for the 10-year storm is expected to increase significantly compared to the present 10-year storm.

One of the great benefits of developing the Charles River stormwater flood model with 2D capability is that we can identify specific areas that may experience noteworthy increases in the extents and depths of flooding. One example occurs in the Stop River, shown in Figure 3.9, where additional areas are expected to become flood-prone by 2070 and flood depths in existing flood-prone areas are expected to deepen significantly.

Specifically, additional flooding is expected immediately upstream of Noonhill Road, along Seekonk Street near its intersection with Indian Hill Road, and immediately downstream of Clark Street.

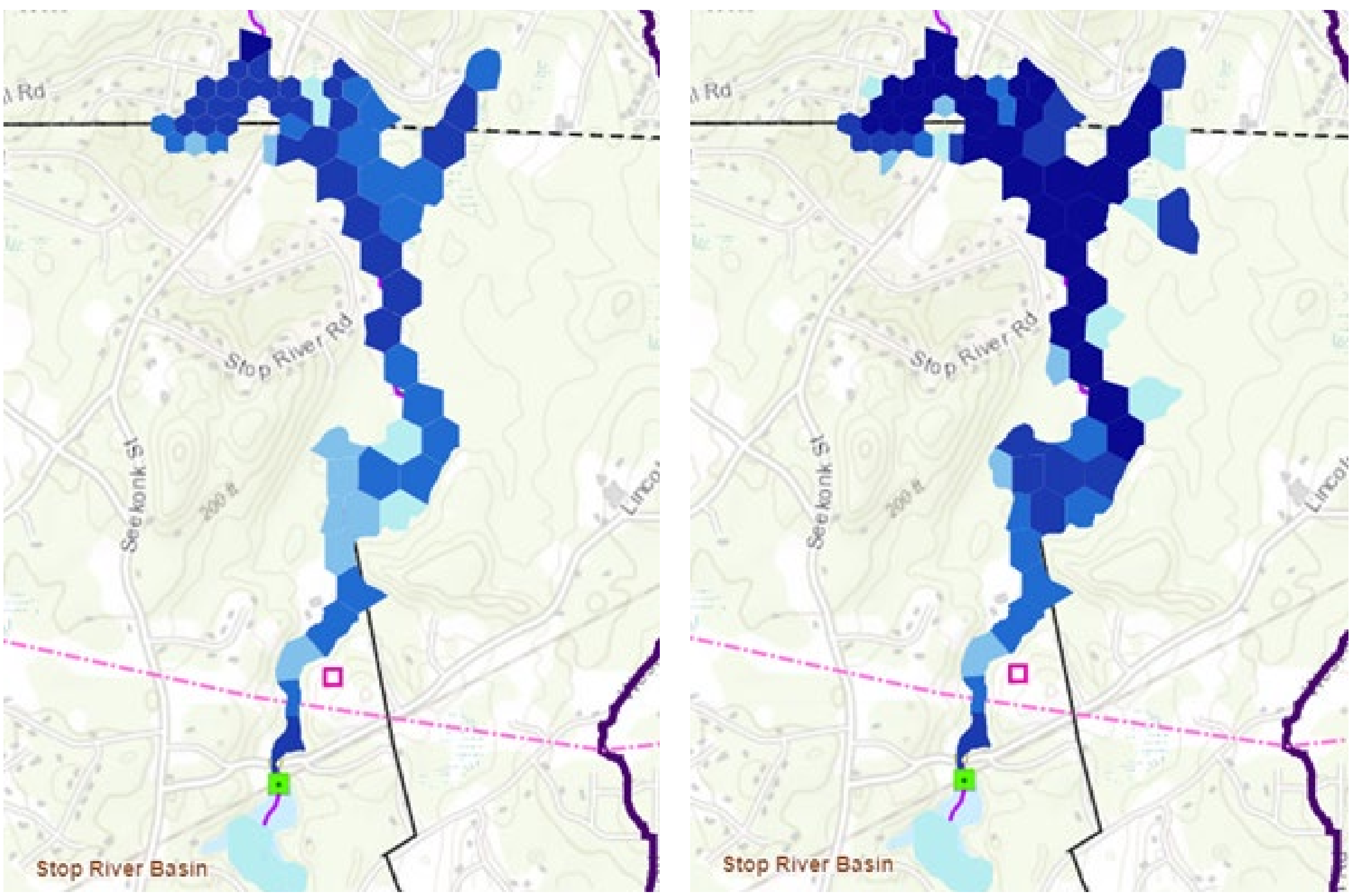


FIGURE 3.9 Comparison of flooding extents and depth during baseline 10-yr (left) and 2070 10-yr (right) design events in the Stop River

Flood depths are also expected to increase significantly, as well with flood depths in a sizeable flood-prone area along Stop River Road expected to increase from the 1 to 2-foot range under baseline conditions to 3+ feet under a 2070 climate scenario.

Another good example of the ability of the 2D Charles River stormwater flood model to reveal site-specific changes with respect to flooding in the Charles River itself, for example in Dedham, as shown in Figure 3.10.

Specifically, significantly more flooding – both extents and depth – are expected along the Charles between I-95 southbound and Rte. 135 and in the area near Chestnut Street as far downstream as Wildwood Drive and as far upstream as Powissett Brook. Wildwood Drive and as far upstream as Powissett Brook.

The model output hydrographs from various events help compare how peak discharge rates vary within the watershed and how these are likely to change with time. For instance, Figure 3.4 shows the expected streamflow in the Charles River between Dover and Wellesley during the baseline and 2070 10-year events. Under a baseline climate, the Charles River is expected to reach nearly 1,174 cfs during the 10-year flood event. By 2070, peak streamflow is expected to increase by 27% to 1,490 cfs. This increase in peak discharge also implies anticipated increases to flood-prone areas shown in Figures 3.9 and 3.10.

To understand the impacts of extreme flooding that may occur in the future, Tables 3.8 and 3.9 summarizes model simulation results for the 100-

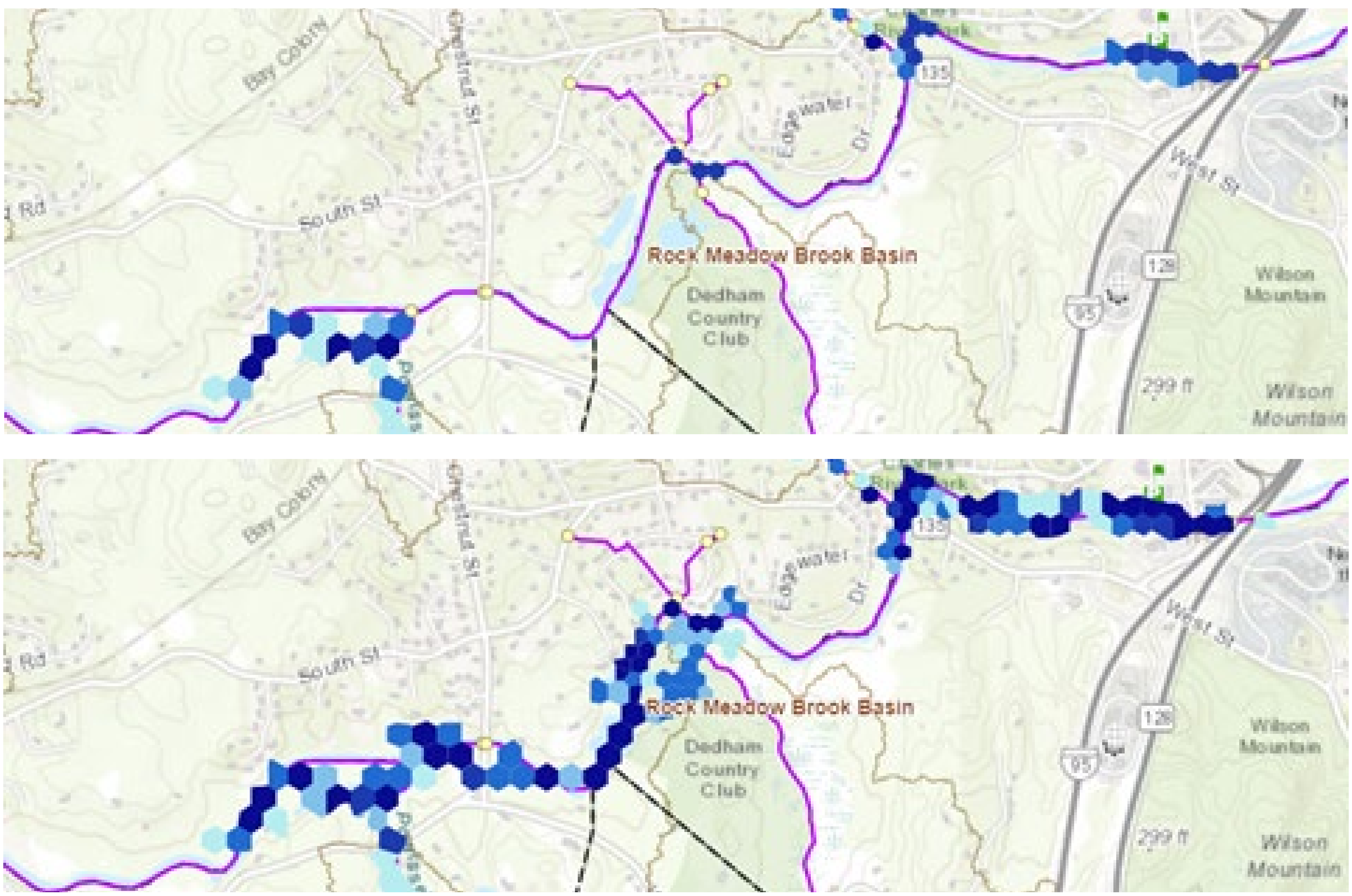


FIGURE 3.10 Comparison of flooding extents and depth during baseline 10-yr (top) and 2070 10-yr (bottom) design events in the Charles River in Dedham

year event for the 2030 planning horizon, less than 10 years away.

As with the 10-year storm events, there is considerable variability throughout the watershed in the anticipated increase in flood-prone areas from baseline to 2030 during the 100-year event, with several sub-basins (14) experiencing a 1% increase or less while others (4) are expected to experience greater than a 10% increase in flood-prone areas. In general, however, the increase in total inundated area across the watershed is relatively modest, approximately 5%, particularly when compared to the increase associated with the 2070 10-year event, 23%. Increases to total runoff volume from the watershed are similarly modest, 19% compared to 45% for the 2070 10-year runoff volume. Also, no additional critical infrastructure is expected to fall within the flood-prone areas by 2030, during the 100-year event compared to present day. However, flood depths are likely deeper at currently impacted infrastructure. These findings suggest that while climate change-driven increases to flooding in the Charles River are significant, there is still some time to take action in order to mitigate those anticipated increases.

However, during more extreme events, such as the 11.7 inches of rain in 24 hours, significant increases are expected in terms of all types of flooding impacts in sub-basins throughout the watershed. Tables 3.10 and 3.11 highlight some of those impacts.

Tables 3.10 and 3.11 summarize the results of flood impacts from the more extreme storm of 11.7 inches in 24 hours within each of the 33 subbasins. The average inundated area watershed-wide is projected to be 394 acres. Noanet Brook subbasin experiences the least flooding with no inundated area while the Chales River between Medway and Bogastow Brook is projected to experience the most with 2,021 acres of flooded area. Noanet Brook subbasin is estimated to have the lowest total runoff volume with 167 million gallons and Bogastow Brook subbasin is estimated to have the highest with 2,498 million gallons. The average total runoff volume per sub-basin is projected to be 933 million gallons. Peak discharges are projected to vary from 201 cfs in Stall Brook to 5,754 cfs in the Charles River between Wellesley and Stony Brook. Peak discharges are estimated to average around 1,670 cfs. By late-century, the flooding impacts from extreme storm events are expected to increase significantly. The team identified and evaluated several nature-based solutions across the watershed that may mitigate some of these increased impacts. Results were presented to the project team at Workshop 2 Part 3 on May 26th (Appendix A.1)

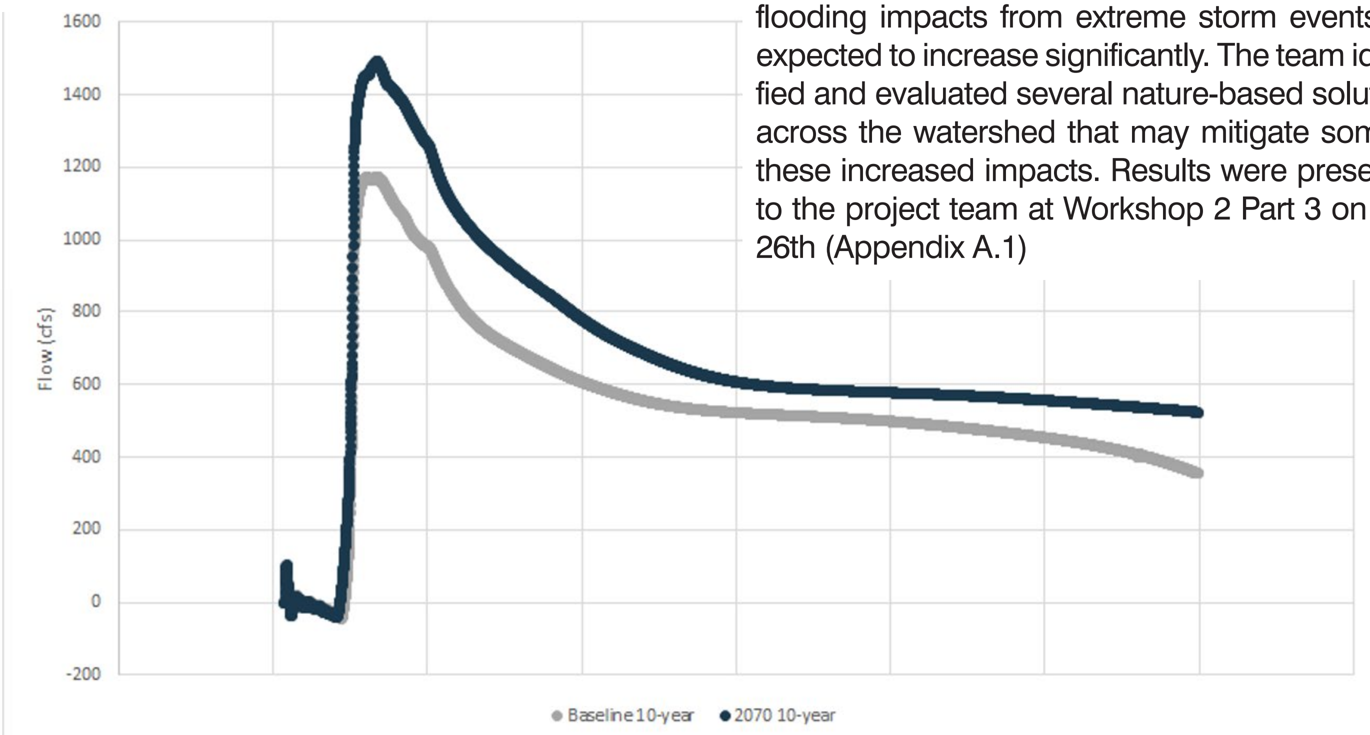


FIGURE 3.11 Hydrograph comparison of baseline 10-yr and 2070 10-yr events in the Charles River between Dover and Wellesley

TABLE 3.8 Summary of inundation extents for the 2030 100-year event, by sub-basin

Sub-Basin	Inundated Area (acres)		
	Baseline 100-year	2030 100-year	Increase over Baseline (%)
Alder Brook	6	6	0%
Beaver Brook	129	133	3%
Bogastow Brook	865	881	2%
Bogle Brook	340	355	4%
Charles River - Bogastow Brook to Dover	449	477	6%
Charles River: Box Pond Dam to Medway	496	518	4%
Charles River: Dover to Wellesley	1,209	1,318	9%
Charles River: Medway to Bogastow Brook	1,842	1,893	3%
Charles River: Stony Brook to Watertown	122	186	53%
Charles River: Wellesley to Stony Brook	245	285	16%
Charles River Headwaters	398	411	3%
Cheese Cake Brook	16	16	0%
Chester Brook	75	79	6%
Chicken Brook	47	47	0%
Davis Brook	19	19	0%
Hobbs Brook	636	643	1%
Hopping Brook	345	345	0%
Indian Brook	187	221	18%
Lowder Brook	177	188	6%
Mill River	374	374	0%
Mine Brook	799	839	5%
Noanet Brook	0	0	0%
Powissett Brook	40	40	0%
Rock Meadow Brook	103	112	8%
Rosemary Brook	44	44	0%
Sawmill Brook	39	39	0%
Seaverns Brook	28	28	0%
Shepherds Brook	46	53	15%
South Meadow Brook	58	60	2%
Stall Brook	175	177	1%
Stony Brook	503	508	1%
Stop River	1,134	1,217	7%
Trout Brook	120	123	3%

TABLE 3.9 Summary of total runoff volume, and peak discharge for the 2030 100-year event, by sub-basin

Sub-Basin	Total Runoff (MG)			Peak Discharge (cfs)		
	Baseline 100-year	2030 100-year	Increase over Baseline (%)	Baseline 100-year	2030 100-year	Increase over Baseline (%)
Alder Brook	131	152	17%	358	363	2%
Beaver Brook	486	571	18%	1,459	2,010	38%
Bogastow Brook	1,318	1,607	22%	1,657	2,077	25%
Bogle Brook	921	1,105	20%	607	666	10%
Charles River - Bogastow Brook to Dover	638	801	25%	1,727	2,039	18%
Charles River: Box Pond Dam to Medway	434	521	20%	1,557	1,705	10%
Charles River: Dover to Wellesley	937	1,095	17%	1,787	2,072	16%
Charles River: Medway to Bogastow Brook	962	1,177	22%	1,718	1,810	5%
Charles River: Stony Brook to Watertown	568	647	14%	3,529	3,620	3%
Charles River: Wellesley to Stony Brook	522	616	18%	2,982	3,756	26%
Charles River Headwaters	1,131	1,346	19%	541	682	26%
Cheese Cake Brook	248	288	16%	1,551	1,748	13%
Chester Brook	426	497	17%	1,113	1,447	30%
Chicken Brook	418	504	21%	316	333	6%
Davis Brook	115	136	18%	385	473	23%
Hobbs Brook	903	1,016	12%	995	1,006	1%
Hopping Brook	564	689	22%	365	365	0%
Indian Brook	275	333	21%	265	332	25%
Lowder Brook	283	329	16%	248	276	12%
Mill River	728	911	25%	1,290	1,284	0%
Mine Brook	1,007	1,200	19%	416	462	11%
Noanet Brook	77	98	28%	265	396	50%
Powissett Brook	101	120	20%	606	803	33%
Rock Meadow Brook	148	179	21%	563	644	15%
Rosemary Brook	267	316	18%	564	694	23%
Sawmill Brook	220	255	16%	2,127	2,497	17%
Seaverns Brook	89	113	27%	251	275	10%
Shepherds Brook	259	311	20%	310	310	0%
South Meadow Brook	267	308	15%	908	981	8%
Stall Brook	282	332	18%	123	138	12%
Stony Brook	1,494	1,719	15%	984	1,106	12%
Stop River	894	1,094	22%	431	494	15%
Trout Brook	209	261	25%	443	736	66%

TABLE 3.10 Summary of inundation extents and impacted critical infrastructure for the more extreme storm of 11.7 inches in 24 hours, by subbasin

Sub-Basin	Inundated Area (acres)			Critical Infrastructure Inundated		
	Baseline 100-year	Mystic 2070 100-year	Baseline 100-year	Increase over Baseline (%)	Mystic 2070 100-year	Increase over Baseline (%)
Alder Brook	6	6	0%	0	0	0%
Beaver Brook	129	142	10%	4	4	0%
Bogastow Brook	865	1,017	18%	2	2	0%
Bogle Brook	340	511	50%	4	5	25%
Charles River - Bogastow Brook to Dover	449	669	49%	2	6	200%
Charles River: Box Pond Dam to Medway	496	576	16%	4	4	0%
Charles River: Dover to Wellesley	1,209	1,479	22%	6	6	0%
Charles River: Medway to Bogastow Brook	1,842	2,021	10%	5	6	20%
Charles River: Stony Brook to Watertown	122	235	93%	3	4	33%
Charles River: Wellesley to Stony Brook	245	314	28%	3	3	0%
Charles River Headwaters	398	449	13%	11	11	0%
Cheese Cake Brook	16	16	0%	0	0	0%
Chester Brook	75	81	8%	2	2	0%
Chicken Brook	47	47	0%	1	1	0%
Davis Brook	19	19	0%	0	0	0%
Hobbs Brook	636	664	4%	2	2	0%
Hopping Brook	345	391	13%	2	2	0%
Indian Brook	187	286	53%	0	0	0%
Lowder Brook	177	217	23%	0	0	0%
Mill River	374	418	12%	1	1	0%
Mine Brook	799	902	13%	3	3	0%
Noanet Brook	0	0	0%	0	0	0%
Powissett Brook	40	40	0%	0	0	0%
Rock Meadow Brook	103	139	35%	2	2	0%
Rosemary Brook	44	48	7%	2	2	0%
Sawmill Brook	39	39	0%	0	0	0%
Seaverns Brook	28	30	8%	1	1	0%
Shepherds Brook	46	53	15%	0	0	0%
South Meadow Brook	58	67	15%	0	0	0%
Stall Brook	175	183	5%	0	0	0%
Stony Brook	503	513	2%	5	5	0%
Stop River	1,134	1,300	15%	1	1	0%
Trout Brook	120	129	7%	0	0	0%

TABLE 3.11 Summary of total discharge and peak discharge for the for the more extreme storm of 11.7 inches in 24 hours, by subbasin.

Sub-Basin	Total Runoff (MG)			Peak Discharge (cfs)		
	Baseline 100-year	Mystic 2070 100-year	Baseline 100-year	Increase over Baseline (%)	Mystic 2070 100-year	Increase over Baseline (%)
Alder Brook	131	218	67%	358	697	95%
Beaver Brook	486	830	71%	1,459	3,945	170%
Bogastow Brook	1,318	2,498	90%	1,657	3,191	93%
Bogle Brook	921	1,670	81%	607	947	56%
Charles River - Bogastow Brook to Dover	638	1,305	104%	1,727	2,764	60%
Charles River: Box Pond Dam to Medway	434	788	82%	1,557	2,284	47%
Charles River: Dover to Wellesley	937	1,574	68%	1,787	2,638	48%
Charles River: Medway to Bogastow Brook	962	1,842	91%	1,718	1,826	6%
Charles River: Stony Brook to Watertown	568	879	55%	3,529	4,676	33%
Charles River: Wellesley to Stony Brook	522	903	73%	2,982	5,754	93%
Charles River Headwaters	1,131	1,999	77%	541	1,393	158%
Cheese Cake Brook	248	408	65%	1,551	2,181	41%
Chester Brook	426	711	67%	1,113	2,436	119%
Chicken Brook	418	770	84%	316	367	16%
Davis Brook	115	201	74%	385	657	71%
Hobbs Brook	903	1,346	49%	995	1,025	3%
Hopping Brook	564	1,075	91%	365	366	0%
Indian Brook	275	510	85%	265	699	164%
Lowder Brook	283	466	65%	248	337	36%
Mill River	728	1,479	103%	1,290	1,853	44%
Mine Brook	1,007	1,788	78%	416	663	59%
Noanet Brook	77	167	117%	265	960	262%
Powissett Brook	101	180	79%	606	1,489	146%
Rock Meadow Brook	148	275	86%	563	1,257	123%
Rosemary Brook	267	466	75%	564	1,128	100%
Sawmill Brook	220	359	63%	2,127	3,712	75%
Seaverns Brook	89	188	111%	251	442	76%
Shepherds Brook	259	468	81%	310	825	166%
South Meadow Brook	267	430	61%	908	1,195	32%
Stall Brook	282	482	71%	123	201	63%
Stony Brook	1,494	2,387	60%	984	1,457	48%
Stop River	894	1,710	91%	431	704	63%
Trout Brook	209	421	101%	443	1,053	138%

PRIORITY WATERSHED CLIMATE ADAPTATION STRATEGIES

4.1 FLOOD MITIGATION STRATEGIES

A key objective of the project was to use the model to assess the benefits of various flood mitigation strategies. The team prioritized the assessment of nature-based solutions for flood mitigation over grey infrastructure strategies during this project phase. To obtain input on which flood mitigation strategies to assess, the team used multiple surveys, the same surveys that were used to gauge input on modeling future timeframes. Nature-based flood mitigation strategies were presented in seven categories:

- Green Stormwater Infrastructure
- Reduce Impervious Cover
- Dam Removal
- Floodplain Reconnection
- Land Conservation
- Increase Tree Canopy
- Wetland Restoration

CRWA administered a survey to the full project team and two surveys to the general public, one for attendees of the initial virtual event, and a modified version for individuals with limited introduction to the project.

4.1.1 Public Surveys

To prioritize the categories above, both public surveys contained the following questions:

- Which of these would you like to see explored as possible nature-based solutions to help mitigate potential flooding impacts of climate change? (check all that apply)
- Which of these nature-based solutions do you think would be possible in your community?

CRWA and CREW partnered to distribute the surveys. The survey for webinar attendees was shared during the webinar and sent via email in the follow up email. The survey received 70 responses. The general survey was also administered via email and social media. CREW also hosted three virtual meetings for community-based organizations that work in the watershed, especially those working in environmental justice communities and on equity issues, to discuss the project, answer questions and obtain input. Meetings included a brief break for attendees to complete the survey. The survey received 104 responses.

4.1.2 Project Team Survey

The project team survey contained the following questions:

- What nature-based solution(s) are you pursuing within your community? (check all that apply)
- What nature-based solution(s) are you interested in exploring through this project? (check all that apply)

The project team survey also contained the following questions:

What types of strategies are you most interested in seeing modeled through this project? (select one):

A. Small scale strategies implemented consistently across the watershed (ex. 10% reduction in impervious cover, 25% green streets, increase in tree canopy cover, land conservation)

B. Large scale flood storage opportunities, along the river and upland (ex. wetland restoration, floodplain reconnection, use of parks/fields for flood storages)

C. Large scale infrastructure changes - grey to green or green/gray mix (ex. Dam removal, culvert replacement)

- A and B
- A and C
- B and C

Are there large (>1 acre) open spaces (parks, *athletic fields parking lots, vacant lots, etc.) that could have the potential to be used for permanent or temporary stormwater/flood storage?*

- Yes
- No

Which of the following, if any, do you think are NOT feasible for your community even if funding for implementation was available?

- Decrease directly connected / effective impervious cover by 10-25%
- Increase tree canopy by up to 25%
- Restore culverted streams
- Permanently protect >50% of available open space
- Green infrastructure stores 1.5” storm runoff from 50% of all impervious cover town-wide
- All undeveloped lots > 2 acres available to provide flood storage
- Dam removal
- Dam management changes
- Move development out of flood plain
- Wetland construction (river adjacent and upland)
- None (all are feasible if funding is available)

Do you have any additional suggestions for nature-based solutions to investigate?

The project team survey was administered following the first team workshop. A response was received from each of the participating communities.

4.1.2 Survey Results

Survey responses were summarized for the project team at Workshop #2, results are summarized in the May 5th presentation (Appendix A.1). The three categories prioritized by both the public and the project team were:

- More green stormwater infrastructure
- Land conservation
- Less paved surfaces

Wetland restoration was also selected as a top priority in the public survey but scored low with the project team. The project team also demonstrated preference to explore dam removal and floodplain reconnection, however, these two categories received the lowest votes on the public survey.

Based on survey responses, CRWA and Weston & Sampson identified specific strategies in each of these categories that could be input into the model. These strategies were presented to the project team Nature-Based Solutions Subcommittee for input and feedback. Following the subcommittee meeting the strategies were finalized and presented to the full project team. Following the presentation, the project team voted on the specific strategies. Results of this prioritization were presented at the following full project team meeting and are summarized in Table 4.1 below. A more detailed summary of results is available in the May 12th presentation (Appendix A.1).

4.2 PRIORITIZED FLOOD MITIGATION STRATEGIES

The alternate scenarios were identified in the event that technical, or other, issues arose that prevented successful modeling of one of the other six scenarios. These scenarios could have been selected without a need to reconvene the project team, however, only the initial six scenarios were modeled. Scenario 2 was initially identified as 10% of feasible/priority land area is GSI, however, in the process of identifying the land to input as priority GSI sites, the team easily identified 20% of the land area through GIS analysis described below. Instead of pursing additional GIS analysis, CRWA suggested the increase from 10% to 20% and the project team agreed.

Multiple scenarios evaluated for flood mitigation build off data presented in the Charles River Watershed Conservation and Restoration Prioritization Tool. This Tool was developed by CRWA and The Nature Conservancy prior to the start of this project and uses desktop GIS analyses to prioritize land area in the watershed for conservation and restoration actions based on some traditional criteria and metrics, such as habitat quality, while also incorporating criteria relevant to the expected impacts of climate change in the northeast, such as protecting land subject to flooding or preserving and promoting infiltration opportunities on high quality soils to build resilience to drought. The Tool is available online and accessible to the public .[3]

Scenario 2 is based on the priority Upland Restoration opportunities identified in the Tool (Figure 4.1). Restoration suitability takes into account the current need for restoration, feasibility based on physical and management characteristics, and provides recommendations for opportunities to address equity through restoration projects. Table 4.3 summarizes the prioritization methodology for the upland restoration priority areas. Section 5 describes how 20% of this area was selected for input into the model.

Scenario 5 is also based on the Charles River Watershed Conservation and Restoration Prioritization Tool. The Tool allows users to identify conservation opportunities based on a variety of different factors including inland/coastal flooding and water resource protection, and habitat value (Figure 4.2). There is presently about 120,000 acres of undeveloped/unprotected land in the watershed. Table 4.3 demonstrates the prioritization methodology for identifying 50% of this for continued protection, allowing the remaining 50% to be assumed to be developed.

In Scenario 3, large public properties were primarily identified using the MassGIS 2016 Land Use Land Cover dataset, details are described in Section 5. The primary types of properties identified included schools, municipal buildings / facilities, such as Natick and Medway High Schools.

TABLE 4.1 Summarizes the priority flood mitigation strategies that were selected to be modeled during this project phase.

Category	Scenario Number	Strategy
Green Stormwater Infrastructure	1	Green stormwater infrastructure (GSI) stores 2" storm runoff from up to 50% of all impervious cover town-wide
	2	20% of feasible/priority land area is GSI
	3	Storage on large (>5 acres) public properties (GSI, underground storage, "blue roofs") (site specific strategy)
Reduce Impervious Cover	4	Reduce effective impervious cover watershed wide by 10% (for subbasins over 10%)
Land Conservation	5	Allow 50% of remaining undeveloped/unprotected land to become impervious
Increase Tree Canopy	6	25% public ROWS become green streets: tree box filters/bioswales connected to leaching catch basins (site specific strategy)

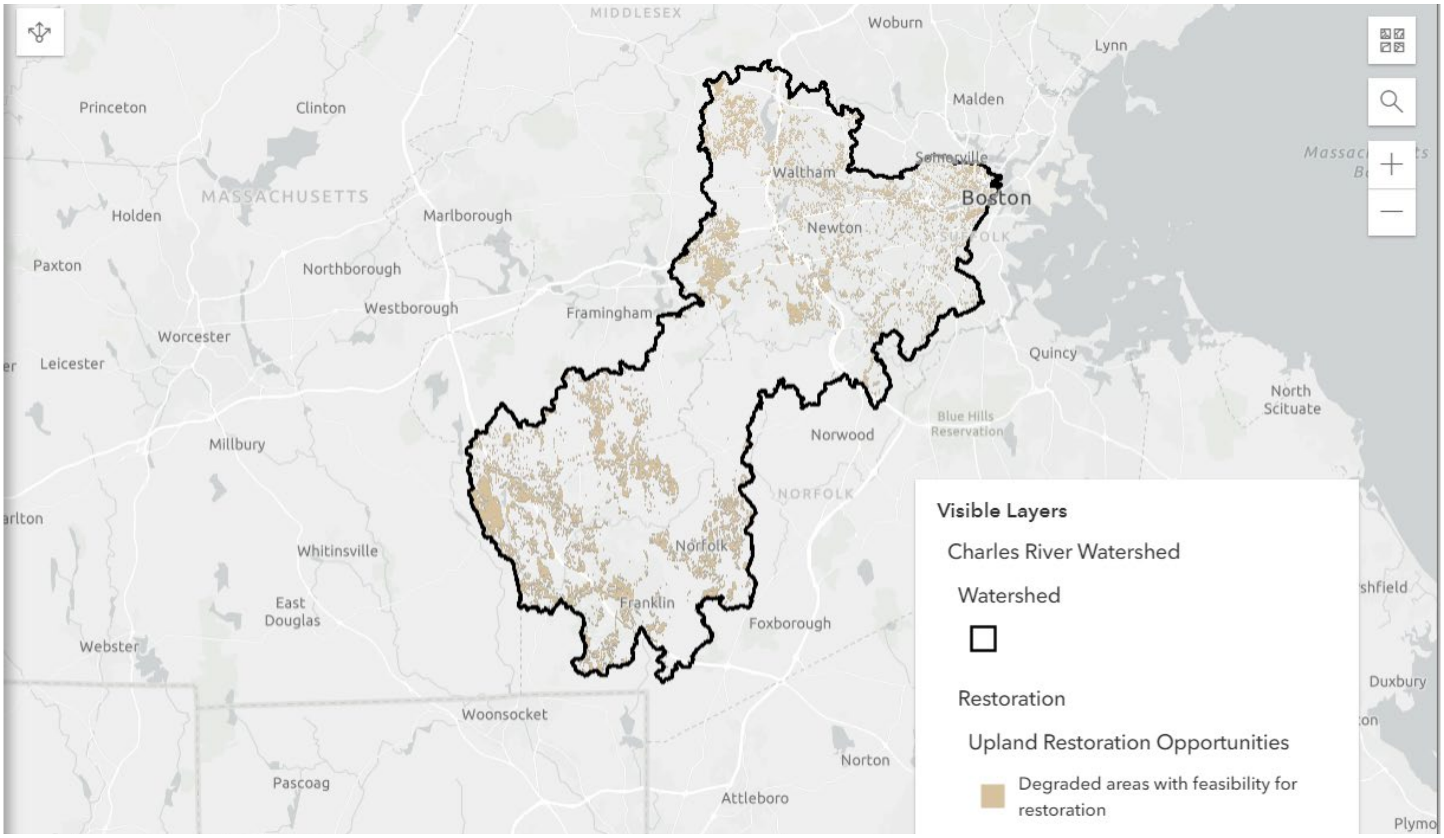


FIGURE 4.1 Upland Restoration Priority Areas via the Charles River Watershed Conservation and Restoration Prioritization Tool

TABLE 4.2 Upland Restoration Prioritization Methodology from the Charles River Watershed Conservation and Restoration Prioritization Tool

Criteria Subcategory	Degradation			Feasibility	
Criterion Overview	Indicates need for restoration			Indicates high feasibility areas to implementing effective green infrastructure	
Criteria Shorthand	Areas with groundwater depletion	Properties with high impervious cover	Areas with high pollution loading	Areas with well draining soils	Areas with space availability
Layer Details (GIS file)	MassDEP Sustainable Water Management Initiative (SWMI) net groundwater depletion	Building Structures, MassGIS	• Impervious cover, MA Land Use/Land cover 2016 • MA Land Use 2005	NRCS Hydrologic Soil Groups	Existing parks and open spaces, MassGIS 2017
Analysis	Categories 4 or 5	Building Structure Footprints >1 acre	Commercial, Industrial, High-Density Residential land Land cover = impervious	Soil groups A and B, and unknown	Publicly owned parks and open space
Analysis Detail	Basins whose unaffected August median flow is more than 25% depleted after accounting for groundwater and groundwater discharges	Buildings with large footprints often have large parking lots	High pollutant, impervious areas are ideal areas to target large pollutant loads	A and B soils have high infiltration capacity, making them ideal areas to implement green infrastructure. Unknown soils were included to not exclude urban areas with little information.	Upland restoration projects can often be implemented in existing, publicly owned parks and open spaces
Co-benefits (displayed as overlays)	• Environmental Justice Communities (MA_CharlesRiver_EnvJustice) • Greenspace Deserts (MA_CharlesRiver_GreenspaceDeserts)				
Excluded	• Activity/Use Limitation (AUL) sites, 21(e) sites, and underground storage tanks (MassGIS 2016 with 200' buffer) • Forested areas (MA Land Use 2005) • Wellhead Protection Zone I and Zone II areas (MassGIS 2016) • Surface water and buffer zones				
Prioritization	• Priority upland restoration opportunities occur at sites that have at least one degradation indicator and/or at least one feasibility indicator.				

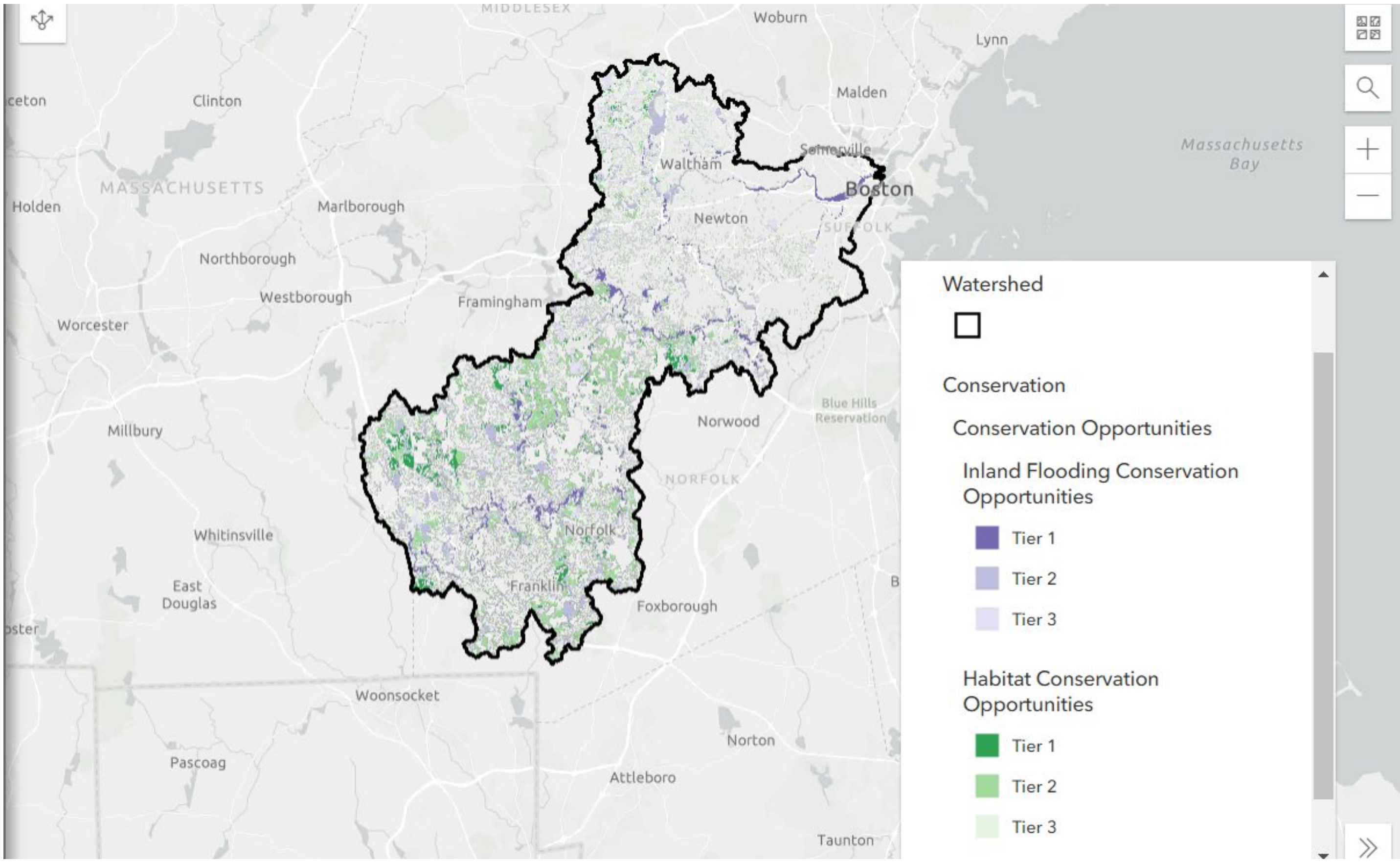


FIGURE 4.2 Conservation Priority Areas via the Charles River Watershed Conservation and Restoration Prioritization Tool

TABLE 4.3 Methodology to Identify Priority Areas to Remain Undeveloped (Scenario 5 allows all the remaining undeveloped/unprotected land to be developed with no flood control mitigation).

Conservation Opportunity Category	**Data Criteria for Land that *Remains* Undeveloped**	**Prioritization for Land the *Remains* Undeveloped**
Inland Flooding	• Low lying areas within each sub- basin. (The lowest 10th percentile elevation in each sub-basin based on LIDAR elevation.) • FEMA 100 year and 500 year floodplain • Wetlands with a 100 ft. buffer	Areas with one or two data criteria were prioritized to remain undeveloped
Habitat	• BioMap2 Core Habitat and Critical Natural Landscape • High Integrity Wetlands • Above average resilience • Marsh migration areas • Habitat connectivity - Regional flow connecting habitat clusters (Tier 2 only)	Area with ***at least one*** high quality habitat indicator
Excluded	• Protected and Recreation Open Space (MassGIS) • Developed Land[1] (MassGIS LandUse 2005)	

[1]Cemetery, Commercial, Cranberry Bog, Cropland, Golf Course, High Density Residential, Industrial, Junkyard, Low Density Residential, Marina, Medium Density Residential, Mining, Multi-Family Residential, Nursery, Orchard, Participation Recreation, Spectator Recreation, Transitional, Urban Public/Institutional, Very Low Density Residential, Waste Disposal, Water-Based Recreation

WATERSHED ADAPTATION RECOMMENDATIONS

5.1 PRIORITY MITIGATION MEASURES MODEL RESULTS

Six nature-based flood mitigation strategies were identified through a prioritization process described in section 4. In order to evaluate the projects, six scenarios were developed grouping the strategies as presented in Table 4.1. The following subsections describe how each scenario was modeled and how each is expected to reduce flooding in the Charles River watershed. Results were presented at project team Workshop 3 on June 24th (Appendix A.2) and are currently available online in the flood viewer and story maps.

5.1.1 GI SCENARIO 1 -- ADDITIONAL 2 INCHES OF ONSITE STORAGE

GI Scenario 1 was developed to represent the on-site storage of an additional 2 inches of runoff originating from 50% of impervious cover across the watershed. This scenario was incorporated into the Charles River stormwater model by increasing the storage coefficient for the impervious fraction of every one of the 705 subcatchments. As 2 inches of additional storage over 50% of impervious surfaces is equivalent to 1 inch of additional storage across 100% of impervious surfaces, the impervious storage coefficient, "Dstore_impervious", was increased by 1 inch for all subcatchments. This change represented a more than 26-fold increase in that storage parameter. Figure 5.1 illustrates the distribution of impervious surfaces within a few example subcatchments.

The potential flood reduction benefits of this green infrastructure scenario were evaluated by comparing it to a "no-action" condition during baseline 10-year and 2070 10-year flood events. The present and 2070 10-year storms comparison for GI Scenario 1 compared to "no-action" is summarized watershed-wide in Table 5.1. The 2070 comparison is summarized by sub-basin in Table 5.2.

TABLE 5.1 Summary of number of critical facilities impacted, inundation extents, and total runoff for GI Scenario 1 during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from "no action"

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + GI Sc 1	48	6,891	6,646
Change from No Action	-5 (-9%)	-352 (-5%)	-722 (-10%)
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + GI Sc 1	56	8,641	9,923
Change from No Action	---	-287 (-3%)	-728 (-7%)

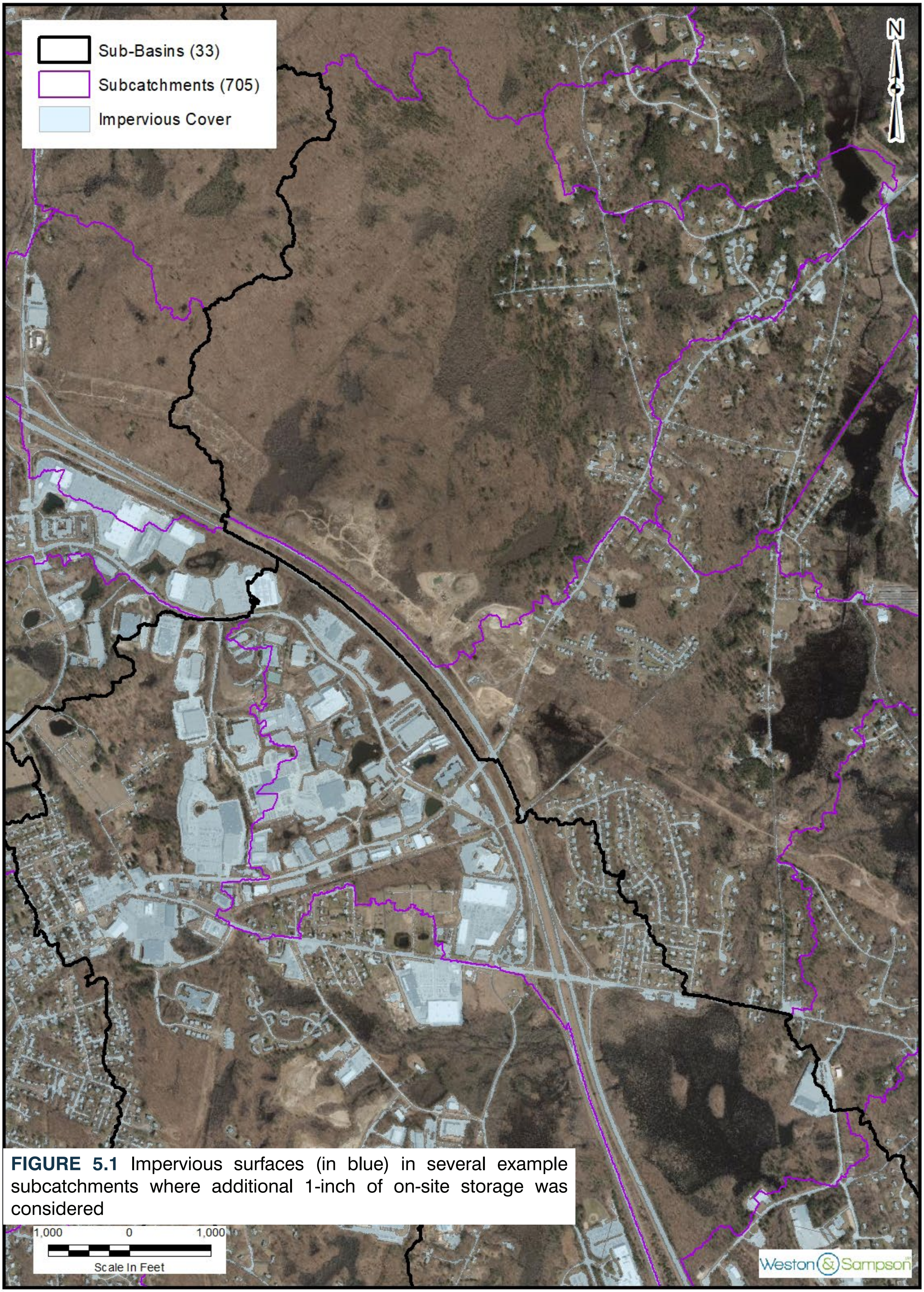


FIGURE 5.1 Impervious surfaces (in blue) in several example subcatchments where additional 1-inch of on-site storage was considered

TABLE 5.2 Summary of inundation extents, total runoff, and peak discharge for GI Scenario 1 during the 2070 10-year event, by sub-basin, and the percent reduction from no action.

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	77	-11%	349	349	0%
Beaver Brook	116	115	-1%	313	282	-10%	605	593	-2%
Bogastow Brook	715	684	-4%	744	704	-5%	1,076	1,064	-1%
Bogle Brook	295	290	-1%	560	507	-10%	435	291	-33%
Charles River: Bogastow Brook to Dover	340	284	-16%	320	304	-5%	1,077	1,022	-5%
Charles River: Box Pond Dam to Medway	408	370	-9%	259	243	-6%	1,208	1,177	-3%
Charles River: Dover to Wellesley	805	755	-6%	613	570	-7%	1,490	1,372	-8%
Charles River: Medway to Bogastow Brook	1,386	1,385	0%	535	505	-5%	1,346	1,303	-3%
Charles River: Stony Brook to Watertown	73	69	-5%	406	358	-12%	2,048	1,800	-12%
Charles River: Wellesley to Stony Brook	175	164	-6%	333	293	-12%	2,010	1,860	-7%
Charles River Headwaters	328	316	-4%	699	653	-7%	378	373	-1%
Cheese Cake Brook	16	16	-3%	167	145	-13%	1,143	1,141	0%
Chester Brook	67	66	-1%	285	254	-11%	670	588	-12%
Chicken Brook	24	24	0%	245	232	-5%	307	306	0%
Davis Brook	19	19	0%	72	68	-5%	270	262	-3%
Hobbs Brook	624	624	0%	665	642	-4%	762	751	-1%
Hopping Brook	310	307	-1%	315	302	-4%	206	201	-3%
Indian Brook	137	132	-4%	160	151	-6%	134	129	-4%
Lowder Brook	155	154	-1%	189	172	-9%	164	154	-6%
Mill River	271	254	-6%	369	338	-8%	403	361	-10%
Mine Brook	763	747	-2%	619	575	-7%	268	245	-9%
Noanet Brook	0	0	0%	34	33	-4%	132	132	0%
Powissett Brook	40	40	0%	61	60	-1%	276	271	-2%
Rock Meadow Brook	32	31	-3%	85	80	-6%	563	563	0%
Rosemary Brook	44	44	0%	168	149	-11%	384	335	-13%
Sawmill Brook	39	39	0%	150	135	-10%	1,443	1,429	-1%
Seaverns Brook	17	15	-12%	44	40	-9%	198	197	0%
Shepherds Brook	46	46	0%	156	147	-5%	233	228	-2%
South Meadow Brook	52	52	0%	183	162	-12%	695	682	-2%
Stall Brook	149	137	-8%	181	167	-8%	100	99	-1%
Stony Brook	453	451	-1%	1,028	999	-3%	759	730	-4%
Stop River	930	922	-1%	499	471	-6%	231	214	-7%
Trout Brook	92	83	-10%	107	102	-5%	233	230	-1%

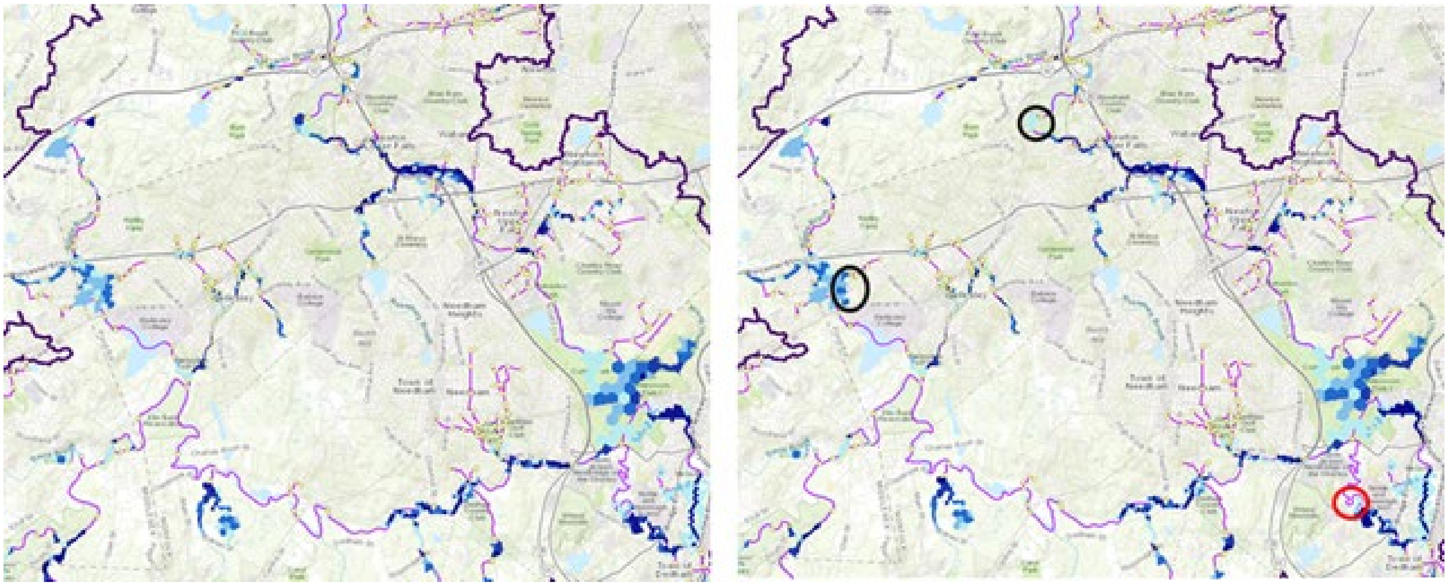


FIGURE 5.2 Areas of flooding from 2070 10-year storm under "no-action" (left) and under GI Scenario 1 (right) (red = eliminated flooding, black = reduced flooding)

As shown in Table 5.2, GI Scenario 1 reduces the flooding extents, total runoff volume, and peak discharge rates from most sub-basins within the watershed. Across the entire watershed, this scenario reduces flooding extents by 287 acres or 3%. The percent change varies considerably by sub-basin, however. Eleven sub-basins are not expected to experience a significant change in flood-prone area, while others, like Charles River (Bogastow to Dover) and Seaverns Brook will experience reductions as high as 16 and 12%, respectively. Despite these reductions in flood-prone area, it is worth mentioning that no critical infrastructure that would be impacted under a 2070 No Action scenario would become dry as a result of GI Scenario 1

Reductions in flood-prone area are generally driven by reductions in runoff volume and peak discharge from a sub-basin. On average, GI Scenario 1 is expected to reduce runoff volumes by 7%. While seven sub-basins are expected to see reductions of greater than 10%, and two sub-basins, Powissett Brook and Stony Brook, are expected to experience relatively small reductions, 1 and 3%, respectively. Most sub-basins are expected to experience reductions in total runoff volume of between 4 and 10%. Reductions in peak discharge are more modest with a watershed wide average reduction of 5%. Twelve sub-basins are not expected to experience a significant change in flood-prone area (1% or less) while five sub-basins, such as Bogle Brook and Rosemary Brook, are expected to see reductions of greater than 10%. Most sub-basins, however, are expected to experience reductions in peak discharge of between 2 and 10%.

Based on the 2D capacity of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.2, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of GI Scenario 1. Areas circled in red are areas where flooding has been eliminated while areas circled in black are areas with reduced flooding from Scenario 1.

TABLE 5.3 Summary of Co-benefits for Scenario 1

Co-Benefit Type	Co-Benefit Description
Nature-Based Solutions Scenarios	Green infrastructure stores 2" storm runoff from up to 50% of all impervious cover town-wide (assume some infiltration on good quality soils).
Promotes Biodiversity	In this scenario, there is an additional 36,893 acres of green stormwater infrastructure providing additional greenery and habitat. GSI system typically function best with native or nativized vegetation which also provide habitat for local wildlife.
Restores or Remediates Sites	Careful site planning and selection of practices allow green infrastructure to work on contaminated sites and sites with poor soils.
Promotes Sustainable Development / Reduces Development in Climate Vulnerable Areas	GSI can provide green jobs and protection for surrounding properties, and amenities to surrounding residents. This scenario demonstrates where flooding impacts will occur with and without intervention.
Improved Water Quality	According the the EPA, if a stream's watershed has greater than 25% impervious cover, the stream is a non-supporting, or unhealthy, stream. Treating and infiltrating stormwater runoff onsite will remove pollutants and reduce pollutant loading in the Charles River and the watershed. A biofiltration system similar to the FocalPoint has a 66% phosphorus removal rate. Bioretention systems and rain gardens have a removal efficiency of: • 90% TSS removal with adequate pretreatment • 30-50% total nitrogen • 30-90% total phosphorus • 40-90% metal pollutant A detention basin has pollutant removal efficiencies of: • 50% TSS removal with adequate pretreatment • 15-50% total nitrogen • 10-30% total phosphorus • 30-50% metal pollutant • Less than 10% pathogen removal
Annual Recharge	Using the Stormwater Recharge Calculator developed by Abt Associates with support from CRWA, it is estimated this scenario can recharge 16,288 million gallons per year (MGY).
Improved Air Quality	Improves air quality by filtering air pollutants and particulates. Larger impact if trees are incorporated into Green Stormwater Infrastructure systems.
Climate Mitigation	Increases in vegetation mean more direct carbon sequestration along with more shade and heat dissapation, lowering outdoor temperatures. Additionally, a reduction in impervious cover will lead to less heat absorbed, also helping reduce temperatures. Less energy spent on cooling purposes, will result in a decrease in carbon dioxide emissions.
Public Health	Infiltration practices will assist with groundwater recharge and restoring levels for drinking water. Provides flood management and reduces opportunity for combine sewer overflow events and associated hazards and displacement from flooding.
Reduce Long-term Maintenance	N/A
Raise Awareness of Nature-Based Solutions	Engages public in stormwater management issues with visual demonstration. Familiarizes public with GI practices

5.1.2. GI SCENARIO 2 -- GREEN STORMWATER INFRASTRUCTURE ON 20% OF ALL FEASIBLE LAND

GI Scenario 2 was developed to represent the construction of Green Stormwater Infrastructure (GSI) on 20% of all feasible land. In this scenario, feasible land is defined by the "Upland Restoration Priority" areas identified in the Charles River Watershed Conservation and Restoration Prioritization Tool developed by CRWA and The Nature Conservancy. This Tool utilizes desktop GIS analysis to prioritize land for various nature-based solution interventions that build climate resilience. Figure 4.1 demonstrates the prioritization methodology for the upland restoration priority areas. To select 20% of this feasible land,[4] CRWA selected only areas that are presently impervious, and then eliminated the highest and lowest elevation areas (in each section of the watershed) and wetland areas protected by the Wetlands Protection Act. Ultimately, the GSI projects envisioned under GI Scenario 2 provide two benefits - they increase the storage capacity of impervious areas of a subcatchment and they slow runoff generation down by routing runoff from some impervious surfaces onto pervious surfaces instead of directly downstream.

Within the Charles River stormwater flood model, the effects of GI Scenario 2 were incorporated by modifying the two relevant input parameters, namely "Dstore_Impervious" and "Percent Routed (to Pervious)". It was assumed that the GSI projects envisioned in this scenario would capture 2" of runoff from the identified 20% of feasible land. Each subcatchment's impervious storage parameter was increased by a depth equal to 2" times the fraction of total impervious surface that was identified within the 20% feasible land . On average, across the whole watershed, 1.09 inches of additional storage was added to impervious areas. The Percent Routed parameter, which defines the fraction of a subcatchment's impervious surface that runs off to pervious surfaces rather than directly downstream was also increased by the fraction of total impervious surface that was identified within the 20% feasible land for each subcatchment. Figure 5.3 illustrates the distribution of the 20% feasible land that was identified within a few example subcatchments.

The potential flood reduction benefits of this green infrastructure scenario were evaluated by comparing it to a no-action condition during baseline 10-year and 2070 10-year flood events. The present and 2070 10-year storms comparison for GI Scenario 2 compared to "no-action" is summarized watershed-wide in Table 5.3. The 2070 comparison is summarized by sub-basin in

As shown in Tables 5.3 and 5.4, GI Scenario 2 reduces the flooding extents, total runoff volume, and peak discharge rates from most sub-basins within the watershed. Across the entire watershed, this scenario reduces flooding extents by 427 acres or 5%. However, the

TABLE 5.4 Summary of number of critical facilities impacted, inundation extents, and total runoff for GI Scenario 2 during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from "no action"

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + GI Sc 2	45	6,694	6,493
Change from No Action	-8 (-15%)	-549 (-8%)	-875(-12%)
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + GI Sc 2	55	8,501	9,817
Change from No Action	-1 (-2%)	-427 (-5%)	-834 (-8%)

FIGURE 5.3 20% Feasible Land identified in several example subcatchments west and northwest of Morses Pond in Wellesley.

TABLE 5.5 Summary of inundation extents, total runoff, and peak discharge for GI Scenario 2 during the 2070 10-year event, by sub-basin, and the percent reduction from "no action"

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	70	-19%	349	336	-4%
Beaver Brook	116	112	-4%	313	271	-13%	605	493	-19%
Bogastow Brook	715	675	-6%	744	691	-7%	1,076	1,066	-1%
Bogle Brook	295	271	-8%	560	494	-12%	435	258	-41%
Charles River: Bogastow Brook to Dover	340	293	-14%	320	303	-6%	1,077	1,028	-5%
Charles River: Box Pond Dam to Medway	408	368	-10%	259	237	-8%	1,208	1,158	-4%
Charles River: Dover to Wellesley	805	701	-13%	613	560	-9%	1,490	1,336	-10%
Charles River: Medway to Bogastow Brook	1,386	1,385	0%	535	519	-3%	1,346	1,311	-3%
Charles River: Stony Brook to Watertown	73	63	-13%	406	371	-9%	2,048	1,657	-19%
Charles River: Wellesley to Stony Brook	175	155	-11%	333	278	-16%	2,010	1,882	-6%
Charles River Headwaters	328	316	-4%	699	654	-6%	378	378	0%
Cheese Cake Brook	16	15	-8%	167	144	-14%	1,143	858	-25%
Chester Brook	67	59	-12%	285	247	-13%	670	573	-14%
Chicken Brook	24	24	0%	245	229	-7%	307	306	0%
Davis Brook	19	19	0%	72	69	-5%	270	278	3%
Hobbs Brook	624	624	0%	665	640	-4%	762	724	-5%
Hopping Brook	310	307	-1%	315	296	-6%	206	214	4%
Indian Brook	137	132	-4%	160	147	-8%	134	131	-3%
Lowder Brook	155	154	-1%	189	173	-9%	164	152	-7%
Mill River	271	271	0%	369	352	-4%	403	387	-4%
Mine Brook	763	700	-8%	619	564	-9%	268	239	-11%
Noanet Brook	0	0	0%	34	33	-4%	132	100	-24%
Powissett Brook	40	40	0%	61	61	0%	276	276	0%
Rock Meadow Brook	32	31	-3%	85	83	-2%	563	563	0%
Rosemary Brook	44	44	0%	168	148	-12%	384	283	-27%
Sawmill Brook	39	39	0%	150	125	-16%	1,443	657	-54%
Seaverns Brook	17	14	-20%	44	37	-14%	198	81	-59%
Shepherds Brook	46	46	0%	156	146	-6%	233	227	-3%
South Meadow Brook	52	52	0%	183	152	-17%	695	614	-12%
Stall Brook	149	137	-8%	181	164	-9%	100	99	-1%
Stony Brook	453	447	-1%	1,028	990	-4%	759	722	-5%
Stop River	930	910	-2%	499	465	-7%	231	216	-6%
Trout Brook	92	92	0%	107	103	-4%	233	203	-13%

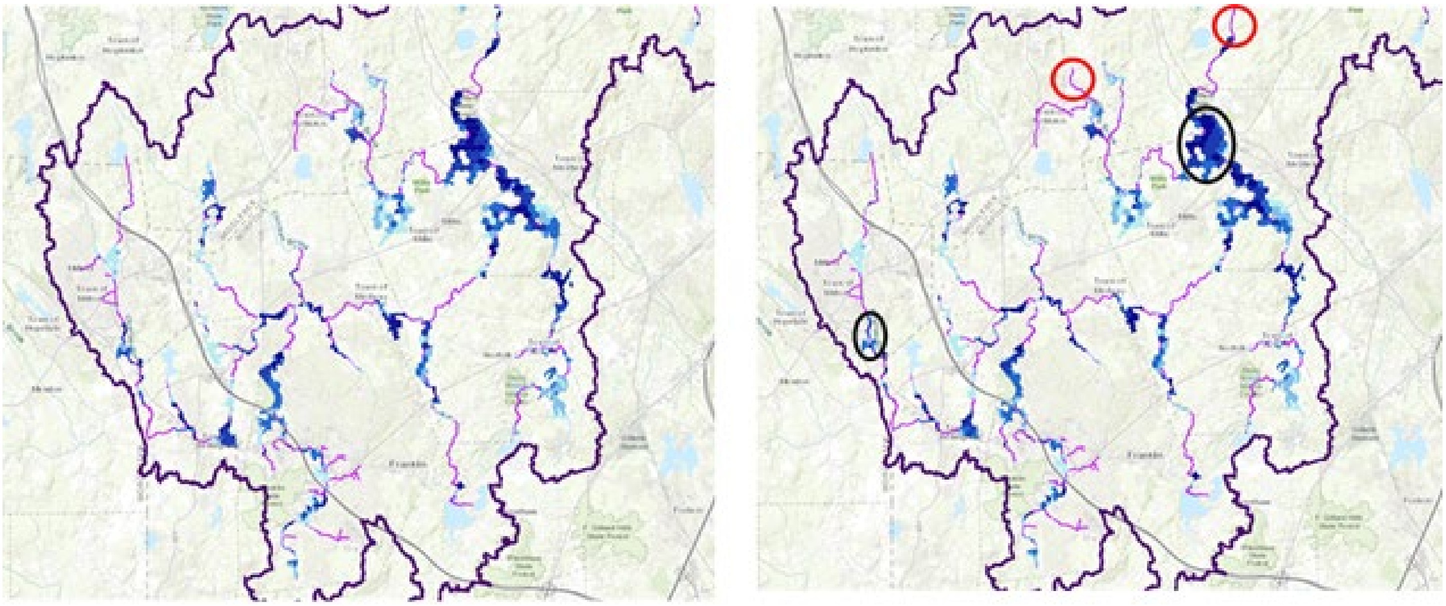


FIGURE 5.4 Areas of flooding from 2070 10-year storm under “no-action” (left) and under GI Scenario 2 (right) (red = eliminated flooding, black = reduced flooding)

percent change varies considerably by sub-basin. Thirteen sub-basins are not expected to experience a significant change in flood-prone area, while others, like Charles River (Bogastow to Dover) and Seaverns Brook will experience reductions as high as 14 and 20%, respectively. Despite these reductions in flood-prone area, it is worth mentioning that the number of critical infrastructure impacted would only be reduced by one as a result of GI Scenario 2. This additional dry infrastructure is located in Bogle Brook.

Reductions in flood-prone area are generally driven by reductions in runoff volume and peak discharge from a sub-basin. On average, GI Scenario 2 is expected to reduce runoff volumes by 9%. While ten sub-basins are expected to see reductions of greater than 10%, and three sub-basins, Powissett Brook, Rock Meadow Brook, and Charles River (Medway to Bogastow Brook), are expected to experience relatively small reductions, 0, 2, and 3%, respectively, most sub-basins are expected to experience reductions in total runoff volume of between 4 and 10%. Reductions in peak discharge are perhaps more significant with a watershed wide average reduction of 11%. Six sub-basins not expected to experience a significant change in flood-prone area (1% or less) while Twelve sub-basins are expected to see reductions of greater than 10%. Sawmill Brook and Seaverns Brook subbasins are expected to experience up to 54 and 59% reductions, respectively. Nearly half of the sub-basins, however, are expected to experience reductions in peak discharge of between 2 and 10%.

Based on the 2D modeling ability of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.4, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of GI Scenario 2. Areas circled in red are areas where flooding has been eliminated while areas circled in black are areas with reduced flooding.

5.1.3 GI SCENARIO 3 -- FLOOD STORAGE ON LARGE (>5 ACRES) PUBLIC PROPERTIES

GI Scenario 3 was developed to represent the creation of flood storage on large (>5 acres) public properties through the construction of

TABLE 5.6 Summary of Co-benefits for Scenario 2

Co-Benefit Type	Co-Benefit Description
Nature-Based Solutions Scenarios	20% of feasible/priority land area is GSI (also assumed some infiltration on good quality soils and then filtration for the rest of the systems - can assume mostly systems with plants - i.e. not underground)
Promotes Biodiversity	In this scenario, there is an additional 32,242 acres of green stormwater infrastructure providing additional greenery and habitat. GSI system typically function best with native or nativized vegetation which also provide habitat for local wildlife.
Restores or Remediates Sites	Careful site planning and selection of practices allow green infrastructure to work on contaminated sites and sites with poor soils.
Promotes Sustainable Development / Reduces Development in Climate Vulnerable Areas	GSI can provide green jobs and protection for surrounding properties, and amenities to surrounding residents. This scenario demonstrates where flooding impacts will occur with and without intervention.
Improved Water Quality	According the the EPA, if a stream's watershed has greater than 25% impervious cover, the stream is a non-supporting, or unhealthy, stream. Treating and infiltrating stormwater runoff onsite will remove pollutants and reduce pollutant loading in the Charles River and the watershed. A biofiltration system similar to the FocalPoint has a 66% phosphorus removal rate. Bioretention systems and rain gardens have a removal efficiency of: • Total suspended solids (TSS): 90% with adequate pretreatment • Total nitrogen: 30-50% • Total phosphorus: 30-90% • Metals (copper, lead, zinc, cadmium): 40-90% metal pollutant A detention basin has pollutant removal efficiencies of: • TSS: 50% with adequate pretreatment • Total Nitrogen: 15-50% • Total phosphorus:10-30% • Metals (copper, lead, zinc, cadmium): 30-50% • Pathogens (coliform, E. Coli): Less than 10%
Annual Recharge	Using the Stormwater Recharge Calculator developed by Abt Associates with support from CRWA, it is estimated this scenario can recharge 87,923 MGY (area of GSI 10% of treatment)
Improved Air Quality	Improves air quality by filtering air pollutants and particulates. Larger impact if trees are incorporated. GI can also provide traffic and street noise abatement
Climate Mitigation	This scenario proposes treating an area of around 105,000 acres. Increases in vegetation mean more direct carbon sequestration along with more shade and heat dissapation. Additionally, a reduction in impervious cover means less heat absorbed, resulting in cooler temperatures. Less energy spent on cooling purposes, will result in a decrease in carbon dioxide emissions.
Public Health	Vegetation provides shade, dissipates ambient heat through evapotranspiration, and deflects radiation from the sun, which provide cooling (reduces heat island effect) and decrease opportunity for heat related deaths. Vegetation also releases moisture into the atmosphere. GSI improves aesthetics and increases exposure to greenness which can improve mental health and provide a possible reduction in the risk of crime. Mitigates the risk of flooding and combine sewer overflow events and associated hazards.
Reduce Long-term Maintenance	N/A
Raise Awareness of Nature-Based Solutions	Engages public in stormwater management issues with visual demonstration. Increases space and opportunity for social interaction. Familiarizes public with GSI practices.

GSI, underground storage, “blue roofs”, and other site-specific strategies. The process of identifying potential sites started with the identification of approximately 1,200 parcels with areas in excess of 5 acres that have a tax-exempt status. The impervious surfaces within those parcels were extracted, and then areas within protected conservation land, and within 100 feet of MassDEP-mapped wetlands were removed from consideration. In this manner, 284 potential sites were identified across the watershed. Fig. 5.5 illustrates the distribution of such sites within a few example subcatchments.

The impervious surfaces identified through this process consisted primarily of parking lots, roadways, and roofs. The potential for stormwater storage varies depending on the surface type and land use. Underground storage beneath parking lot could easily consist of chambers that are 3 feet deep while “blue roofs” would be limited to storing just a few inches of water. For simplification, it was assumed that all surfaces identified through the process described above would storage an additional 12 inches of runoff. Each subcatchment’s impervious storage parameter, Dstore_Impervious, was, therefore, increased by a depth equal to 12 inches times the fraction of total impervious surface that was identified as having potential for one or more stormwater storage projects. Increases ranged from 0.0 inches of storage in 396 subcatchments, in which no acceptable parcels or impervious surfaces were identified, to a maximum of 10.2 inches. On average, across the whole watershed, 0.5 inches of additional storage was created in impervious areas.

The present and 2070 10-year storms comparison for GI Scenario 3 compared to “no-action” is summarized watershed-wide in Table 5.7. The 2070 comparison is summarized by sub-basin in Table 5.8.

As shown in Table 5.7 and Table 5.8, GI Scenario 3 reduces the flooding extents, total runoff volume, and peak discharge rates from most sub-basins within the watershed. Across the entire watershed, this scenario reduces flooding extents by 131 acres or 2%. The percent change varies considerably by sub-basin, however. Twenty sub-basins are not expected to experience a significant change in flood-prone area, while others, like Seaverns Brook will experience reductions as high as 27%. Despite these reductions in flood-prone area, it is worth mentioning that no critical infrastructure that would be impacted under a 2070 No Action scenario would become “dry” as a result of GI Scenario 3.

Reductions in flood-prone area are generally driven by reductions in runoff volume and peak discharge from a sub-basin. On average, GI Scenario 3 is expected to reduce runoff volumes by 4%. While three sub-basins are

TABLE 5.7 Summary of number of critical facilities impacted, inundation extents, and total runoff for GI Scenario 3 during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from “no action”

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + GI Sc 3	51	7,072	6,950
Change from No Action	-2 (-4%)	-171 (-2%)	-418(-6%)
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + GI Sc 3	56	8,798	10,226
Change from No Action	---	-130 (-2%)	-425 (-4%)

FIGURE 5.5 Impervious surfaces with potential for stormwater storage on the Fernald School campus in Waltham

TABLE 5.8 Summary of inundation extents, total runoff, and peak discharge for GI Scenario 2 during the 2070 10-year event, by sub-basin, and the percent reduction from no action.

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	80	-7%	349	347	-1%
Beaver Brook	116	114	-2%	313	261	-16%	605	587	-3%
Bogastow Brook	715	696	-3%	744	730	-2%	1,076	1,073	0%
Bogle Brook	295	289	-2%	560	500	-11%	435	401	-8%
Charles River: Bogastow Brook to Dover	340	316	-7%	320	317	-1%	1,077	1,034	-4%
Charles River: Box Pond Dam to Medway	408	404	-1%	259	254	-2%	1,208	1,196	-1%
Charles River: Dover to Wellesley	805	767	-5%	613	573	-7%	1,490	1,426	-4%
Charles River: Medway to Bogastow Brook	1,386	1,385	0%	535	528	-1%	1,346	1,333	-1%
Charles River: Stony Brook to Watertown	73	66	-9%	406	385	-5%	2,048	1,757	-14%
Charles River: Wellesley to Stony Brook	175	166	-6%	333	320	-4%	2,010	1,879	-7%
Charles River Headwaters	328	327	0%	699	687	-2%	378	377	0%
Cheese Cake Brook	16	16	-3%	167	161	-3%	1,143	1,067	-7%
Chester Brook	67	67	0%	285	266	-7%	670	608	-9%
Chicken Brook	24	24	0%	245	238	-3%	307	306	0%
Davis Brook	19	19	0%	72	72	-1%	270	265	-2%
Hobbs Brook	624	624	0%	665	655	-2%	762	758	0%
Hopping Brook	310	309	0%	315	315	0%	206	206	0%
Indian Brook	137	137	0%	160	152	-5%	134	131	-2%
Lowder Brook	155	155	0%	189	186	-2%	164	162	-2%
Mill River	271	271	0%	369	358	-3%	403	390	-3%
Mine Brook	763	757	-1%	619	595	-4%	268	257	-4%
Noanet Brook	0	0	0%	34	34	0%	132	132	0%
Powissett Brook	40	40	0%	61	61	0%	276	276	0%
Rock Meadow Brook	32	31	-3%	85	83	-2%	563	563	0%
Rosemary Brook	44	44	0%	168	143	-15%	384	282	-27%
Sawmill Brook	39	39	0%	150	145	-3%	1,443	1,442	0%
Seaverns Brook	17	13	-27%	44	39	-10%	198	198	0%
Shepherds Brook	46	46	0%	156	153	-2%	233	232	-1%
South Meadow Brook	52	52	0%	183	172	-6%	695	679	-2%
Stall Brook	149	149	0%	181	179	-1%	100	100	0%
Stony Brook	453	451	-1%	1,028	1,007	-2%	759	736	-3%
Stop River	930	926	0%	499	469	-6%	231	225	-3%
Trout Brook	92	92	0%	107	107	0%	233	238	2%

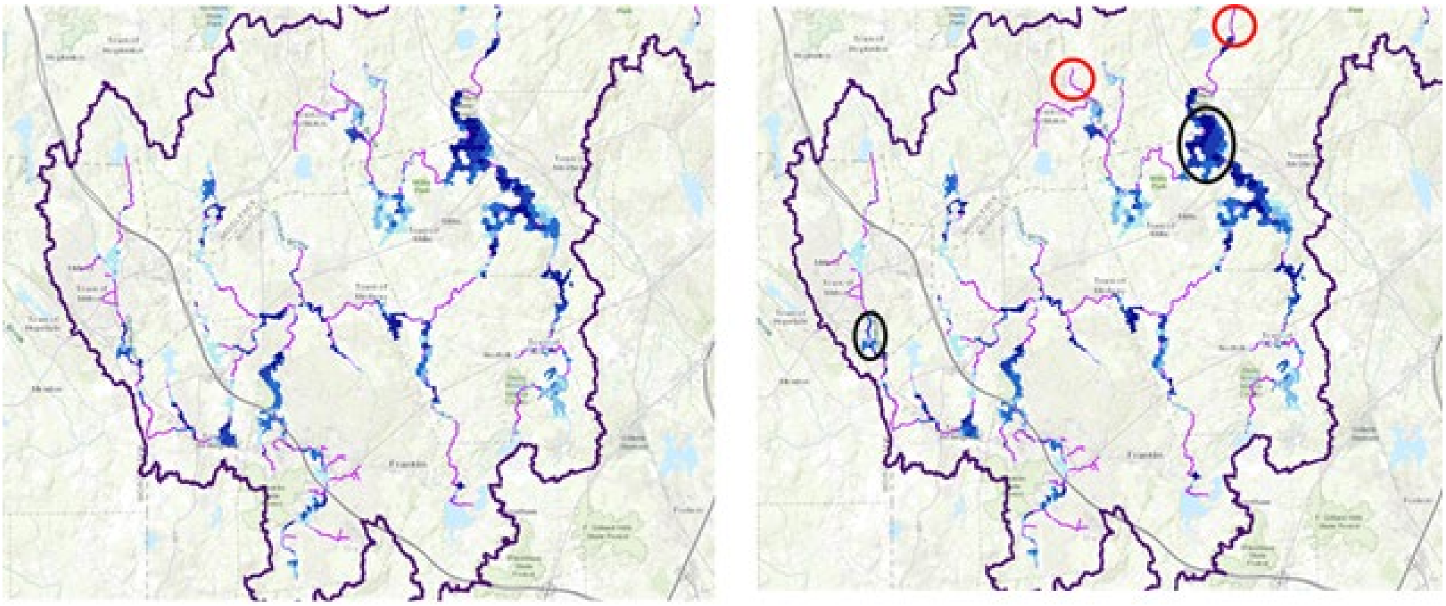


FIGURE 5.6 Areas of flooding from 2070 10-year storm under “no-action” (left) and under GI Scenario 3 (right) (red = eliminated flooding, black = reduced flooding)

expected to see reductions of greater than 10%, and one sub-basin, Seaverns Brook, is expected to experience relatively moderate reduction of 10%, most sub-basins are expected to experience small reductions in total runoff volume of between 0 and 7%. Reductions in peak discharge are perhaps more modest with a watershed wide average reduction of 3%. Fifteen sub-basins are not expected to experience a significant change in flood-prone areas (1% or less) while two sub-basins, Charles River (Stony Brook to Watertown) and Rosemary Brook, are expected to see reductions of greater than 10%. Most sub-basins, however, are expected to experience reductions in peak discharge of between 2 and 10%.

Based on the 2D modeling ability of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.6, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of GI Scenario 3.

TABLE 5.9 Summary of Co-benefits for Scenario 3

Co-Benefit Type	Co-Benefit Description
Nature-Based Solutions Scenarios	Storage on large (>5 acres) public properties (assumes mix of underground and surface based systems)
Promotes Biodiversity	This scenario would include constructed wetlands or other large scale storage systems that create new habitat.
Restores or Remediates Sites	At certain sites green infrastructure solutions such as green roofs and cisterns that function without infiltrating stormwater into the soil can be assessed to add storage on sites not suitible for infiltration.
Promotes Sustainable Development / Reduces Development in Climate Vulnerable Areas	Provides amenities to surrounding communities. Increases property values and opportunity for green jobs. Provides large scale environmental protection. Wetlands play a crucial role in many state and tribal fishing economies.
Improved Water Quality	Constructed stormwater wetlands have a high pollutatant removal efficiency for soluble pollutants and particles. A constructed weltand has the following pollutant removal efficiencies: • TSS: 80% with pretreatment • Total nitrogen: 20% - 55% • Total phosphorus: 40% - 60% • Metal (copper, lead, zinc, cadmium): 20% - 85% • Pathogens (coliform, E. Coli): Up to 75%
Annual Recharge	Approximately 280 sites were identified as possibly “large scale” storage opportunities, if even a portion of these could provide infiltration for small rain events along with additional storage for large events this would result in considerable annual groundwater recharge.
Improved Air Quality	N/A
Climate Mitigation	Increases in vegetation mean more direct carbon sequestration along with more shade and heat dissapation.
Public Health	Increases opportunity for bird and wildlife viewing and physical activity. Improves aesthetics and increases exposure to greenness which can improve mental health and provide a possible reduction in the risk of crime. Mitigates the risk of flooding and combine sewer overflow events and associated hazards. Supports ecosystems, promotes biodiversity and provides cooling. Filters out pollutants and protects drinking water.
Reduce Long-term Maintenance	N/A
Raise Awareness of Nature-Based Solutions	Increases recreational opportunity and creates space for social interaction.

Areas circled in red are areas where flooding has been eliminated while areas circled in black are areas with reduced flooding.

5.1.4 GI SCENARIO 4 -- ELIMINATION OF 10% OF IMPERVIOUS COVER IN AREAS WHERE IMPERVIOUS SURFACES MAKE UP MORE THAN 10% OF LAND COVER

GI Scenario 4 was developed to represent the elimination of 10% of impervious cover in areas where impervious surfaces make up more than 10% of land cover. Highly developed parts of the watershed, of any watershed, with impervious cover greater than 10% say, produce a disproportionate amount of runoff relative to their size. This scenario attempts to focus on the areas of the watershed where changes in land cover will make the greatest difference in downstream flooding. Approximately 35.5% of the Charles River watershed consists of impervious surfaces like parking lots, roads, and rooftops. Of the 705 subcatchments incorporated into the stormwater model, 591 have greater than 10% impervious cover. Those subcatchments are identified in Figure 5.7. For those subcatchments, the modeled percent impervious cover was reduced by 10%

The potential changes in flooding impacts associated with this scenario were evaluated by comparing it to a no-action condition during baseline 10-year and 2070 10-year flood events. The present and 2070 10-year storms comparison for GI Scenario 4 compared to “no-action” is summarized watershed-wide in Table 5.10. The 2070 comparison is summarized by sub-basin in Table 5.11.

As shown in Table 5.10 and 5.11, GI Scenario 4 reduces the flooding extents, total runoff volume, and peak discharge rates from most sub-basins within the watershed. Across the entire watershed, this scenario reduces flooding extents by 125 acres or 1%. The percent change varies considerably by sub-basin, however. Seventeen sub-basins are not expected to experience a significant change in flood-prone area, while others, like Charles River (Wellesley to Stony Brook) and Charles River (Bogastow Brook to Dover) will experience reductions as high as 8 and 7%, respectively. Despite these reductions in flood-prone area, it is worth mentioning that no critical infrastructure that would be impacted under a 2070 No Action

TABLE 5.10 Summary of number of critical facilities impacted, inundation extents, and total runoff for GI Scenario 4 during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from “no action”

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + GI Sc 4	49	7,111	7,142
Change from No Action	-4 (-4%)	-132 (-2%)	-226(-3%)
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + GI Sc 4	56	8,803	10,401
Change from No Action	---	-125 (-2%)	-250 (-4%)

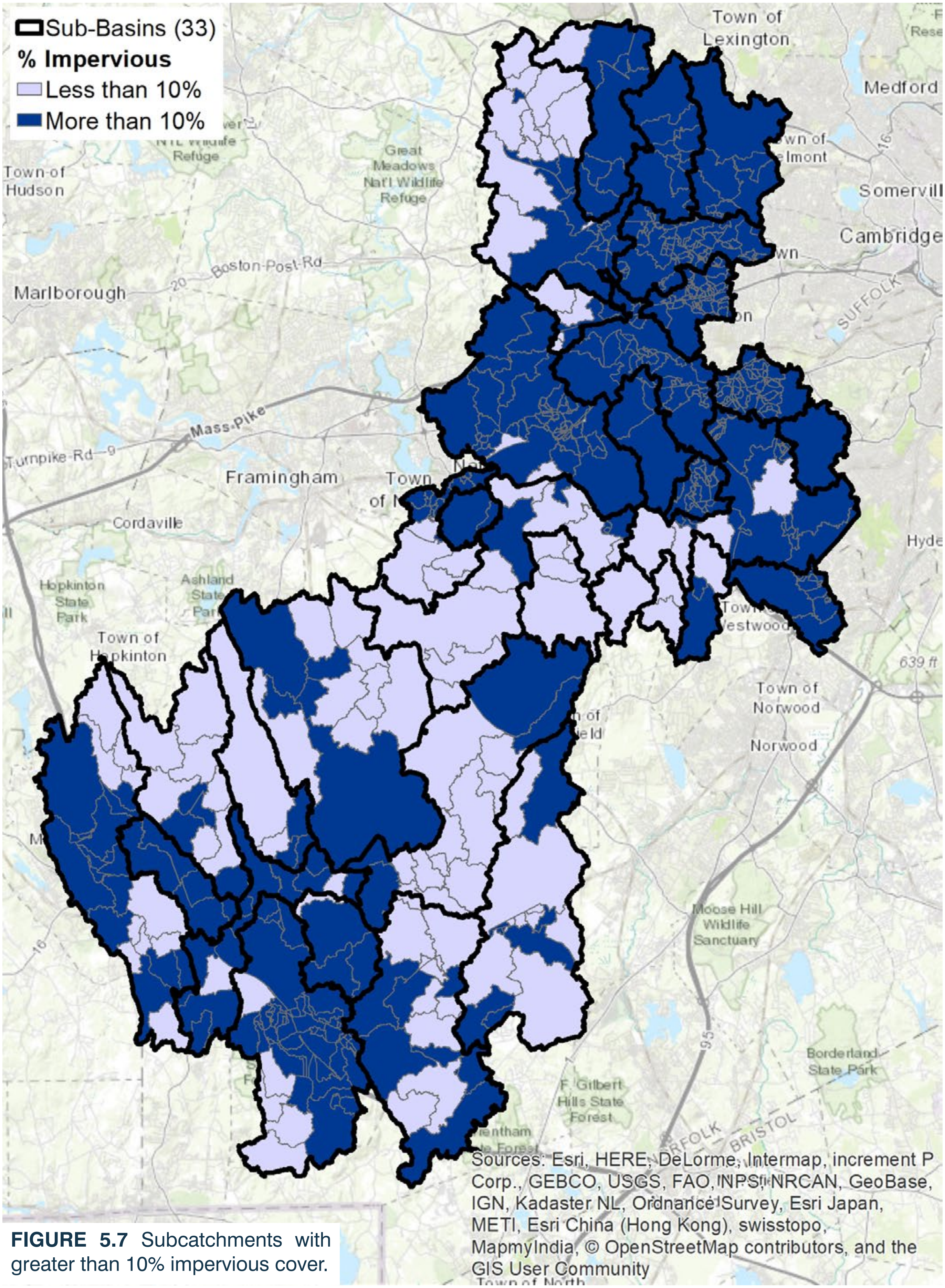


FIGURE 5.7 Subcatchments with greater than 10% impervious cover.

TABLE 5.11 Summary of inundation extents, total runoff, and peak discharge for GI Scenario 4 during the 2070 10-year event, by sub-basin, and the percent reduction from "no action"

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	82	-5%	349	347	0%
Beaver Brook	116	113	-2%	313	298	-5%	605	536	-11%
Bogastow Brook	715	707	-1%	744	732	-2%	1,076	1,071	0%
Bogle Brook	295	287	-3%	560	535	-4%	435	401	-8%
Charles River: Bogastow Brook to Dover	340	316	-7%	320	318	-1%	1,077	1,064	-1%
Charles River: Box Pond Dam to Medway	408	404	-1%	259	252	-2%	1,208	1,199	-1%
Charles River: Dover to Wellesley	805	778	-3%	613	599	-2%	1,490	1,448	-3%
Charles River: Medway to Bogastow Brook	1,386	1,385	0%	535	528	-1%	1,346	1,333	-1%
Charles River: Stony Brook to Watertown	73	70	-4%	406	389	-4%	2,048	1,900	-7%
Charles River: Wellesley to Stony Brook	175	162	-8%	333	312	-6%	2,010	1,908	-5%
Charles River Headwaters	328	319	-3%	699	684	-2%	378	381	1%
Cheese Cake Brook	16	16	-3%	167	156	-6%	1,143	1,035	-9%
Chester Brook	67	66	-1%	285	271	-5%	670	614	-8%
Chicken Brook	24	24	0%	245	243	-1%	307	308	0%
Davis Brook	19	19	0%	72	71	-2%	270	269	-1%
Hobbs Brook	624	624	0%	665	663	0%	762	749	-2%
Hopping Brook	310	309	0%	315	314	0%	206	205	-1%
Indian Brook	137	137	0%	160	158	-1%	134	134	0%
Lowder Brook	155	155	0%	189	183	-4%	164	159	-3%
Mill River	271	271	0%	369	359	-3%	403	383	-5%
Mine Brook	763	752	-1%	619	603	-3%	268	262	-2%
Noanet Brook	0	0	0%	34	34	0%	132	132	0%
Powissett Brook	40	40	0%	61	61	0%	276	276	0%
Rock Meadow Brook	32	31	-3%	85	83	-2%	563	563	0%
Rosemary Brook	44	44	0%	168	158	-6%	384	341	-11%
Sawmill Brook	39	39	0%	150	143	-4%	1,443	1,303	-10%
Seaverns Brook	17	17	0%	44	43	-2%	198	187	-6%
Shepherds Brook	46	46	0%	156	153	-2%	233	230	-1%
South Meadow Brook	52	51	-2%	183	173	-5%	695	656	-6%
Stall Brook	149	141	-5%	181	175	-3%	100	99	-1%
Stony Brook	453	452	0%	1,028	1,025	0%	759	755	-1%
Stop River	930	930	0%	499	494	-1%	231	223	-3%
Trout Brook	92	92	0%	107	107	0%	233	230	-1%

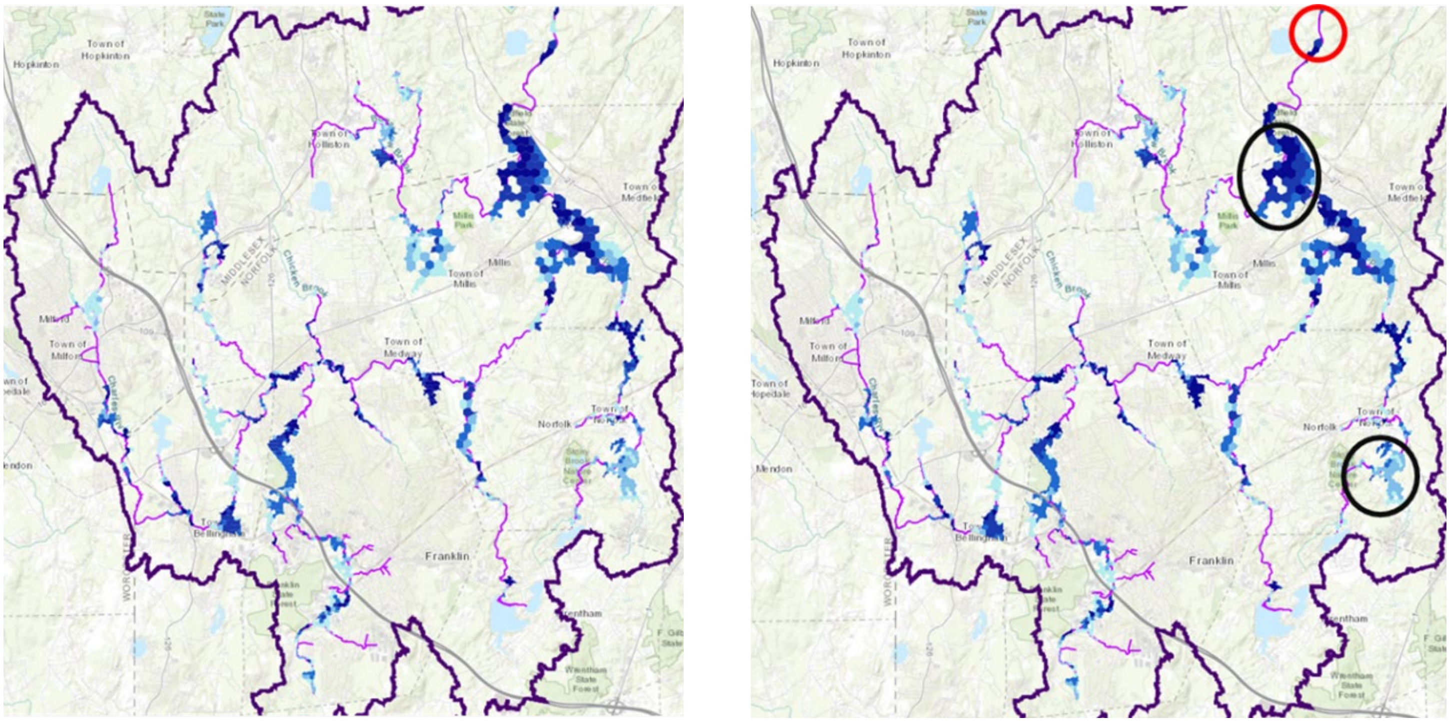


FIGURE 5.8 A Areas of flooding from 2070 10-year storm under “no-action” (left) and under GI Scenario 4 (right) (red = eliminated flooding, black = reduced flooding)

scenario would become dry as a result of GI Scenario 4.

Reductions in flood-prone area are generally driven by reductions in runoff volume and peak discharge from a sub-basin. On average, GI Scenario 4 is expected to reduce runoff volumes by 3%. While six sub-basins are expected to see no reductions in total runoff, most sub-basins are expected to experience reductions in total runoff volume of between 1 and 6%. Reductions in peak discharge are similar across the sub-basins with a watershed wide average reduction of 3%. Seventeen sub-basins not expected to experience a significant change in peak discharge (1% or less) while two sub-basins, such as Beaver Brook and Rosemary Brook, are expected to see reductions of greater than 10%. Most sub-basins, however, are expected to experience reductions in peak discharge of between 2 and 10%.

Based on the 2D modeling ability of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.8, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of GI Scenario 4. Areas circled in red are areas where flooding has been eliminated while areas circled in black are areas with reduced flooding.

TABLE 5.12 Summary of Co-benefits for Scenario 4

Co-Benefit Type	Co-Benefit Description
Nature-Based Solutions Scenarios	Reduce effective impervious cover watershed wide by 10%
Promotes Biodiversity	This scenario would transition over 7300 acres of impervious cover to more natural land covers, increasing habitat and promoting biodiversity.
Restores or Remediates Sites	N/A
Promotes Sustainable Development / Reduces Development in Climate Vulnerable Areas	Protects vulnerable communities through flood mitigation.
Improved Water Quality	According the the EPA, if a stream's watershed has greater than 25% impervious cover, the stream is a non-supporting, or unhealthy, stream. Treating and infiltrating stormwater runoff onsite will remove pollutants and reduce pollutant loading in the Charles River and the watershed.
Annual Recharge	By reducing 10% of effective imperivous cover, an additional estimated 4,536 million gallons of stormwater will be infiltrated annually.
Improved Air Quality	N/A
Climate Mitigation	This scenario proposes over 7,300 more acres of green space. A reduction in impervious cover means less heat absorbed, resulting in cooler temperatures. Less energy spent on cooling purposes, will result in a decrease in carbon dioxide emissions.
Public Health	Reduces stormwater runoff leading to improvements in water quaility. Reduces heat island effect, Creates additional open space.
Reduce Long-term Maintenance	N/A
Raise Awareness of Nature-Based Solutions	Increases visual demonstrations and opportunity of engagement with public. Opportunity for educational material to be built around GSI.

5.1.5 GI SCENARIO 5 -- 50% OF THE REMAINING UNDEVELOPED OR UNPROTECTED LAND TO BECOME IMPERVIOUS

GI Scenario 5 is unlike the other scenarios in that it actually represents a worsening of flood conditions in the watershed. GI Scenario 5 represents a situation where future development causes 50% of the remaining undeveloped or unprotected land to become impervious, creating additional runoff. Scenario 5 is also based on the Charles River Conservation and Restoration Prioritization Tool developed by CRWA and The Nature Conservancy. This Tool identifies land that is currently unprotected and undeveloped (defined by land use). For this scenario it was assumed that only the highest priority undeveloped/unprotected land areas remain intact and the remaining undeveloped/ unprotected areas are developed.

Figure 5.9 demonstrates how half the watershed's remaining undeveloped and unprotected land areas were selected for protection, remaining areas were assumed to be developed. These changes in the watershed were incorporated into the model by increasing each subcatchment's percent impervious by the additional impervious areas identified in Figure 5.9. Of the 705 model subcatchments, the percent increase in impervious cover ranged from 0.0% for the 202 that did not contain any new impervious area, to 79.2%. Overall, the percent impervious cover in the entire watershed increased from 35.5% to 45.9%.

The potential changes in flooding impacts associated with this scenario were evaluated by comparing it to a no-action condition during baseline 10-year and 2070 10-year flood events. The present and 2070 10-year storms comparison for GI Scenario 5 compared to "no-action" is summarized watershed-wide in Table 5.13. The 2070 comparison is summarized by sub-basin in Table 5.14.

As shown in Table 5.13 and Table 5.14, GI Scenario 5 increases the flooding extents, total runoff volume, and peak discharge rates from most sub-basins within the watershed. Across the entire watershed, this scenario increases flooding extents by 1,704 acres or 19%. The percent change varies considerably by sub-basin, however. Nine sub-basins are not expected to experience a significant change in flood-prone area, while others, like Rock Meadow Brook and Chicken Brook will experience increases as high as 173 and 93%, respectively. Critical infrastructure will also be impacted as a result of

TABLE 5.13 Summary of number of critical facilities impacted, inundation extents, and total runoff for GI Scenario 5 during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from "no action"

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + GI Sc 5	64	9,616	11,320
Change from No Action	+11 (+21%)	+2,373 (+33%)	+3,952 (+54%)
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + GI Sc 5	64	10,632	14,991
Change from No Action	+8 (+14%)	+1,704 (+19%)	+4,340 (+41%)

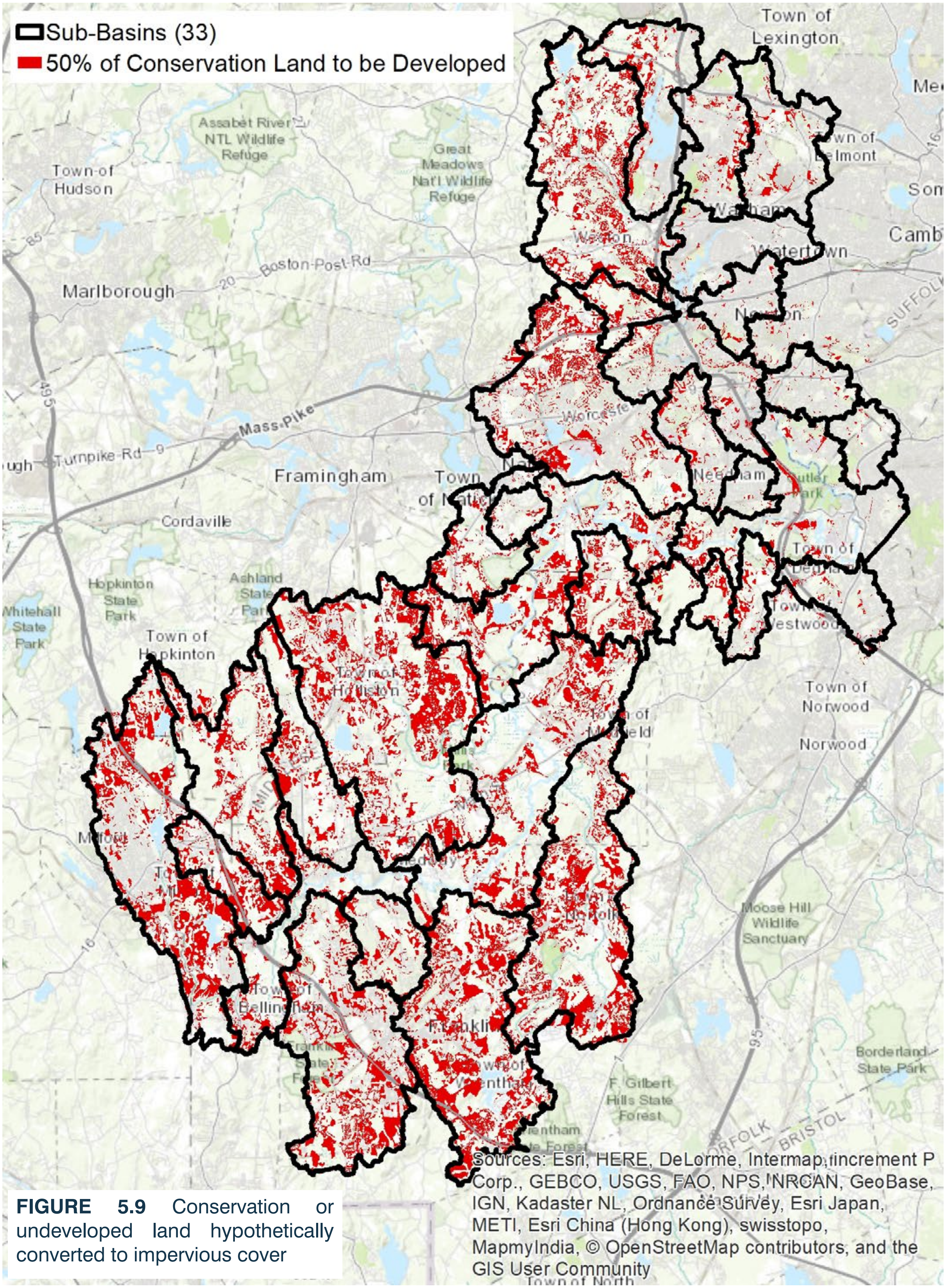


FIGURE 5.9 Conservation or undeveloped land hypothetically converted to impervious cover

TABLE 5.14 Summary of inundation extents, total runoff, and peak discharge for GI Scenario 5 during the 2070 10-year event, by sub-basin, and the percent reduction from "no action"

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	91	5%	349	357	3%
Beaver Brook	116	124	7%	313	352	13%	605	1,044	72%
Bogastow Brook	715	863	21%	744	1,275	72%	1,076	2,078	93%
Bogle Brook	295	334	13%	560	820	46%	435	538	24%
Charles River: Bogastow Brook to Dover	340	442	30%	320	618	93%	1,077	1,508	40%
Charles River: Box Pond Dam to Medway	408	490	20%	259	353	36%	1,208	1,441	19%
Charles River: Dover to Wellesley	805	970	21%	613	687	12%	1,490	1,617	9%
Charles River: Medway to Bogastow Brook	1,386	1,763	27%	535	840	57%	1,346	1,654	23%
Charles River: Stony Brook to Watertown	73	75	3%	406	414	2%	2,048	2,211	8%
Charles River: Wellesley to Stony Brook	175	237	35%	333	398	20%	2,010	2,274	13%
Charles River Headwaters	328	394	20%	699	1,056	51%	378	1,445	282%
Cheese Cake Brook	16	16	-3%	167	179	7%	1,143	1,257	10%
Chester Brook	67	71	5%	285	329	15%	670	770	15%
Chicken Brook	24	47	93%	245	354	45%	307	309	1%
Davis Brook	19	19	0%	72	81	12%	270	287	6%
Hobbs Brook	624	628	1%	665	690	4%	762	834	9%
Hopping Brook	310	349	12%	315	514	63%	206	365	77%
Indian Brook	137	174	28%	160	224	40%	134	223	66%
Lowder Brook	155	155	0%	189	202	7%	164	175	6%
Mill River	271	399	47%	369	888	141%	403	1,314	226%
Mine Brook	763	820	7%	619	938	52%	268	443	65%
Noanet Brook	0	0	0%	34	54	59%	132	576	337%
Powissett Brook	40	40	0%	61	83	36%	276	566	105%
Rock Meadow Brook	32	88	173%	85	119	40%	563	687	22%
Rosemary Brook	44	44	0%	168	208	24%	384	665	73%
Sawmill Brook	39	39	0%	150	153	2%	1,443	1,521	5%
Seaverns Brook	17	25	43%	44	91	108%	198	387	96%
Shepherds Brook	46	46	0%	156	206	32%	233	310	33%
South Meadow Brook	52	52	0%	183	190	4%	695	728	5%
Stall Brook	149	177	19%	181	271	50%	100	163	63%
Stony Brook	453	459	1%	1,028	1,193	16%	759	882	16%
Stop River	930	1,164	25%	499	901	81%	231	431	87%
Trout Brook	92	123	34%	107	218	103%	233	517	122%

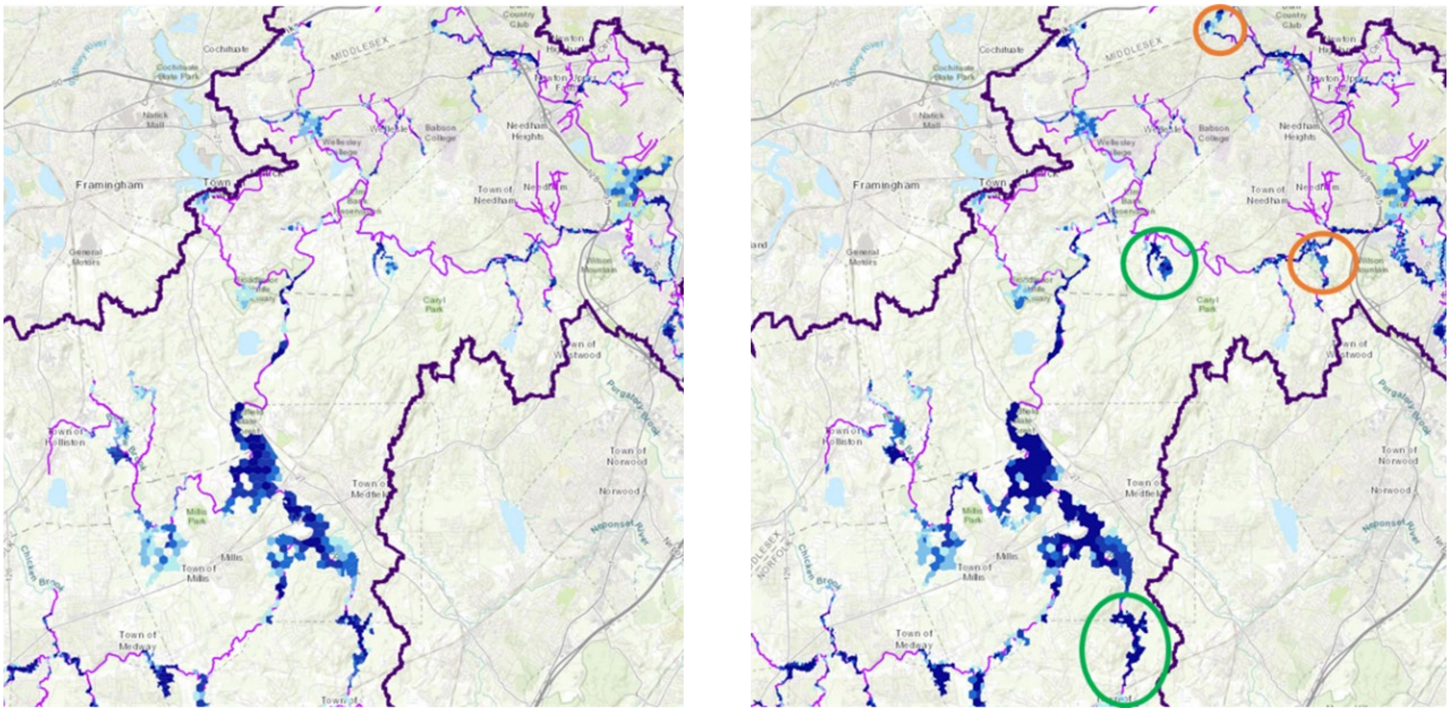


FIGURE 5.10 Areas of flooding from 2070 10-year storm under "no-action" (left) and under GI Scenario 5 (right) ((orange = new flooding, green = worsening flooding)

GI Scenario 5. The number of impacted critical infrastructure is expected to increase by eight.

Changes in flood-prone area are generally driven by changes in runoff volume and peak discharge from a sub-basin. On average, GI Scenario 5 is expected to increase runoff volumes by 41%. While six sub-basins are expected to see increases of less than 10%, and eleven sub-basins are expected to experience increases greater than 50%, most sub-basins are expected to experience increases in total runoff volume of between 10 and 50%. Reductions in peak discharge are similar with a watershed wide average reduction of 62%. Two sub-basins, Chicken Brook sub-basin and Alder Brook sub-basin, are expected to experience a small change in peak, 1 and 3%, respectively. Five sub-basins, such as Noanet Brook and Charles River Headwaters, are expected to see increases of greater than 100%. Most sub-basins, however, are expected to experience reductions in peak discharge of between 5 and 100%.

Based on the 2D modeling ability of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.10, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of GI Scenario 5. Areas circled in orange are areas where new flooding has occurred while areas circled in green are areas with worsening flooding.

TABLE 5.15 Summary of Co-benefits for Scenario 5

Co-Benefit Type	Co-Benefit Description
Nature-Based Solutions Scenarios	Allow 50% of remaining undeveloped/unprotected land to become impervious.
Promotes Biodiversity	Protecting the remaining undeveloped land in the watershed will prevent the further degredation of habitat and biodiversity loss.
Restores or Remediates Sites	N/A
Promotes Sustainable Development / Reduces Development in Climate Vulnerable Areas	Negative impacts for vulnerbale communties. Future development of open space is expected to make flooding worse by as much as 3,389 acres and 1,500 MG compared to present day conditions in a projected 2070 10-yr storm event.
Improved Water Quality	According the the EPA, if a stream's watershed has greater than 25% impervious cover, the stream is a non-supporting, or unhealthy, stream. Increasing impervious area in the watershed will reduce water quality.
Annual Recharge	N/A
Improved Air Quality	N/A
Climate Mitigation	N/A
Public Health	Increases opportunity for transportation of pollutants, degrades water quality, and increases surrounding temperatures all of which have negative effects on public health.
Reduce Long-term Maintenance	N/A
Raise Awareness of Nature-Based Solutions	N/A

5.1.6 GI SCENARIO 6 -- "GREEN STREETS"

GI Scenario 6 represents the creation of "green streets" within the Charles River watershed. As the identification of appropriate locations for green streets can be particularly site specific and, therefore, time consuming, only four of the 33 sub-basins were selected for evaluation. Two sub-basins – Hobbs Brook and Charles River (Wellesley to Stony Brook) – were selected as examples of sub-basins with typical tree cover over roadways; and two sub-basins – Lowder Brook and Alder Brook – were selected as the sub-basins with the least tree cover.

The flood reduction-related benefits of green streets are associated with decreased impervious cover where tree box filters and bioswales are constructed and an increase in stormwater storage in those same systems. Identification of specific reaches of roadway to be converted to green streets began with the state's database of roadway centerlines containing state routes and non-numbered roadways, and a database of existing tree canopy. A buffer of incrementally increasing size was added to the tree canopy footprints until approximately 25% of the roadway centerlines remained, identifying the roadway segments furthest from tree cover. These roadways were selected as opportunity sites, approximating the conversion of 25% of public ROWs to green streets. Figure 5.11 provides an example of the potential location for green streets along Great Plain Ave. in Needham

The potential flood reduction benefits of this green infrastructure scenario were evaluated by comparing it to a no-action condition during baseline 10-year and 2070 10-year flood events. The present and 2070 10-year storms comparison for GI Scenario 6 compared to "no-action" is summarized watershed-wide in Table 5.16. The 2070 comparison is summarized by sub-basin in Table 5.17

As shown in Table 5.16 and Table 5.17, GI Scenario 6 reduces the flooding extents, total runoff volume, and peak discharge rates from a few sub-basins within the watershed. The other twenty-seven sub-basins not listed in the table experienced no changes as a result of GI Scenario 6 as they are located upstream of the scenario, therefore they were not included in the summary table. Across the entire watershed, this scenario reduces flooding extents by 7 acres. The percent change is only noticeable for Charles River (Wellesley to Stony Brook) sub-basin, which experienced a reduction of 2%. Despite these reductions in flood-prone area, it is worth mentioning that no critical infrastructure that would be impacted under a 2070 No Action scenario would become dry as a result of GI Scenario 6.

Reductions in flood-prone area are generally

TABLE 5.16 Summary of number of critical facilities impacted, inundation extents, and total runoff for GI Scenario 6 during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from "no action"

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + GI Sc 6	53	7,240	7,333
Change from No Action	---	---	-35 (-1%)
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + GI Sc 6	56	8,921	10,611
Change from No Action	---	---	---

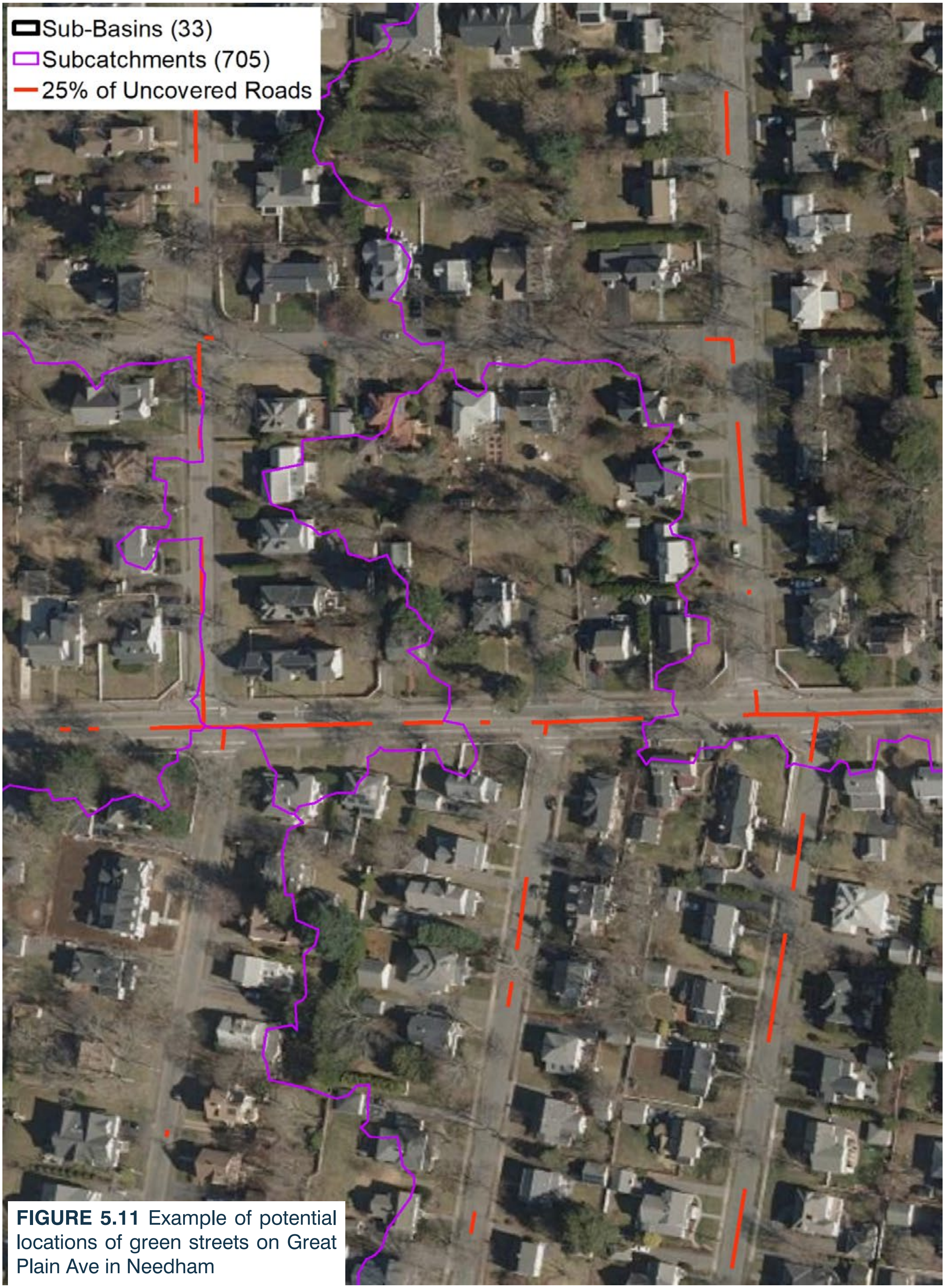


FIGURE 5.11 Example of potential locations of green streets on Great Plain Ave in Needham

driven by reductions in runoff volume and peak discharge from a sub-basin. On average, GI Scenario 6 is expected to reduce runoff volumes by 3% in the six sub-basins. While Alder Brook and Charles River (Wellesley to Stony Brook) sub-basins are expected to see reductions of 5 and 6%, respectively, Hobbs Brook and Lowder Brook, are expected to experience relatively small reductions, 1 and 3%, respectively. The average reduction in peak discharge is 2%. Peak discharge reductions ranged from 1% in Hobbs Brook to 3% in Lowder Brook.

Based on the 2D modeling ability of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.12, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of GI Scenario 6. Areas circled in red are areas where flooding has been eliminated while areas circled in black are areas with reduced flooding

TABLE 5.17 Summary of inundation extents, total runoff, and peak discharge for GI Scenario 6 during the 2070 10-year event, by sub-basin, and the percent reduction from "no action"

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	82	-5%	349	348	0%
Charles River: Dover to Wellesley	805	802	0%	613	613	0%	1,490	1,489	0%
Charles River: Stony Brook to Watertown*	73	73	0%	406	406	0%	2,048	2,054	0%
Charles River: Wellesley to Stony Brook*	175	171	-2%	333	312	-6%	2,010	1,968	-2%
Hobbs Brook	624	624	0%	665	657	-1%	762	754	-1%
Lowder Brook	155	155	0%	189	184	-3%	164	160	-3%

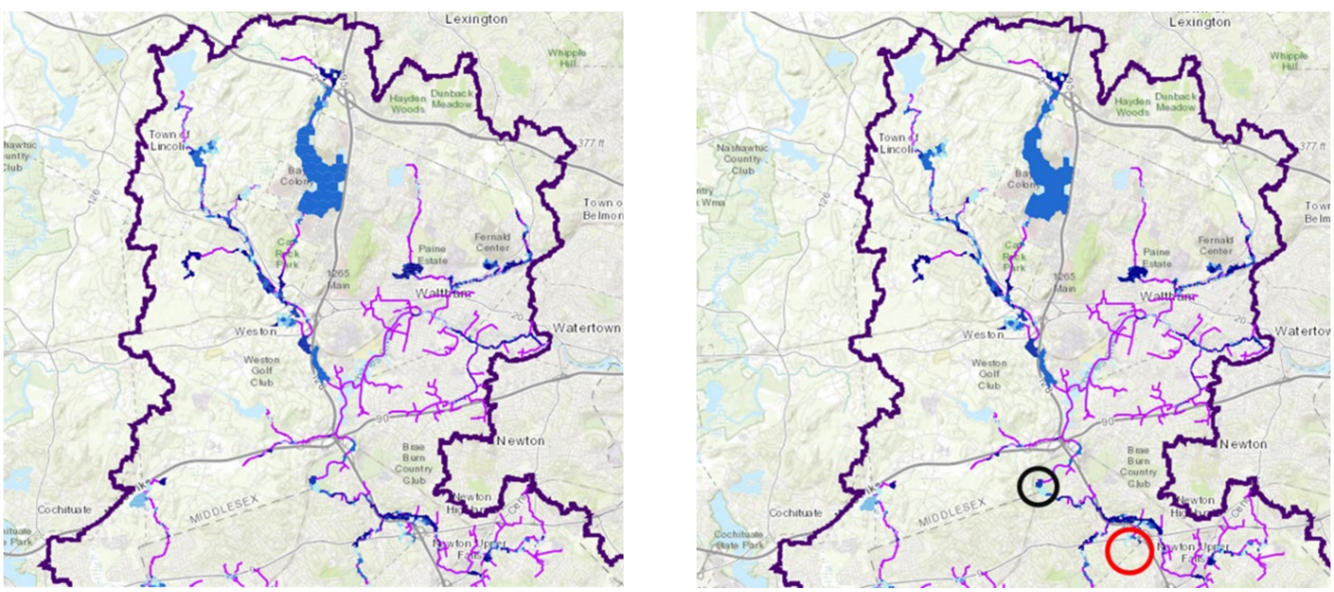


FIGURE 5.12 Areas where flooding is increased (right) as a result of GI Scenario 6 (red = eliminated flooding, black = reduced flooding)

TABLE 5.18 Summary of Co-benefits for Scenario 6

Co-Benefit Type	Co-Benefit Description
Nature-Based Solutions Scenarios	Increase Tree Canopy: 25% public ROWS become green streets (would also probably be a mix of infiltration and filtration)
Promotes Biodiversity	Additional tree canopy cover, especially in areas where it is currently lacking will add biodiversity and habitat to developed areas of the watershed.
Restores or Remediates Sites	Careful site planning and selection of practices allow green infrastructure to work on contaminated sites and sites with poor soils.
Promotes Sustainable Development / Reduces Development in Climate Vulnerable Areas	Protects existing infrastructure and provides traffic and street noise abatement, strengthens soil. A healthy 100-foot-tall tree can absorb 11,000 gallons of water from the soil and release it into the air again, as oxygen and water vapor, in a single growing season.
Improved Water Quality	Vegetation plays a huge part in stormwater nutrient uptake. Installing tree box filters along ROWs can remove 80-90% TTS, 38-65% total nitrogen, 50-80% total phosphorus, and between 40-90% metals.
Annual Recharge	In a single subbasin (Lowder Brook), it is estimated this scenario can recharge 88.5 MGY. Due to the variety of soil types found within the subbasin, a conservative infiltration rate was used.
Improved Air Quality	Large scale improvements to air quality by filtering air pollutants and particulates. Reduction to air temperatures as well. A mature tree absorbs carbon dioxide at a rate of 48 pounds per year.
Climate Mitigation	Increases in tree canopy will reduce carbon dioxide emissions through direct carbon sequestration, and by providing more shade and therefore reducing the amount of energy needed for cooling purposes. Reduction in energy used will then lead to less output of atmospheric carbon dioxide emissions.
Public Health	Vegetation provides shade, dissipates ambient heat through evapotranspiration, and deflects radiation from the sun, which provide cooling (reduces heat island effect) and decrease opportunity for heat related deaths. Vegetation also releases moisture into the atmosphere. GI improves aesthetics and increases exposure to greenness which can improve mental health and provide a possible reduction in the risk of crime. Mitigates the risk of flooding and combine sewer overflow events and associated hazards.
Reduce Long-term Maintenance	N/A
Raise Awareness of Nature-Based Solutions	Increases visual demonstrations and opportunity of engagement with public. Opportunity for educational material to be built around GSI.

5.2 SUMMARY OF CO-BENEFITS

In addition to providing considerable flood mitigation benefits, the scenarios explored in the project would also provide considerable co-benefits which are detailed in Appendix A.3. These include considerable water and air quality benefits provided by plants in green stormwater infrastructure or replacing impervious cover with vegetated land cover. Together these scenarios represent tens of thousands of additional area of green stormwater infrastructure or green land cover which would significantly increase natural habitat and biodiversity in this highly developed watershed. There are also considerable public health benefits from such a significant increase in green space including temperature reduction due to urban heat island effects, recreational opportunities, and improvements to physical and mental health. Reducing temperatures locally also provides climate mitigation benefits by reduce summertime energy demand. Urban Heat Island (UHI) effect was calculated at the subbasin scale, based on the cooling relationship developed by Wang et al. (2017) for Boston Metropolitan Area. The relationship states that 10% decrease in impervious area could yield approximately 0.4°F of cooling. Using that relationship in the project area, it appears that up to 1.3° F of cooling can be achieved in Beaver Brook under GI Scenario 5.

These actions would also result in over 100,000 million gallons of additional groundwater infiltration and recharge each year supporting streamflow and water supplies, especially during dry summer periods. These projects would raise awareness about nature-based solutions and the benefits they provide, this will be critical as we will need to aggressively incorporate these strategies into our communities to truly build resilience. Finally, a critical co-benefit of the project is that it identifies areas that are particularly vulnerable to flooding in the near and long term, and areas where flooding is expected to become significantly worse. This information is now readily accessible by community leaders and community residents, and will allow for informed, data-driven discussions and decision making on the future of such sites.

5.3 ADDITIONAL SCENARIO: UPLAND STORAGE

Based upon preliminary model simulation results, the technical team theorized that in contrast to some of the green infrastructure scenarios that require watershed-wide changes and perhaps decades to phase in changes to ordinances/by-laws, similar or perhaps greater flood reduction benefits could be achieved by increasing flood storage at a relatively small handful of existing ponds and wetlands. Ultimately, 22 existing ponds or wetlands were identified as having potential for increased flood storage. Those 22 sites are shown in Figure 5.13.

In all cases, these waterbodies are already incorporated into the model as storage nodes. The concept of creating additional flood storage in these locations was incorporated by raising their overflow elevations, representative of raising dam or roadway crest elevations to retain greater flood volumes, and or lowering their outlet elevations, representative of retrofitting culverts or spillways with stop logs or gates in order to release water at the onset of large storm events and create additional space for stormwater runoff. Configured in this way, impacts to normal water levels and ecological resources would be minimal but significant additional flood storage could be created. Additional flood storage conceptualized for these 22 sites ranged from 1.5 to 3 feet, which translates to considerable volumes given their low-lying topography. The estimated total additional storage volume is 2,534 acre-feet.

The potential flood reduction benefits of this gray infrastructure scenario were evaluated by comparing it to a no-action condition during baseline 10-year and 2070 10-year flood events. The present and 2070 10-year storms comparison for Additional Scenario - Upland Storage compared to “no-action” is summarized watershed-wide in Table 5.19. The 2070 comparison is summarized by sub-basin in Table 5.20.

As shown in Table 5.19 and Table 5.20, upland storage reduces the flooding extents, total runoff volume, and peak discharge rates from many sub-basins within the watershed. Across the entire watershed, this scenario reduces flooding extents by 205 acres or 2%. The percent change varies considerably by sub-basin, however. Twenty-one sub-basins are not expected to experience a significant change in flood-prone area, while others, like Mill River and Seaverns Brook will experience reductions as high as 16 and 27%, respectively. Despite these reductions in flood-prone area, it is worth mentioning that no critical infrastructure that would be impacted

TABLE 5.19 Summary of number of critical facilities impacted, inundation extents, and total runoff for Additional Scenario - Upland Storage during the present and the 2070 10-year events at the watershed-wide scale showing the percent reduction from “no action”

	Critical Facilities Impacted	Inundated Area (acres)	Total Runoff (MG)
Present 10-yr storm – No Action	53	7,243	7,368
Present 10-yr storm + Upland Storage	51	7,025	7,368
Change from No Action	-2 (-4%)	-218 (-3%)	---
2070 10-yr storm – No Action	56	8,928	10,651
2070 10-yr storm + Upland Storage	55	8,921	10,611
Change from No Action	-1 (-2%)	-205 (-2%)	---

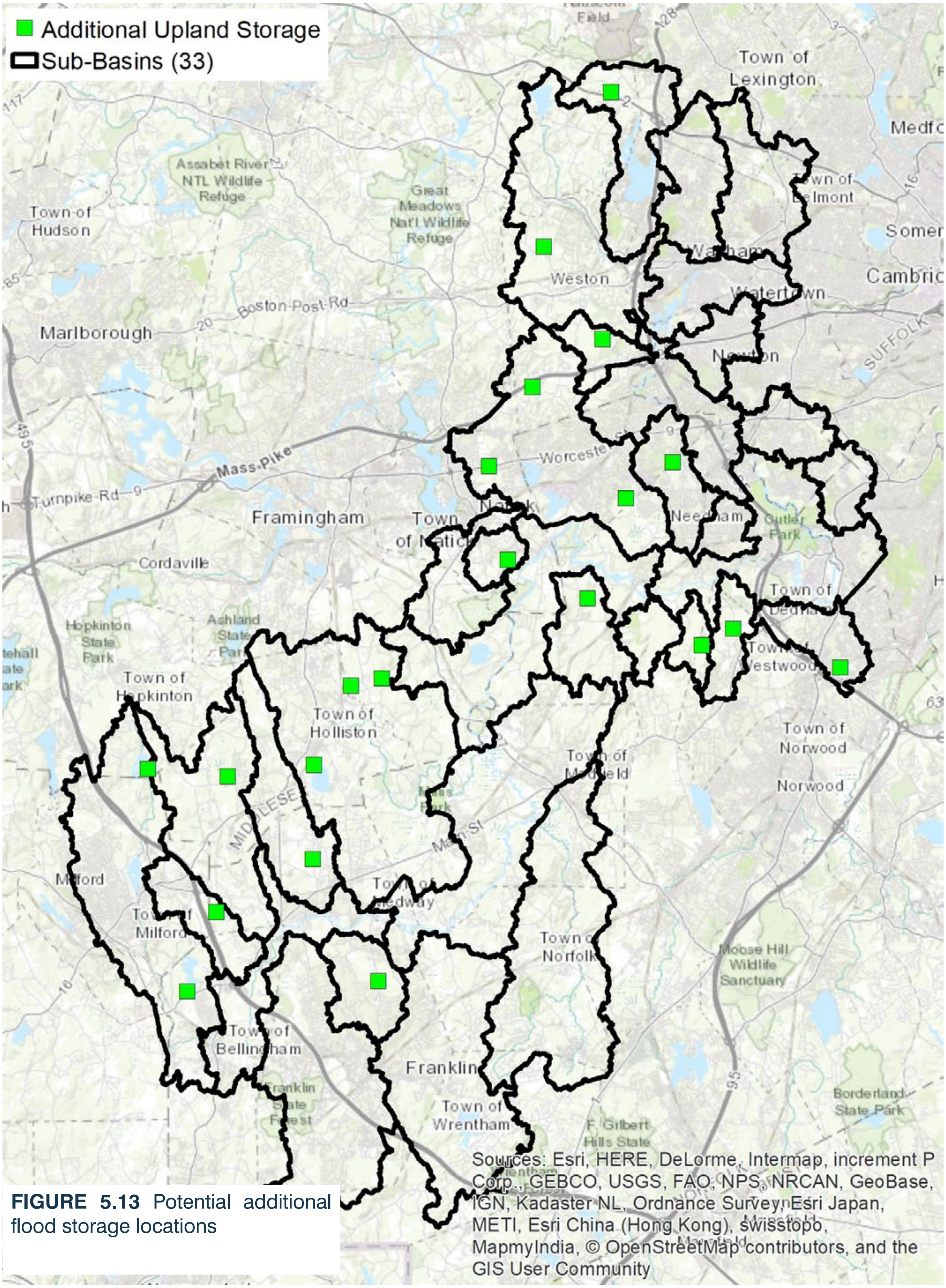


FIGURE 5.13 Potential additional flood storage locations

TABLE 5.20 Summary of inundation extents, total runoff, and peak discharge for Additional Scenario - Upland Storage during the 2070 10-year event, by sub-basin, and the percent reduction from "no action"

Sub-Basin	Inundated Area (acres)			Total Runoff (MG)			Peak Discharge (cfs)		
	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action	2070 10-year	GI 2070 10-year	% No Change over No Action
Alder Brook	6	6	0%	86	86	0%	349	357	0%
Beaver Brook	116	116	0%	313	313	0%	605	605	0%
Bogastow Brook	715	692	-3%	744	744	0%	1,076	1,076	0%
Bogle Brook	295	295	0%	560	560	0%	435	435	0%
Charles River: Bogastow Brook to Dover	340	284	-16%	320	320	0%	1,077	1,063	-1%
Charles River: Box Pond Dam to Medway	408	408	0%	259	259	0%	1,208	1,113	-6%
Charles River: Dover to Wellesley	805	800	-1%	613	613	0%	1,490	1,490	0%
Charles River: Medway to Bogastow Brook	1,386	1,383	0%	535	535	0%	1,346	1,346	0%
Charles River: Stony Brook to Watertown	73	73	0%	406	406	0%	2,048	2,048	0%
Charles River: Wellesley to Stony Brook	175	166	-6%	333	333	0%	2,010	1,884	-6%
Charles River Headwaters	328	299	-9%	699	699	0%	378	378	0%
Cheese Cake Brook	16	16	0%	167	167	0%	1,143	1,157	1%
Chester Brook	67	67	0%	285	265	0%	670	670	0%
Chicken Brook	24	24	0%	245	245	0%	307	292	-5%
Davis Brook	19	19	0%	72	72	0%	270	348	29%
Hobbs Brook	624	624	0%	665	665	0%	762	762	0%
Hopping Brook	310	300	-3%	315	315	0%	206	206	0%
Indian Brook	137	137	0%	160	160	0%	134	134	0%
Lowder Brook	155	155	0%	189	189	0%	164	164	0%
Mill River	271	229	-16%	369	369	0%	403	232	-43%
Mine Brook	763	763	0%	619	619	0%	268	210	0%
Noanet Brook	0	0	0%	34	34	0%	132	132	0%
Powissett Brook	40	40	0%	61	61	0%	276	210	-24%
Rock Meadow Brook	32	31	-3%	85	85	0%	563	563	0%
Rosemary Brook	44	44	0%	168	168	0%	384	374	-10%
Sawmill Brook	39	39	0%	150	150	0%	1,443	1,443	0%
Seaverns Brook	17	13	-27%	44	44	0%	198	198	0%
Shepherds Brook	46	46	0%	156	156	0%	233	229	-2%
South Meadow Brook	52	52	0%	183	183	0%	695	695	0%
Stall Brook	149	149	0%	181	181	0%	100	100	0%
Stony Brook	453	453	0%	1,028	1,028	0%	759	759	0%
Stop River	930	923	-1%	499	499	0%	231	231	0%
Trout Brook	92	78	-15%	107	107	0%	233	169	-28%

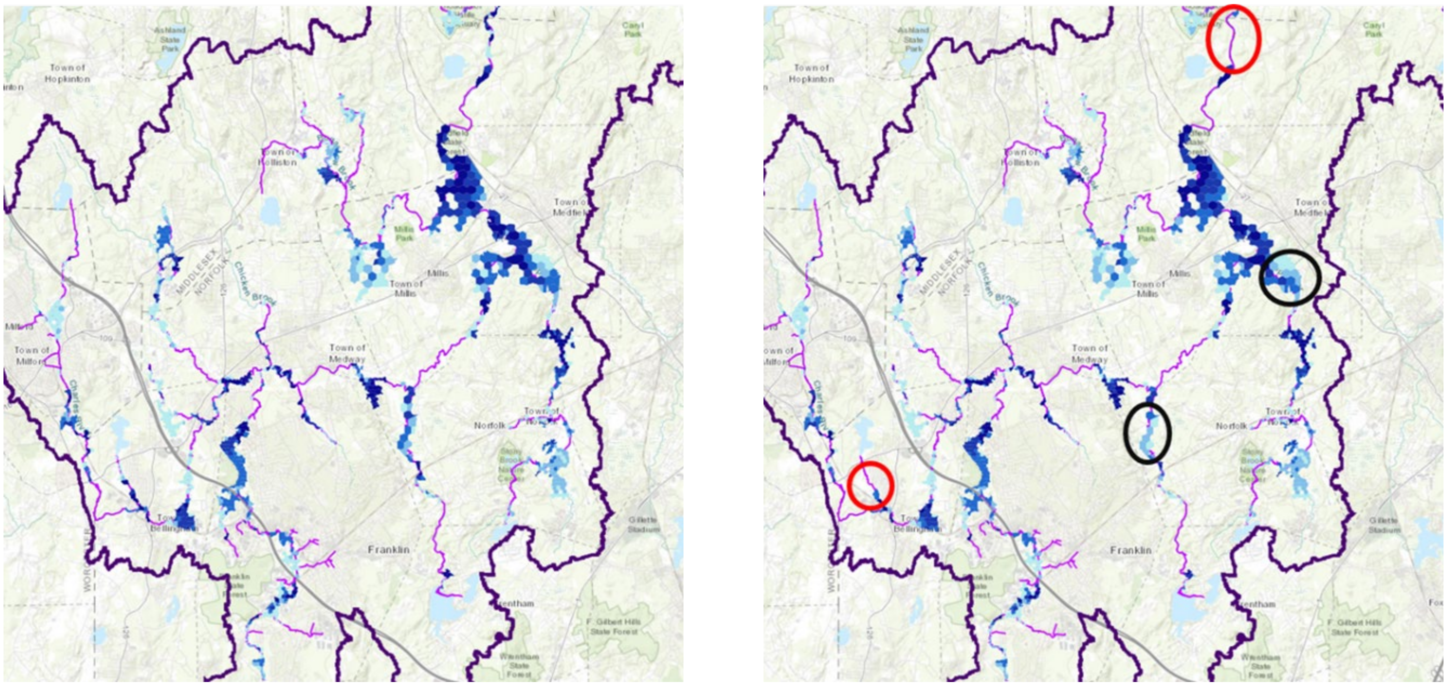


FIGURE 5.14 Areas where flooding is reduced (right) as a result of Additional Scenario – Upland Storage (red = eliminated flooding, black = reduced flooding)

under a 2070 No Action scenario would become dry as a result of GI Scenario 1.

Reductions in flood-prone area are generally driven by reductions in runoff volume and peak discharge from a sub-basin. Upland storage is not expected to reduce runoff volumes. Reductions in peak discharge are perhaps more significant with a watershed wide average reduction of 3%. Twenty-three sub-basins are not expected to experience a significant change in peak discharge (1% or less) while three sub-basins, such as Trout Brook and Rosemary Brook, are expected to see reductions of 10% or greater. Most sub-basins, however, are expected to experience reductions in peak discharge of between 2 and 6%, indicating that this site specific strategy may be worth pursing in certain locations but not in others.

Based on the 2D capacity of the Charles River stormwater flood model, it is possible to highlight specific areas that are likely to experience a particularly noteworthy reduction in flooding. In Figure 5.14, two maps are shown. The map on the left is 2070 10-year No Action conditions and the map on the right is 2070 10-year conditions as a result of Additional Scenario – Upland Storage. Areas circled in red are areas where flooding has been eliminated while areas circled in black are areas with reduced flooding.

5.4 PRIORITIZATION OF FLOOD MITIGATION ALTERNATIVES

One of the goals of assessing the Green Infrastructure scenarios evaluated as part of this project is to identify nature-based solutions that have the potential to mitigate or even roll back increases in flooding impacts that are anticipated to occur as a result of climate change. It is useful, therefore, to compare anticipated flood impacts associated with each of the GI scenarios against one another and against a No Action condition.

Figures 5.15 and 5.16 summarize the watershed-wide inundated area for each of the GI scenarios under baseline and 2070 climate conditions compared to the baseline and 2070 No Action conditions. The light and dark blue dashed lines mark the no action inundated area value. Values in parentheses are the reductions from the No Action conditions as a result of the GI scenarios and Additional Scenario: Upland Storage. With the exception of Scenario 5, all scenarios show a reduction in flooding impacts compared to No Action. These reductions are slightly smaller during late-century climate than during baseline climate. Inundated area is expected to increase by 1,685 acres by late-century. Future development of open space (Scenario 5) is expected to make this worse during late-century by as much as 3,389 acres over baseline No Action. The other five GI scenarios and the Upland Storage scenario are expected to reduce flooding to varying degrees. The most effective GI scenarios are GI Scenarios 1 and 2. Scenarios 1 and 2 had the most significant reductions in inundated area compared to the other GI scenarios. The least

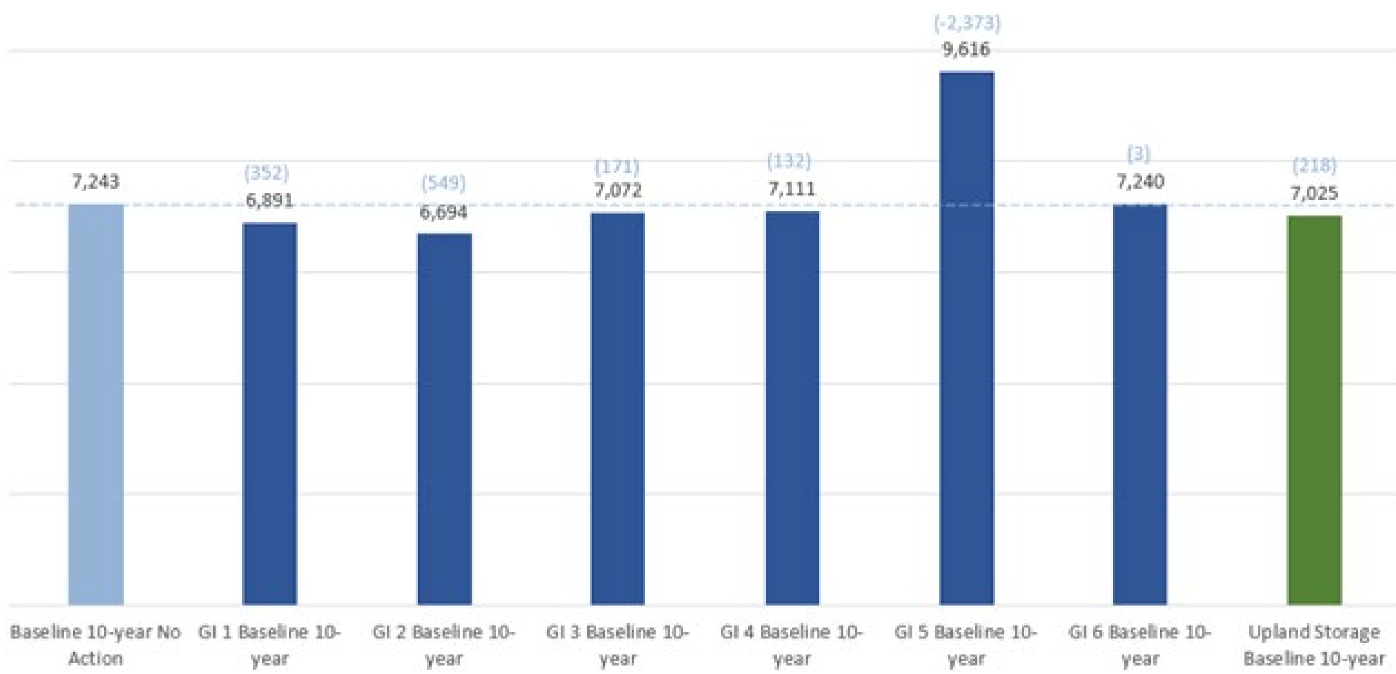


FIGURE 5.15 Total watershed-wide inundation area by scenario for baseline climate

effective GI scenarios, excluding Scenario 5, are GI Scenarios 4 and 6. Scenarios 4 and 6 had more modest reductions in inundated area.

Figures 5.17 and 5.18 summarize the watershed-wide total runoff volumes for each of the GI scenarios under baseline and 2070 climate conditions compared to the baseline and 2070 No Action conditions. The light and dark blue dashed lines mark the no action inundated area value. Values in parentheses are the reductions from the No Action conditions as a result of the GI scenarios and Additional Scenario: Upland Storage. With the exception of Scenario 5, all scenarios show a reduction in flooding impacts compared to No Action. These reductions are slightly smaller during late-century climate than during baseline climate. Total runoff volume is expected to increase by 757 MG by late-century. Future development of open space (Scenario 5) is expected to make this worse during late -century by as much as 1,501 MG over baseline No Action. The other five GI scenarios and the Upland Storage scenario are expected to reduce flooding to varying degrees. The most effective GI scenarios are GI Scenarios 1 and 2. Scenarios 1 and 2 had the most significant reductions in total runoff compared to the other GI scenarios. The least effective GI scenarios, excluding Scenario 5, are GI Scenarios 4 and 6. Scenarios 4 and 6 had more modest reductions in total runoff.

None of the scenarios assessed here are sufficient for mitigating the anticipated impacts of climate change by 2070. In order to mitigate impacts, it will likely require the implementation of several nature based solutions, potentially

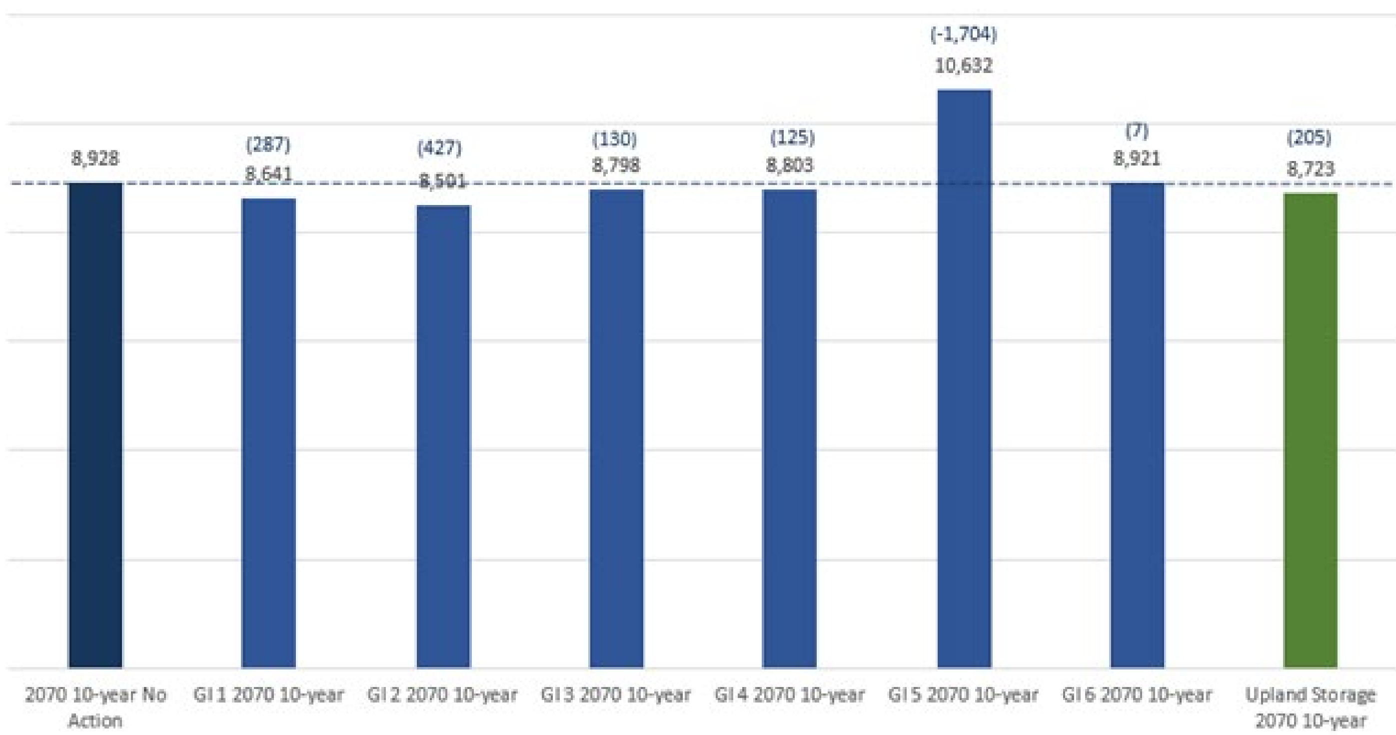


FIGURE 5.16 Total watershed-wide inundation area by scenario for 2070 climate

in combination with more traditional "gray" infrastructure projects. Additionally, scenarios assed here may have been too conservative and based on present day concepts of what is "feasible", adapting to climate change will take more aggressive actions than are considered in these scenarios if the watershed communities are to ensure that flooding does not worsen over present-day conditions. After reviewing the model results, project team municipal participants ranked the scenarios based on feasibility. At the time of writing this report, 10 of the 15 communities responded. The survey had a total of 11 responses with multiple responses received from Sherborn. Responses were not limited to one per town because individuals in different staff positions within a community bring different perspectives and expertise.

The project team identified storage on large public properties (scenario 3) and 20% of feasible land becoming green stormwater infrastructure (scenario 2) as the most readily implementable in the near term (defined as implementation underway in a systematic way to achieve a target within the next 2-3 years) in their communities. Conversely, when asked which strategies would be unlikely to be initiated in their community in the next two years, it was a tie between all the remaining scenarios (1, 4-6). Each respondent selected two scenarios for each question.

When respondents were asked to select their single top priority for near-term implementation in their community, however, every scenario got at least one vote. Scenarios ranked as follows:

1. Scenario 2. 20% of feasible/priority land area is GSI (3)

2. Scenario 3. Storage on large (>5 acres) public properties (2)

2. Scenario 4. Reduce effective impervious cover watershed wide by 10% (for subbasins over 10%) (2)

2. Scenario 5. Allow 50% of remaining undeveloped/unprotected land to become impervious (2)

3. Scenario 1. Green infrastructure stores 2" storm runoff from up to 50% of all impervious cover town-wide (1)

3. Scenario 6. 25% public ROWS become green streets: tree box filters/bioswales connected to leaching catch basins (1)

Finally, when asked about a priority for long-term implementation, one strategy was the clear favorite: Scenario 6. 25% public ROWS become green streets: tree box filters/bioswales connected to leaching catch basins, followed by Scenario 1. Green infrastructure stores 2" storm runoff from up to 50% of all impervious cover town-wide. This indicates that these strategies are desirable, but project team municipal staff think they will take longer to implement.

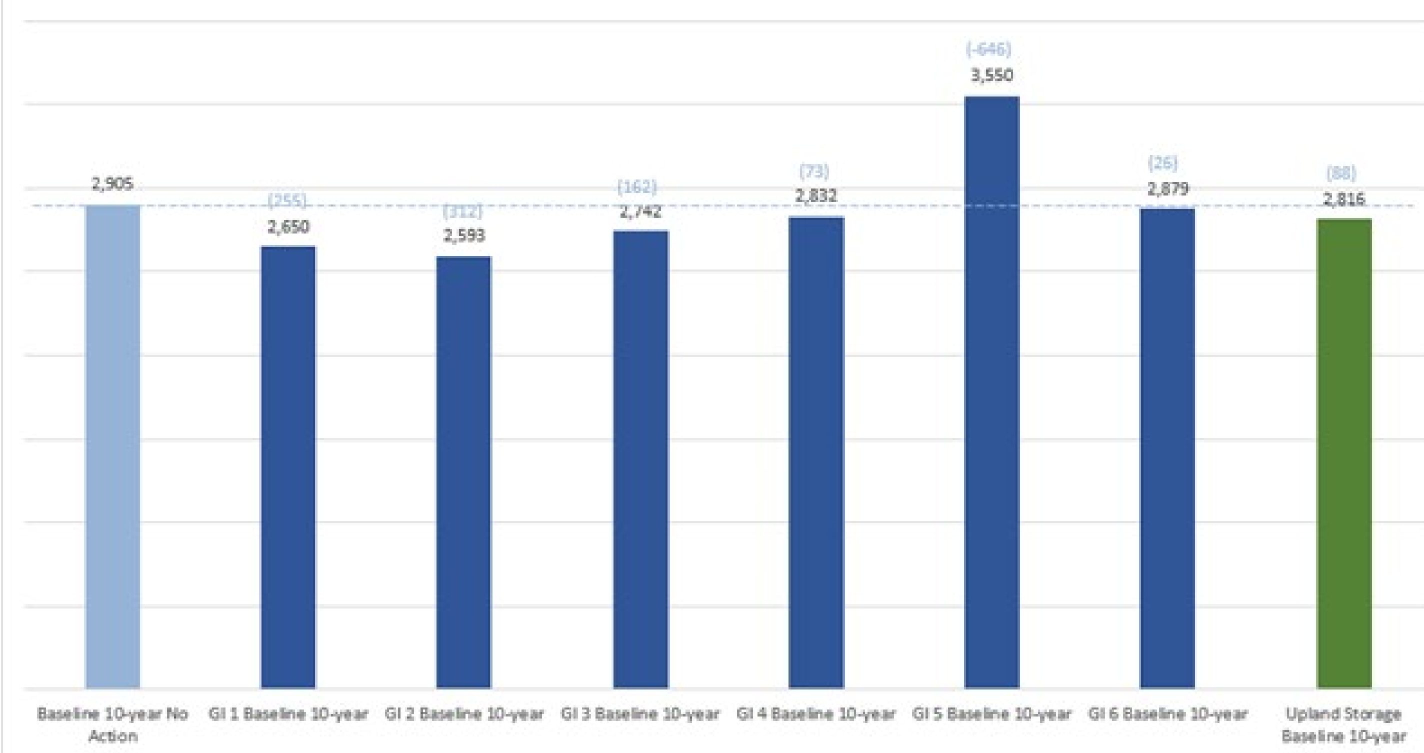


FIGURE 5.17 Total watershed-wide runoff volume by scenario for baseline climate

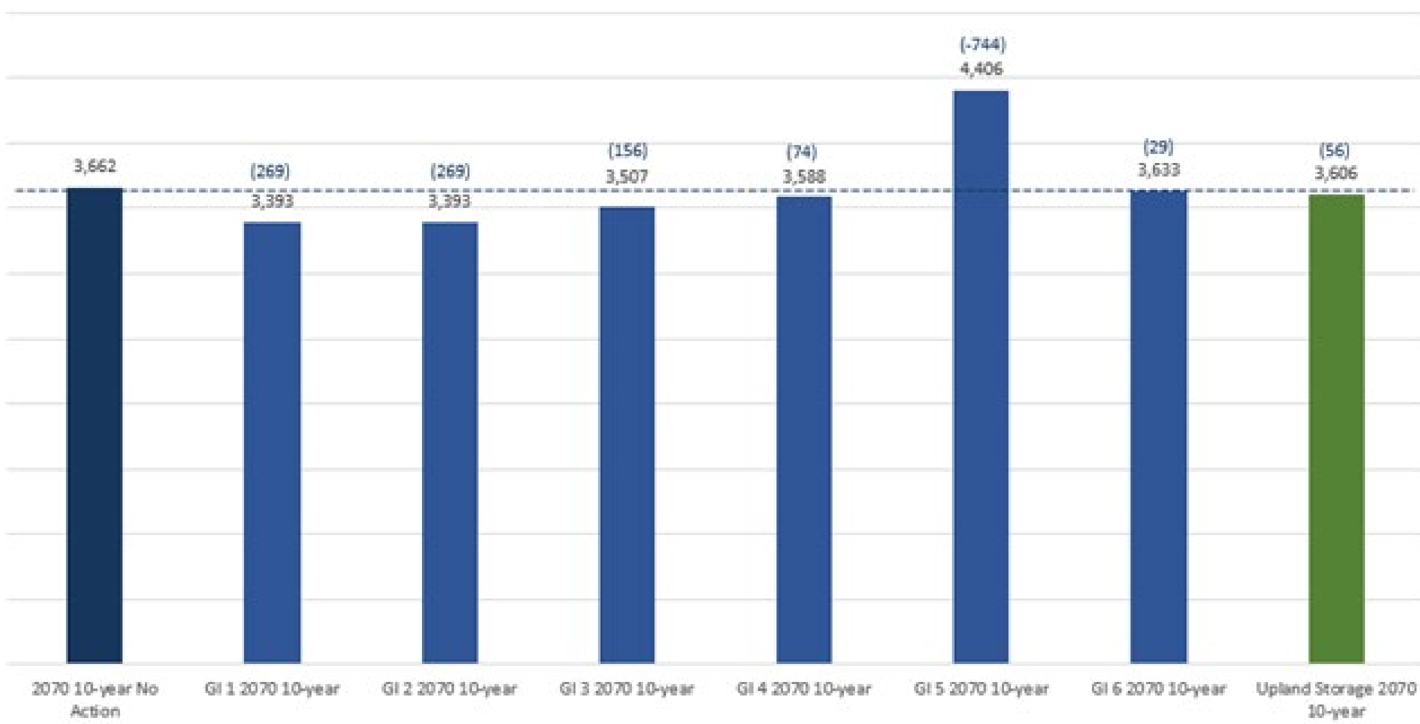


FIGURE 5.18 Total watershed-wide runoff volume by scenario for 2070 climate

6

PUBLIC ENGAGEMENT

The project involved extensive public engagement. Communities Responding to Extreme Weather – CREW, a network of local leaders building grassroots climate resilience through inclusive and hands-on education, service, and planning, was a partner on this task and played a critical role in engaging watershed residents and climate justice advocates. CRWA and CREW worked closely on all project engagement activities.

Table 6.1 summarizes the outreach meetings all of which were held virtually due to the pandemic.

The engagement meetings targeted community-based organizations working across the watershed, particularly groups working on environmental justice and equity issues. In addition to holding five online meetings, CRWA and CREW also undertook the following engagement activities:

- Project website
- Project flyer (in 4 languages)
- Resident input survey (available in 4 languages) close to 200 responses
- Project video
- E-newsletter/social media updates
- Online survey results viewer and story map
- Communication's kit for project team outreach

Community engagement efforts on this project had three primary objectives:

1. Raise awareness about and build trust in the Charles River Flood Model as an effective planning and decision-making tool to be used by watershed communities
2. Obtain actional input on planning horizons and nature-based solutions to define modeling scenarios run during this phase of the project
3. Get direct feedback or gain a better understanding of effective communications and outreach strategies around the technical aspects of the project

To achieve objective number 1, all project outreach activities and materials included a general project description. Project materials were reviewed by technical and non-technical staff to ensure accuracy as well as accessibility.

TABLE 6.1 Summary of the outreach meetings

Date	Outreach Meeting
1/28/21	Virtual Event / Public Webinar: Project introduction (evening event)
3/3/21	Lower watershed engagement meeting (evening event)
4/1/21	Middle watershed engagement meeting (evening event)
4/7/21	Upper watershed engagement meeting (evening event)
6/23/21	Virtual Event / Public Webinar: Project results (evening event)

Hundreds of residents were engaged through meetings and surveys; however, the ongoing pandemic and the tight project timeline did present challenges, these are discussed in more detail below.

To achieve objectives 2 and 3, the team primarily used the online surveys described above and the engagement meetings. Input on climate planning timelines and nature-based solutions were incorporated into the selection of model runs and nature-based solution scenarios. To obtain input on reaching a broad audience and effective communication the resident survey asked: How could we make our work more accessible to you or members of the public who you think might be interested in learning more in the future? (Check all that apply). The top responses were:

1. Offer shorter programing
2. Offer materials and/or presentations in multiple languages
3. Offer live American sign language

The project team recorded a five minute video of the project which was posted to YouTube and although the video does not have American sign language translation it does include closed captioning which was done by a professional service. Written informational materials were developed and published in the top four watershed languages: English, Spanish, Portuguese, and Traditional Chinese. Non-English language materials were made available on the project web page but were also distributed to community groups that CREW has relationships with that work with non-English speaking clients.

Many respondents also suggested communicating information through local groups and libraries. Now that libraries are opening up, the final project flyer is being posted in libraries across the watershed to encourage residents to explore the results in the online viewer. A brief tutorial on using the online viewer is also available to assist people in navigating the results.

CRWA and CREW also developed a communication's kit to support the project team in communicating information about the project with residents in their communities (Appendix A.4). It includes a customizable PowerPoint presentation, press release, social media templates (in multiple languages), and the final project flyer. The communications kit also includes a user guide. The contents of the communication's kit were informed by the public feedback obtained throughout the project.

CRWA organized a training for the full project team focused on engaging climate vulnerable residents in municipal planning. This very informative event included three highly experienced speakers, Dr. Atyia Martin, All Aces, Inc.; Cate Mingoya, Groundwork USA; and Ethan McDonough from CREW. Every presentation included actionable information relevant to municipal staff members. CREW also prepared an extremely comprehensive toolkit with information and resources on addressing social vulnerability. This toolkit was shared with all the participating communities.

Finally, the team did face some challenges on this task. The primary challenges were:

- Engaging groups and individuals who are busy and/or overburden and do not view their work as directly connected to climate change or flood planning, this challenge was particularly evident during the ongoing pandemic when face to face interaction were not possible and people lives were disrupted.
- Timely translation of materials, this had to be outsourced on this project and the process took slightly longer than expected when working with translated materials that are highly formatted or in certain software platforms that were not what translators

were expecting, such as Canva and Google Forms

- Entering communities where trust is essential to buy-in was also a challenge during the pandemic and due to the project's tight timeline.
- Technical challenges and technological limitations in the ongoing pandemic. As noted above all meetings occurred on Zoom which created technical challenges both for the project team and also creates a barrier to entry. Multiple meetings included technical challenges, including challenges with displaying live closed captions during the final presentation.

The team will learn from these challenges as we continue to promote the project and this amazing resource.

FIGURE 6.1 Group photo from technical team meeting.

7

SUMMARY AND FUTURE WORK

The Charles River watershed will experience more flooding from the larger storm events expected to become more common in our area due to climate change. While many communities anticipated this, and had identified stormwater and riverine flooding as top climate vulnerabilities, the Charles River Flood Model provides information on where and when this flooding is expected to occur. The CRFM also provides data on how deep flooding is expected to be in vulnerable areas to provide a more complete picture of flooding, allowing model users to distinguish between flooding that is likely to damage property and threaten life and flooding that may be more a nuisance.

From the current day (baseline) 10-year event to the 2070 10-year event, a 23% increase in flood-prone area is expected across the watershed. This is an additional 1,600 acres (about twice the area of Central Park in New York City) that would not be flooded in today's storm but will be flooded in the future. Certain areas will be more impacted than others with multiple sub-basins expected to experience increases of more than double to the size of their flood-prone or inundated areas and/or impacts to additional critical infrastructure.

In a 100-year storm event, as expected flooding impacts are more severe overall, however, the difference between the present day and the 2070 storm event is actually a bit more modest with an additional 1,400 acres projected to experience flooding in the future than would be flooded today. The 2070 100-year storm is predicted to flood about 12,500 acres of watershed land, compared to an estimated 10,500 acres of flooding during the March 2010 storm, one of the most significant freshwater flood damage events to impact our region recently. Finally, an extreme storm, modeled here as the Mystic 2070 100-yr storm, is predicted to flood about 13,000 acres of the watershed. This means many more homes, businesses, schools, roads, and potentially critical infrastructure that will be flooded. Therefore, new and major retrofits for infrastructure improvements and development projects (both public and private) in the watershed area should consider these future design storm parameters in the planning and design phases.

Model results further demonstrate that nature-based solutions can mitigate the impacts of future flooding. A key finding of this study, however, is that it will take considerable investment and on the ground changes, beyond what may be considered "feasible" today to truly mitigate these impacts. As described in detail above, feasibility was a key metric in selecting nature-based solution strategies to model. As a result, none of the scenarios modeled were able to fully mitigate the expected impacts of climate change. Having established this will help guide future planning by establishing a shared understanding across the region that it will require bold and aggressive action to mitigate expected flooding and we are in need of a mind shift with respect to what is "feasible".

One scenario in particular, scenario 5, demonstrates the need to quickly deviate from "business as usual". This scenario tests the impact of developing land instead of conserving or protecting it. Developing half of the watershed's remaining undeveloped and unprotected land would result in an increase in 33% flooded area in the present day 10-yr storm and 20% increase in flooded area in the 2070

10-yr storm compared to not allowing the land to be developed. Allowing undeveloped land to be developed without considerable flood protection will cause downstream flooding and likely impact vulnerable residents.

In the next phase of the project, the project team hopes to pursue more aggressive scenarios and test multiple strategies in concert to identify effective mechanism to reduce flooding down to present day levels and better. Additionally, the team hopes to start putting some of these strategies into place because although the model indicates there may be some time to adapt our landscape, extreme rain events can come at any time and we know we have considerable changes to make.

The team is actively pursuing funding to:

- Increase the model detail and extent by adding additional stormwater infrastructure data, additional communities, and conducting additional field verifications as needed
- Develop regional policy goals and tools to begin to operationalize the lessons of this project, namely development cannot occur unabated and green stormwater infrastructure can help mitigate flooding
- Identify large scale flood opportunities with significant local or regional benefits and begin system designs

In the next project phase, the Charles River Climate Compact hopes to develop the Charles River Watershed Climate Adaptation Implementation Plan to document how model results will be used to put flood mitigation measures into practice on the ground starting now. This will be critical to the success of this effort because this initiative is taking an innovative and novel approach by planning at the watershed scale. Planning and implementation practices are well established at the municipal, state, and to some extent, regional scale, while planning at the watershed scale is a relatively niche practice that this project is helping to advance in the region. As such, the CRCC has identified moving forward with a documented and transparent Implementation Plan that involves public input as a necessary next step to build trust within and among participating communities (residents, staff, leadership).

Furthermore, it will provide an opportunity for the group to collectively prioritize projects and set them up for implementation and funding in the near-term. Without dedicated funding to do this at the regional scale, implementation will involve a piece-meal approach unlikely to be as effective, and be significantly limited in scope. Finally, supporting this work at the regional scale allows for a more complete understanding of costs and benefits as projects in upstream communities may have considerable benefits (or impacts) beyond their own borders.

LIMITATIONS

The Charles River stormwater flood model spanning across 272 square miles was developed as a comprehensive flood model to account for piped infrastructure and riverine flood risks across the Upper and Middle Charles River watersheds. While the effective duration of this project was just over 6 months, the model was developed in a period of 3 months since a considerable amount of time was spent by the Technical Team in gathering data and conducting field investigations to fill data gaps for the stormwater infrastructure from the communities. Since the timeline for developing this model was extremely constricted and the model was based on the accuracy of the data received from the communities by the Technical Team, there are opportunities to increase the accuracy of the model by including additional details from the topography, bathymetry and stormwater drainage data.

The current model includes drainage pipes that are 24 inches in diameter or greater and associated drainage structures with these pipes. This threshold was used since developing a watershed-wide model that includes every single drainage structure across multiple communities would be resource intensive and would need significantly longer time to develop. While this drainage size threshold is a limitation of the current model, the Technical Team proposes to address this limitation in subsequent phases by adding smaller pipes and associated drainage structures to better simulate flood risks and flood reduction benefits at localized scales in the watershed.

The model was developed by conducting field verification of over 442 structures. However, there were additional structures that had been flagged as data gaps, which were not possible to field-verify since some of these structures could not be accessed physically. The Technical Team proposes to address this limitation in the subsequent phase of this project by conducting more detailed site-specific survey at select locations and potentially using advanced surveying techniques.

The future flood risks that have been evaluated as part of this project using this model are focused on 24-hour duration storms. Flood risks in the watershed and at localized spots related to high-intensity shorter duration storms (e.g. 2-hr, 6-hr storms) have not been evaluated. Similarly, flood risks related to longer duration storms (e.g., 48-hr, 72-hr storms) have not been evaluated in this project. In the case of shorter duration storms, flooding is mostly attributed to limitations of the stormwater inlets not being able to keep up with collecting stormwater as rainfall intensities increase. A separate modeling approach is needed to accurately simulate the impacts of these shorter duration storms, and this approach also needs much finer drainage infrastructure detail since every single catch basin and inlet structure will need to be considered to better understand flood risks. These additional details and model enhancements can be built open the current version of the model as part of subsequent phases.

Finally, the Charles River stormwater flood model was developed to primarily understand precipitation-driven flood risks in the watershed. However, as sea level rises and storm surges become more intense and as the Charles River Dam is projected to be flanked and overtopped in the future, there are portions of the watershed that are likely to experience the impacts of both precipitation driven and coastal flood risks. These combined impacts of coastal and stormwater flooding are aspects that have not been evaluated using the current model but can be evaluated in subsequent phases.

END NOTES & REFERENCES

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2. Climate Resilience Design Standards & Guidelines. Resilient MA, Climate Change Clearinghouse for the Commonwealth, 2021. https://resilientma.org/climateresiliencestandardstool/docs/Section%203%20-%20Climate%20Resilience%20Design%20Standards%20Overview.pdf

3. Charles River Watershed Model Online Viewer:
https://crwa.maps.arcgis.com/apps/webappviewer/index.html?id=4649d032ebb74cafb20767e4f3e369df

4. As the surface area of feasible land varied widely across the 705 model subcatchments, so too did the increase in the storage parameter. Increases ranged from 0.0 inches of storage in 51 subcatchments, in which feasible land was absent, to a maximum of 2.0 inches in 45 subcatchments, in which all of the impervious surface was included in the identified 20% feasible land.

5. Charles River Watershed Model Green Infrastructure Storymap:
https://storymaps.arcgis.com/stories/42320322eab245b7b437f3824026cd84

6. Charles River Watershed Model Stormwater Modeling Storymap:
https://storymaps.arcgis.com/stories/5e214750da174c46bf6a8b8da12630e9