Sea Level Rise and Coastal Storm Surge Projections

Climate Change Vulnerability Assessment

Part 2 – Sea Level Rise and Storm Surge

City of Cambridge, Massachusetts

February 2017

Disclaimer: The CCVA Part 2 Vulnerability Assessment is based on best available information for sea level rise and storm surge projections at the time the analysis was conducted. Updates will be provided as new information is made available and key findings re-assessed accordingly.

Acknowledgments

City of Cambridge

Louis A. DePasquale, City Manager
Lisa C. Peterson, Deputy City Manager

Project Steering Committee

John Bolduc, Environmental Planner, Community Development Department, Project Manager
Iram Farooq, Assistant City Manager for Community Development
Sam Lipson, Environmental Health Director, Public Health Department
Owen O'Riordan, Commissioner of Public Works
Susanne Rasmussen, Environmental & Transportation Planning Director, Community Development Department
Kathy Watkins, City Engineer, Department of Public Works
Kari Sasportas, Manager of Community Resilience and Emergency Preparedness, Public Health Department

Produced in Collaboration with

Kleinfelder, Lead Consultant
- Nathalie Beauvais, Project Manager
- Indrani Ghosh, Technical Lead
- Nasser Brahim, Vulnerability Assessment
- Rita Fordiani, Technical Review
- Christopher Balerna, Project Coordination

MWH; William Pisano, David Bedoya, Water system impacts
Paul Kirshen, UMass Boston, Water system impacts
Ellen Douglas, UMass Boston, Water system impacts
Kirk Bosma, Woods Hole Group, Sea level rise and storm surge impacts

With special thanks to the many contributors from the City of Cambridge for providing valuable expertise to inform the vulnerability and risk assessments and reviewing key findings.

For more information on the project, please visit the City website at
http://www.cambridgema.gov/climateprep

Technical Reports

Sea Level Rise and Storm Surge Maps, Kleinfelder, Woods Hole Group, MWH Global, 2016

BH-FRM Model Simulations and Assessments to Support the CCVA, Woods Hole Group, 2016

Drainage Infrastructure Flood Propagation Assessment during SLR/SS Events With and Without Concurrent Precipitation, MWH Global, 2015

Executive Summary

Modeling Sea Level Rise and Storm Surge Impacts from Climate Change

Purpose

The purpose of this report is to present key findings of sea level rise (SLR) and storm surge modeling for the City of Cambridge, and to summarize the two technical memoranda provided by the Woods Hole Group and MWH Global that explain the detailed modeling results. The technical memorandum titled "BH-FRM model simulations and assessments to support the [Climate Change Vulnerability Assessment] CCVA" by the Woods Hole Group includes the specific analysis of overland flooding from SLR and storm surge for the City of Cambridge utilizing the Boston Harbor Flood Risk Model (BH-FRM). The technical memorandum titled "Drainage infrastructure flood propagation assessment during SLR/SS events with and without concurrent precipitation" by MWH Global includes the impacts of SLR and storm surge on the City's drainage and combined sewer piped infrastructure system, and identifies the low-lying areas in the City that may be flooded from "back-ups" through the piped infrastructure.

Background

Over the past century, sea levels have been rising as a result of climate change. The impacts of SLR and storm surge by 2030 and 2070 for the City of Cambridge were modeled using the BH-FRM developed by the Woods Hole Group for the greater Boston area including Cambridge, and other surrounding communities in Massachusetts. The BH-FRM was developed as part of the MassDOT and the Federal Highway Administration (FHWA) project for assessing potential vulnerabilities in the Central Artery tunnel system. The BH-FRM is comprised of the ADvanced CIRCulation model (ADCIRC), a two-dimensional, depth-integrated, long wave, hydrodynamic model for coastal areas, inlets, rivers, and floodplains that, in this application, is used to predict storm surge flooding, and the Simulating WAves Nearshore model (SWAN), a wave generation and transformation model. The BH-FRM area relevant for Cambridge extends up to the Watertown Dam in the Charles River Basin, and upstream of the Amelia Earhart Dam and downstream of the Alewife Brook in the Alewife Brook Basin shown in Figure 1.

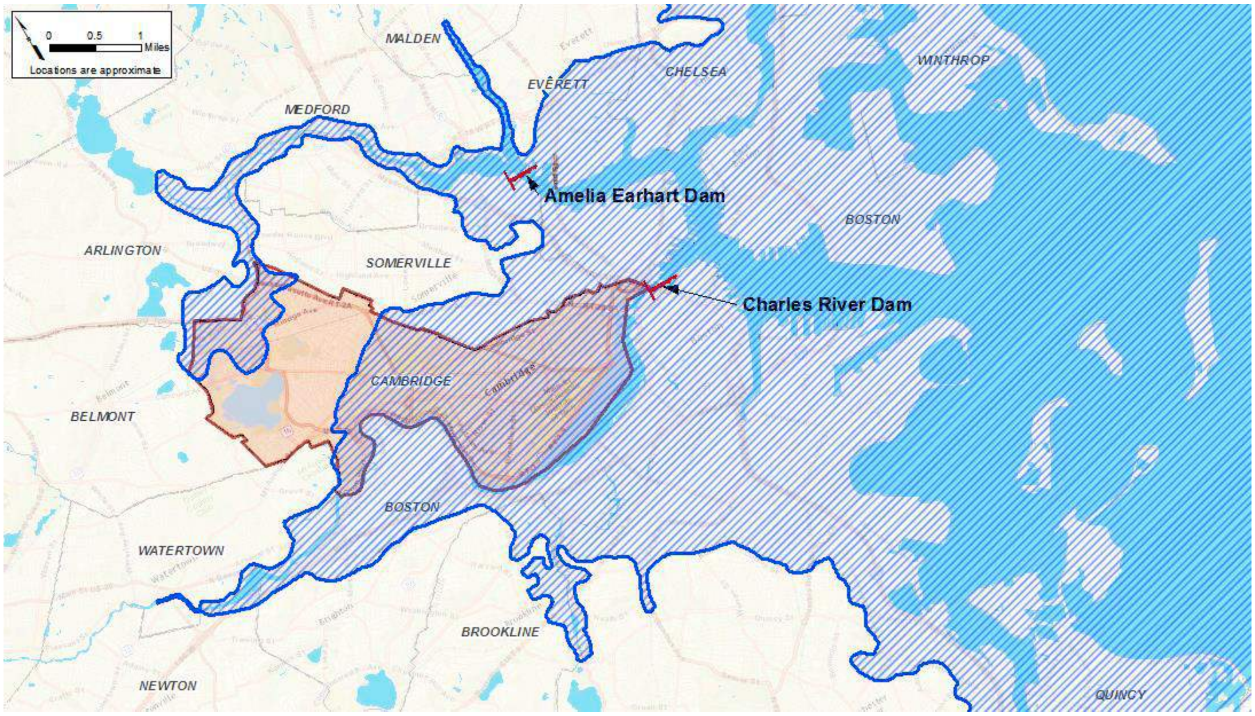


Figure 1: Extents of the BH-FRM used for Cambridge. Shaded area in blue indicates the extent and location of the project area included in this analysis. (Source: MassDOT, Woods Hole Group, UMass Boston, March 2015)

The BH-FRM was refined to better estimate upstream river flooding, particularly the areas upstream of the Charles River Dam and the Amelia Earhart Dam to complement the MassDOT modeling effort that was focused on the Central Artery system and the areas in the vicinity and downstream of the dams. The probability and depth of flooding that could occur during dam flanking and/or overtopping upstream of the Charles River Dam and in the Alewife Brook area were estimated using this refined model.

The SLR scenarios for 2030 and 2070 used in BH-FRM were based on using the “Highest” SLR scenario as published in the NOAA Technical Report “Global Sea Level Rise Scenarios for the United States National Climate Assessment” (December, 2012). Based on estimates of SLR projections in the Boston Harbor area, the relative mean sea level is projected to rise 0.66 feet by 2030 and 3.39 feet by 2070 according to the NOAA “Highest” scenario. These SLR scenarios were incorporated into the BH-FRM. The modeling approach was risk-based using a fully optimized Monte Carlo computational approach to simulate a statistically-robust set of storms (both tropical storms such as hurricanes and extra-tropical storms such as nor’easters) for each SLR scenario. The storm climatology for the hundreds of different types of storms were factored into the Monte Carlo simulations. The storm climatology was based on present climate for planning horizons until 2050. For storm simulations beyond 2050, the 21st century storm climatology was used to simulate the storms. The 21st century climatology projections factored into the BH-FRM are based on climatology projections by MIT professor Dr. Kerry Emmanuel.

Results of the Monte Carlo simulations in BH-FRM were used to generate Cumulative probability Distribution Functions (CDFs) of the storm surge water levels at a high degree of spatial precision. The SLR and storm surge maps for Cambridge (included in Appendix A of this report) using BH-FRM are represented as two types: maps that show annual percent probability of flooding (ranging from 100% to 0.1%) by 2070, and maps that show the depth of flooding above ground for the 1% and 0.1% annual probability of flooding by 2070.

The impacts from increased water surface elevation in the Charles River and the Alewife Brook from flanking and/or overtopping of the dams were evaluated to determine the flood risk generated in the drainage infrastructure in both the Charles River and the Alewife Brook basins. The intent was to evaluate the extent and depth of flooding in the low-lying areas of Cambridge because of higher water levels in the Charles River and Alewife Brook backing up into the City's drainage system. This analysis was conducted using the BH-FRM results as boundary conditions for the City's hydrologic/hydraulic model using ICM-2D. For this assessment, two scenarios were evaluated: 1) flooding impacts from only SLR and storm surge flooding (no rain) "backing up" into the City's drainage system, and 2) flooding impacts from SLR and storm surge flooding coincident with a 10-year 24-hour storm by 2070 "backing up" into the City's drainage system. The peak water surface elevations in the Charles River and the Alewife Brook that were used as the boundary conditions were 21.1 feet-CCB[1] and 23.41feet-CCB, respectively for the 1% annual probability of flooding from SLR and storm surge (without river discharge) in the 2070 time horizon.

Results

Impacts on Dams

Based on the BH-FRM results, there is an insignificant probability of both the Charles River Dam and the Amelia Earhart Dam, location shown in Figure 1, being flanked or overtopped in the 2030 timeframe. As such, the risk of flooding in the City of Cambridge due to combined SLR and storm surge

[1] ft-CCB refers to ft above Cambridge City Base datum, which is a standard vertical datum used by the City of Cambridge. This datum is 11.65 ft above the national standard vertical datum NAVD88, and 11.95 ft above the mean sea level in the Boston area.

events in the 2030 timeframe is relatively insignificant. However, by 2070 both dams have the potential to be overtopped and/or flanked under various extreme storm events.

The BH-FRM results also estimated that both the Amelia Earhart Dam and the Charles River Dam are likely to be flanked 10-15 years before they are likely to be overtopped. This indicates that the local crest elevations and pump systems are more resilient to flood potential than the surrounding landscape. The Amelia Earhart Dam is flanked significantly on the west side of the dam near the Assembly Row area of Somerville (Flood Pathway 1 in Figure 2), as well as a much larger flood pathway initiated in Chelsea and Everett (Flood Pathway 2 in Figure 2). The Amelia Earhart Dam is likely to be flanked and overtopped before the Charles River Dam by approximately 15-20 years. The Amelia Earhart Dam is likely to be flanked as soon as 2030-2035 by a 500-year water surface elevation and by 2045-2050 by a 100-year water surface elevation. The Amelia Earhart Dam is likely to be overtopped by 2040 by a 500-year water surface elevation and by 2055-2060 by a 100-year water surface elevation. The Charles River Dam is likely to be flanked directly south of the dam (Flood Pathway 3 in Figure 2), as well as via a significant flood pathway that initiates from the Mystic River and advances through Somerville and the Sullivan Square area (Flood Pathway 4 in Figure 2). The Charles River Dam is likely to be flanked as soon as 2045 by a 500-year water surface elevation and by 2055-2060 by a 100-year water surface elevation. The Charles River Dam is likely to be overtopped by 2050 by a 500-year water surface elevation and by 2065 by a 100-year water surface elevation. It is important to note that the ability of the dams to pump after an extreme flooding event will affect the duration of flooding in the City.

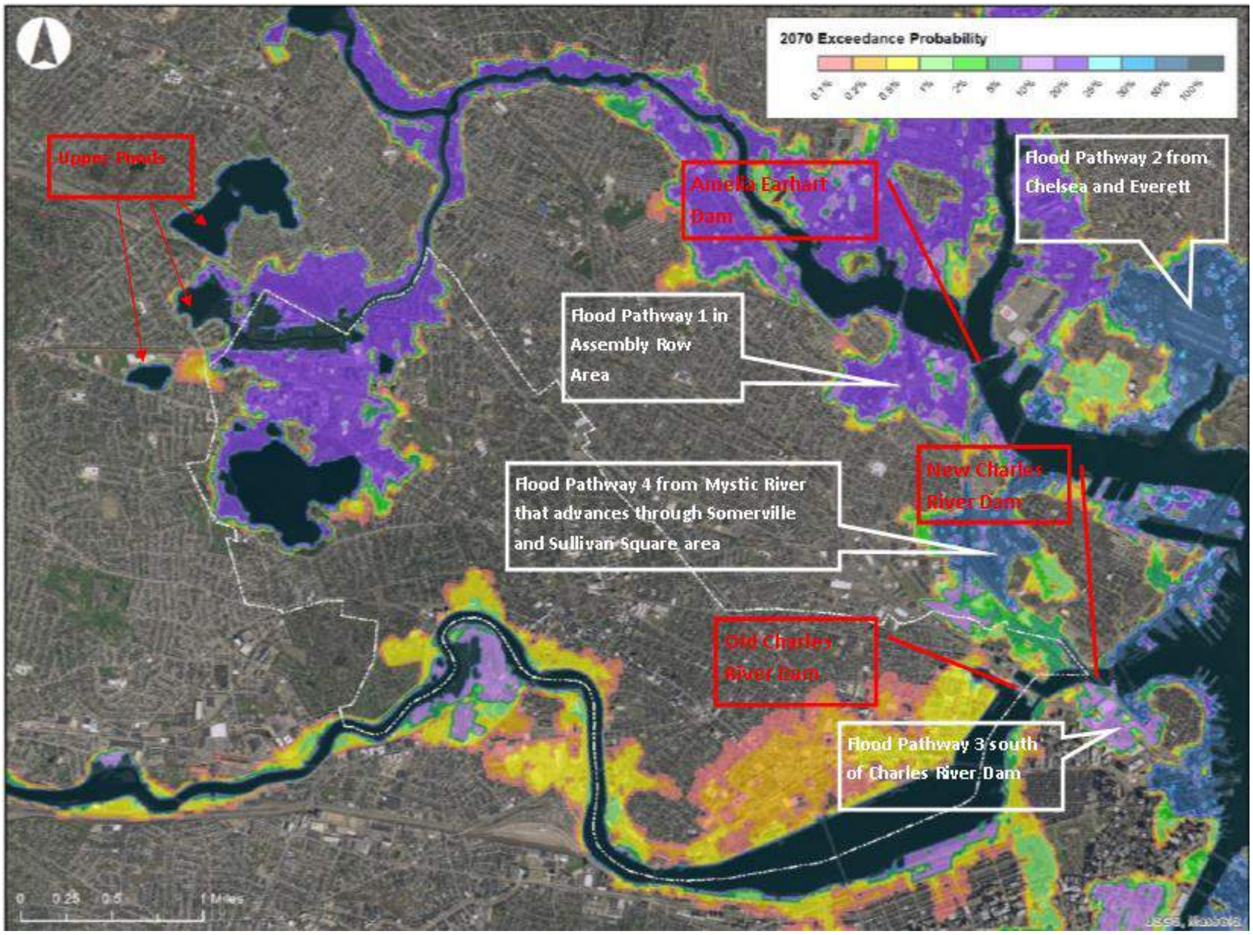


Figure 2. Percent probability of flooding by 2070 for City of Cambridge and surrounding areas showing locations of dams and the different flood pathways for flanking of the Amelia Earhart Dam (Flood Pathways 1 and 2) and the Charles River Dam (Flood Pathways 3 and 4). (Source: Kleinfelder and Woods Hole Group, April 2015

Impacts on Areas

The BH-FRM results show that the Alewife Brook and majority of the areas adjacent to the Alewife Brook have a 10-20% annual probability of flooding (5-10 year return period water surface elevations) in 2070, as shown in Figure 2. In Cambridge specifically, the Upper Ponds adjacent to Alewife Brook (Figure 2) experience a 10-20% annual probability of flooding from SLR and storm surge. The Charles River and areas adjacent to the Charles River have 0.2-1% annual probabilities of flooding (100-500 year return period water surface elevations) in 2070. Along the north bank of the Charles River, annual probabilities of flooding are approximately 0.5% (200-year return period water surface elevation), with an increased annual probability of flooding (2-5%) in the area between the New and Old Charles River dams in the North Point area of Cambridge. The flooded areas adjacent to the Charles River also range between 1-10 feet with much greater spatial variability.

Impacts to Rivers

Another important finding of the BH-FRM results for Cambridge is related to the sensitivity of the SLR and storm surge results to river discharge when the dams are flanked and/or overtopped in the 2070 time frame. This sensitivity was assessed by aligning the 2070 100-year, 24-hour peak river discharge with the peak water surface elevation associated with a 0.2% to 1% annual probability of flooding by 2070. The sensitivity results were measured both in terms of changes in flooding extents, as well as changes in water surface elevation with and without river discharge. The results showed that the flooding extents are relatively insensitive to river discharge because the flood volume from river discharge are relatively small compared to the flood volume from SLR and storm surge flooding due to the dams being flanked and/or overtopped. However, the water surface elevations increased during the combined river discharge and storm surge scenarios as freshwater backed up in the rivers due to the increased tail water caused by the storm surge. For the Charles River, this resulted in increases in the water surface elevations of 3-21 inches, with the greatest increases occurring the furthest distance downstream from the Charles River Dam. For the Amelia Earhart Dam, this consisted of increases in water levels of approximately 3-6 inches near Alewife Brook, but with no significant changes in the downstream portions of the Mystic River. Additional model assumptions and results are presented in the technical memorandum titled “BH-FRM model simulations and assessments to support the CCVA,” prepared by the Woods Hole Group (December 2015).

Impacts to Flooding from Piped Infrastructure

Results from the BH-FRM in combination with results from the ICM-2D model indicate two different flooding mechanisms in the Charles River and the Alewife River basins during SLR/SS events. Although areas of Cambridge in the Charles River Basin are not projected to experience major overbank flooding at the 1% annual probability of flooding from SLR and storm surge by 2070, certain low-lying areas could experience substantial flooding from propagation of flooding through piped infrastructure. On the other hand, areas of Cambridge in the Alewife Brook Basin are likely to be significantly more impacted by overbank flooding of the Alewife Brook from SLR and storm surge. Model runs combining SLR/SS and precipitation resulted in a very significant increase in flood extent and flood depths within the Charles River areas with respect to an “only SLR and storm surge” flooding scenario (i.e., no rain). This indicated that piped infrastructure is very sensitive to increased river water surface elevation increase when it comes to the ability to convey new flows generated by precipitation. Additional details regarding the results of depth of flooding and flood volumes under both the scenarios are presented in the memorandum titled “Drainage infrastructure flood propagation assessment during SLR/SS events with and without concurrent precipitation,” prepared by MWH Global (December 2015).

Next Steps

Finally, the flooding impacts from SLR and storm surge for the City of Cambridge have been determined based on the best available information to date. Several ongoing studies in the greater Boston area are evaluating these impacts at a municipal, regional and state level. Some of these studies include the City of Boston’s Climate Ready Boston initiative (to be completed in June 2016), the Climate Action Plan by the Massachusetts Institute of Technology (October 2015), Vulnerability Assessment Of The Charles River Dam And Amelia Earhart Dam by Department of Conservation and Recreation DCR (to be competed in Spring 2016), the State project funded by Senator Brownsberger on current and future flooding along the Charles and Mystic Rivers (to be completed in Summer 2016), and the Statewide Vulnerability Assessment of Transportation Infrastructure by MassDOT. The City of Cambridge intends to follow the development and findings of these studies during the Preparedness Plan and incorporate the results as appropriate.

For additional details about the SLR/SS projections and scenarios, including methodologies used and results, please refer to the following reports attached to the Executive Summary:

- **Appendix 1: Sea Leve Rise and Storm Surge Maps**, Kleinfelder, Woods Hole Group, MWH Global, 2016
- **Appendix 2: BH-FRM Model Simulations and Assessments to Support the CCVA**, Woods Hole Group, 2016
- **Appendix 3: Drainage Infrastructure Flood Propagation Assessment during SLR/SS Events With and Without Concurrent Precipitation**, MWH Global, 2015

Appendix 1

Sea Level Rise and
Storm Surge Maps

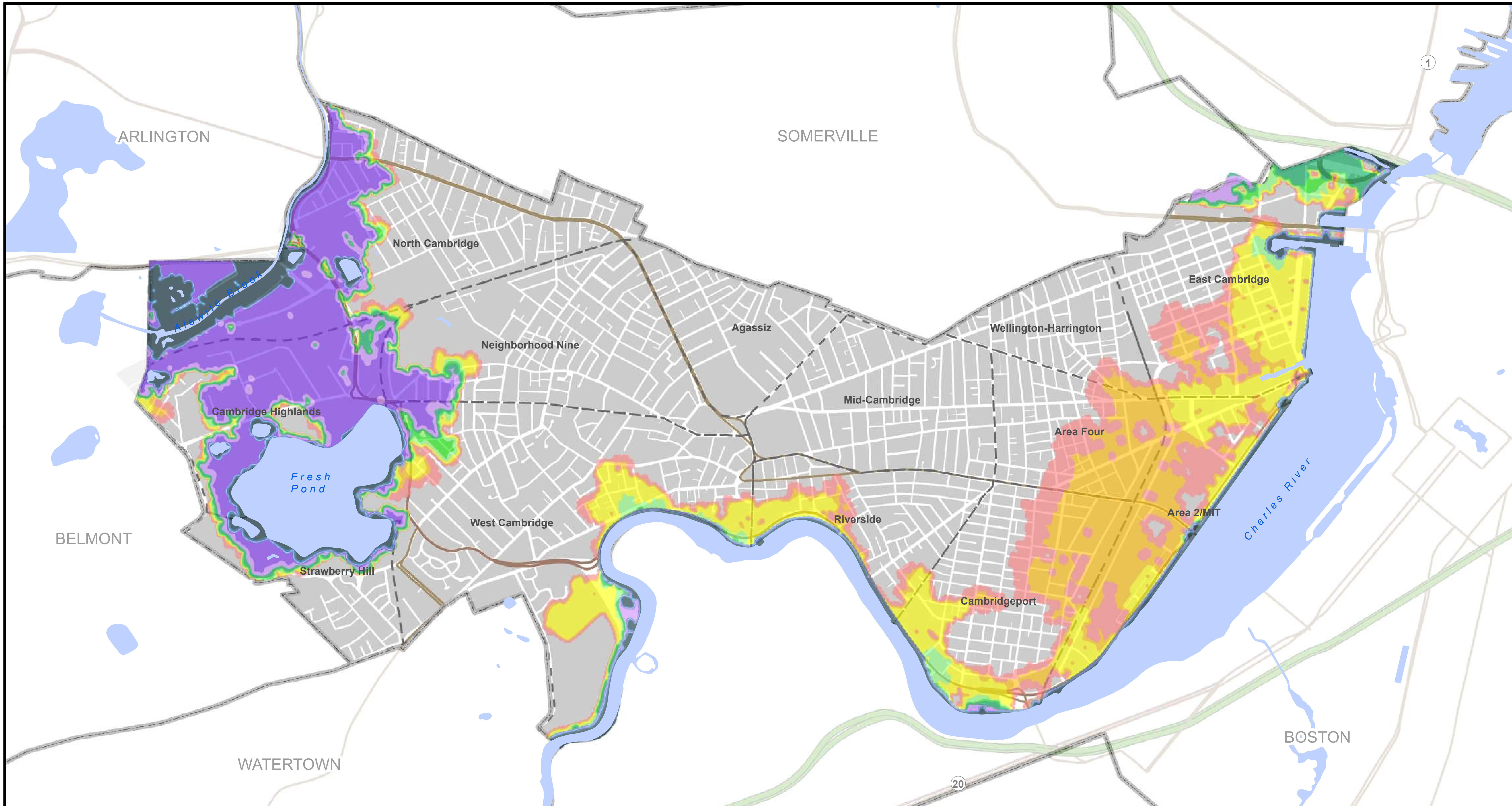
Climate Change Vulnerability Assessment

Part 2 – Sea Level Rise and Storm Surge

City of Cambridge, Massachusetts

February 2017

Disclaimer: The CCVA Part 2 Vulnerability Assessment is based on best available information for sea level rise and storm surge projections at the time the analysis was conducted. Updates will be provided as new information is made available and key findings re-assessed accordingly.



Data sources: City of Cambridge, November 2012; Basemap data from Mass GIS.
Flooding data source: Kleinfelder with SLR/SS overland flooding by Woods Hole Group using BH-FRM and manhole flooding by MHW using ICM-2D, April 2016.

Percent probability of exceedance

Dry	1%	20%	100%
0.1%	2%	25%	
0.2%	5%	30%	
0.5%	10%	50%	

LEGEND

- Water Body
- City of Cambridge Boundary
- Neighborhood Boundary
- Interstate
- US Highway
- State Route

0 1,000 2,000
Feet
Locations are approximate

This information was developed specifically and for the exclusive use for the City of Cambridge's Climate Change Vulnerability Assessment.The materials are not intended to be suitable for re-use on extensions of the project or any other project. Any re-use, without the prior written verification or adaptation by Kleinfelder for the specific purpose intended will be at the user's sole risk without liability or legal exposure to Kleinfelder, ATMOS or the City of Cambridge.

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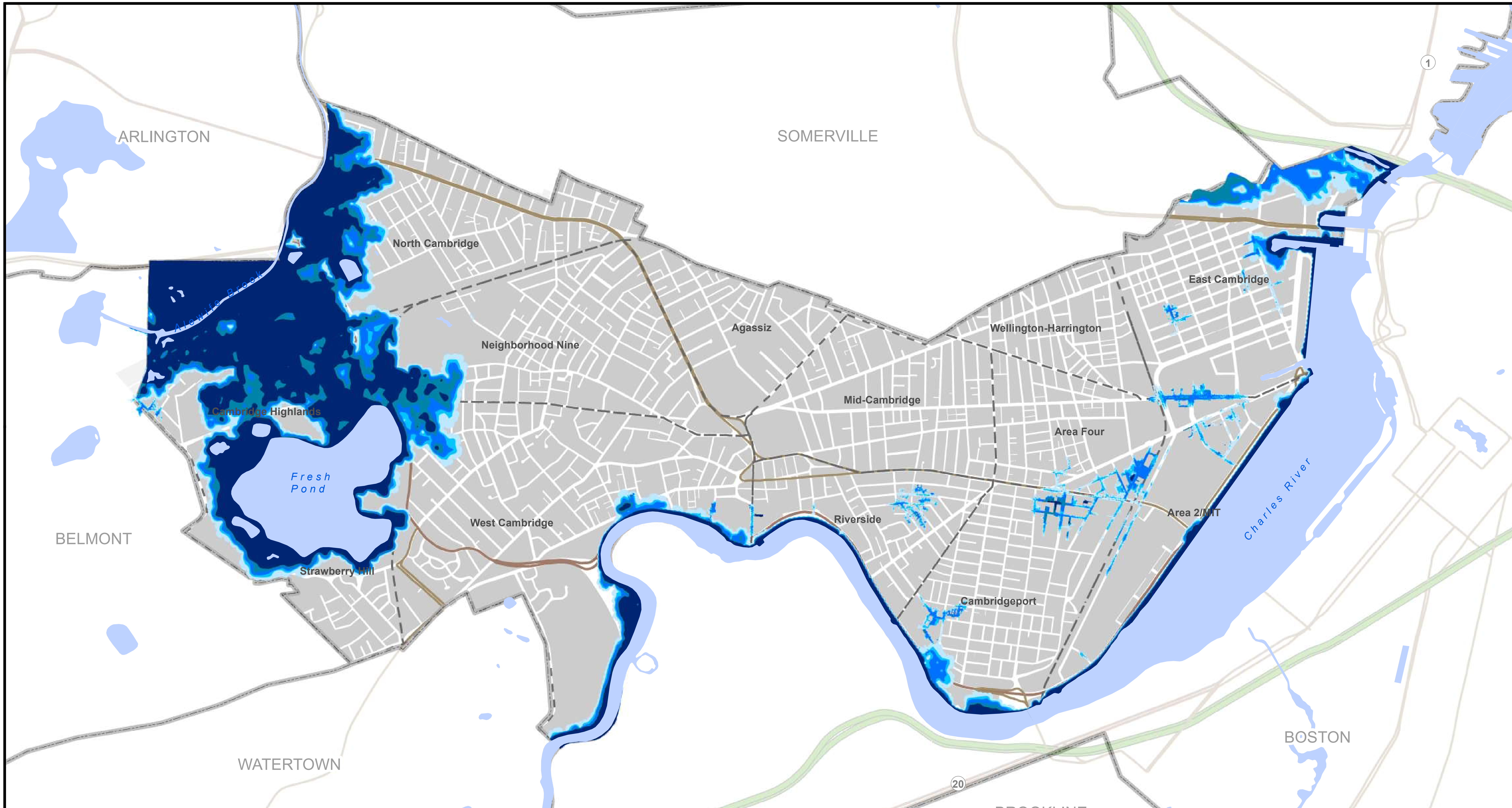
DRAWN BY:	AD
CHECKED BY:	IG
FILE NAME:	

2070 PERCENT PROBABILITY OF SEA LEVEL RISE AND STORM SURGE FLOODING

Climate Change Vulnerability Assessment
Cambridge, Massachusetts

MAP
2



Data sources: City of Cambridge, November 2012; Basemap data from Mass GIS.
Flooding data source: Kleinfelder with SLR/SS overland flooding by Woods Hole Group using BH-FRM and manhole flooding by MHW using ICM-2D, April 2016.

LEGEND

Depth of flooding above ground (ft)

- 0 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- > 3.0

- Water Body
- City of Cambridge Boundary
- Neighborhood Boundary
- Interstate
- US Highway
- State Route

0 1,000 2,000
Feet

Locations are approximate

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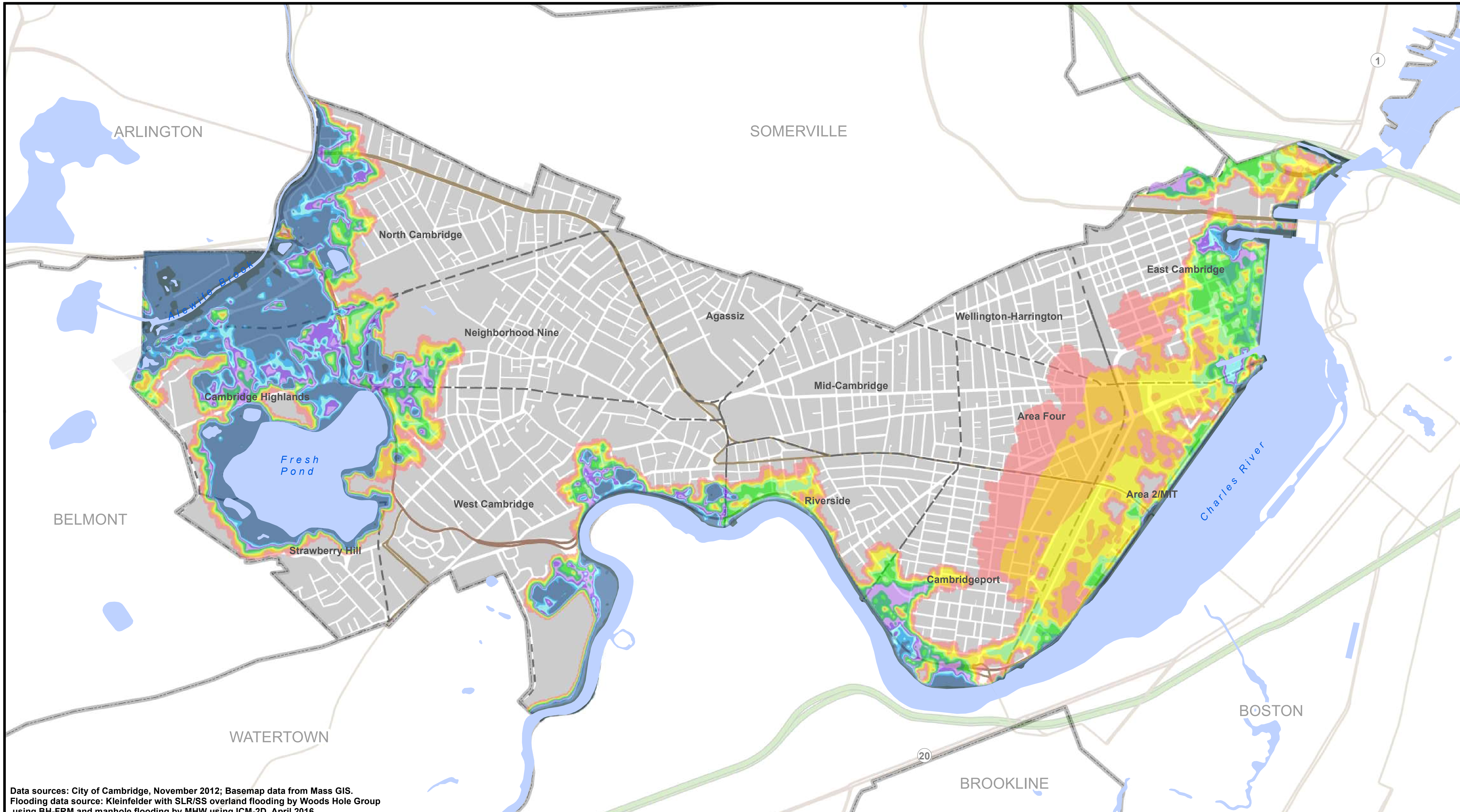
FILE NAME:	

2070 DEPTH OF OVERALL FLOODING FROM SLR AND STOM SURGE AT 1% PROBABILITY + PROPAGATION THROUGH PIPED INFRASTRUCTURE

Climate Change Vulnerability Assessment
Cambridge, Massachusetts

MAP
1



Flooding above ground (ft)

Dry; 0.5 ft; 1 ft; 1.5 ft; 2 ft; 2.5 ft; 3 ft; 3.5 ft; 4 ft; 4.5; 5 ft; 10 ft; > 10 ft

LEGEND

- Water Body
- City of Cambridge Boundary
- Neighborhood Boundary
- Interstate
- US Highway
- State Route

0 1,000 2,000
Feet

Locations are approximate

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FILE NAME:

2070 DEPTH OF FLOODING FROM SEA LEVEL RISE AND STORM SURGE AT 0.1% PROBABILITY

Climate Change Vulnerability Assessment
Cambridge, Massachusetts

MAP
3

Appendix 2

BH-FRM Model Simulations and Assessments to Support the CCVA

Climate Change Vulnerability Assessment

Part 2 – Sea Level Rise and Storm Surge

City of Cambridge, Massachusetts

February 2017

Disclaimer: The CCVA Part 2 Vulnerability Assessment is based on best available information for sea level rise and storm surge projections at the time the analysis was conducted. Updates will be provided as new information is made available and key findings re-assessed accordingly.

TECHNICAL MEMORANDUM

Date: December 9, 2015
To: Kleinfelder, Inc.
From: Woods Hole Group, Inc.
Re: BH-FRM model simulations and assessments to support the CCVA

Introduction

This technical memorandum presents the results from tasks focused on targeted utilization of the Boston Harbor-Flood Risk Model (BH-FRM) to better inform the City of Cambridge's Climate Change Vulnerability Assessment (CCVA). Specifically, the BH-FRM was utilized to simulate specific scenarios to evaluate the combined Sea Level Rise and storm surge impacts on the City of Cambridge, as well as joint probability assessments related to combined increased river (Charles and Mystic) discharges coupled with dam (Charles River Dam [CRD] and Amelia Earhart Dam[AED]) flanking/breaching. The scope of work consisted of three primary tasks geared towards refining the BH-FRM to provide an improved understanding of the probabilities of flooding in the City of Cambridge under projected climate change scenarios. These tasks included:

- Task 1 – Refinement of the upstream river flooding that could occur during dam overtopping/flanking in the Charles River, Mystic River, and Alewife Brook areas. While the existing BH-FRM grid/mesh of the City of Cambridge, Mystic River, and Charles River is already highly refined, the focus of the MassDOT modeling effort was the Central Artery system (Bosma et al., 2015) and the areas in the vicinity of the dams and lower portions of the river. Therefore, limited post-processing and QA/QC was conducted far upstream of the dams (e.g., the Alewife Brook region). So although these upstream areas are in the BH-FRM, the 2070 results in these locations needed to be further post-processed and quality checked to ensure adequate flooding predictions for cases where the dams have been flanked/overtopped.

- Task 2 – Estimation of the time frame for when the dams will be flanked/overtopped at specific probability levels. The dam flanking flood pathways and probabilities, as well as the timing relative to potential dam overtopping was analyzed as part of this task. This task evaluated the time frame of overtopping and flanking relative to various storm probabilities.

- Task 3 – Sensitivity testing of influences of the Charles and Mystic river freshwater discharge. This task used BH-FRM to simulate the water levels in the rivers (Charles and Mystic) upstream of the dams (CRD and AED) with and without river discharge for cases when the dams are flanked/overtopped. This included sensitivity testing for both the CRD and the AED to determine how sensitive the storm surge based flooding results when combined with increased river discharge from precipitation induced flooding.

Results were evaluated to determine the relative importance of river discharge on the flooding in the 2070 timeframe.

TASK 1 – Probability of Flooding and Associated Depths in the City of Cambridge

As presented in the MassDOT report (Bosma et al., 2015), the BH-FRM indicated that both the Charles River Dam and the Amelia Earhart Dam have an insignificant probability of being overtopped or flanked in the 2030 timeframe. Figure 1 presents the inundation probability due to Sea Level Rise and storm surge for the areas surrounding the City of Cambridge in 2030. The Figure shows no flanking or overtopping of the Charles River Dam or Amelia Earhart Dam. However, by 2070, BH-FRM indicated that both dams have the potential to be overtopped and/or flanked under various extreme storm events. As such, the risk of flooding in the City of Cambridge due to combined SLR and storm surge events in the 2030 timeframe is relatively insignificant. This doesn't mean that flooding could not potentially occur due to large precipitation events that cannot adequately drain or due to increased discharge in the Charles River, Alewife Brook, or Mystic River coupled with pump failures at the dams.

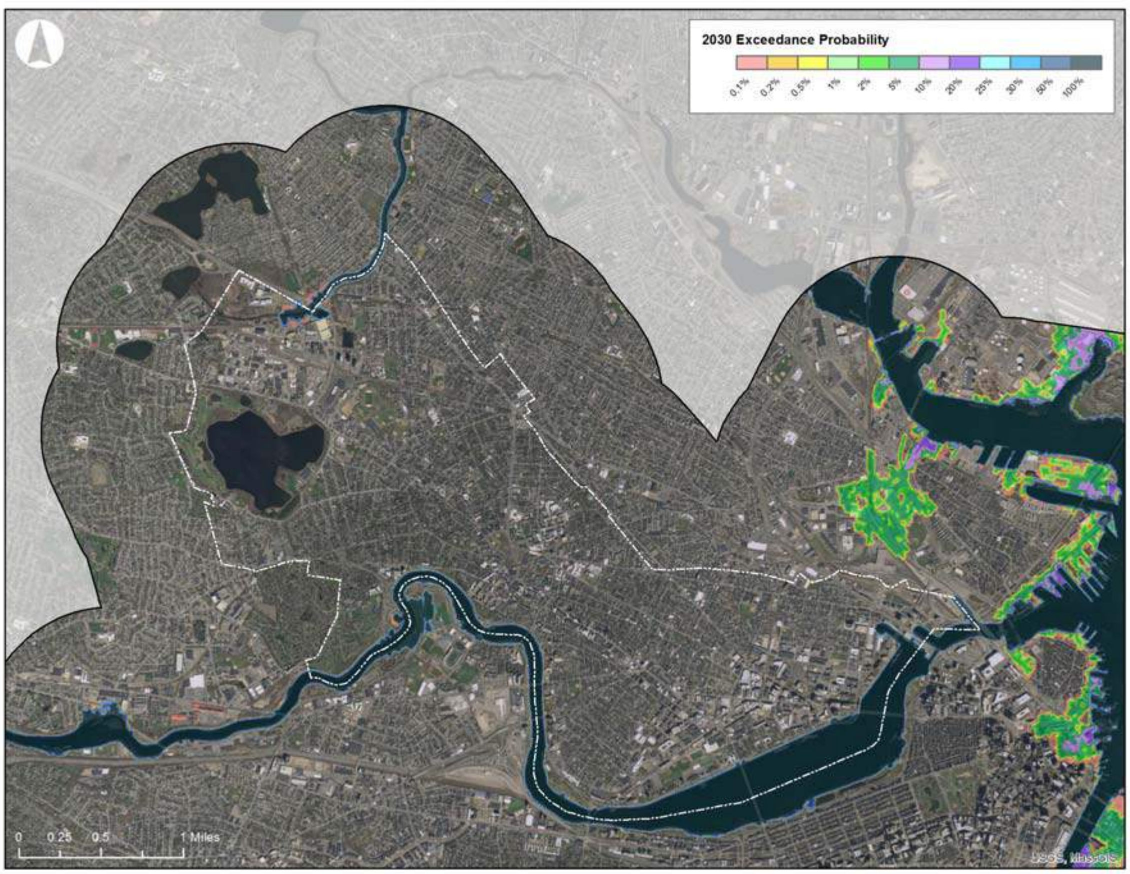


Figure 1. Probability of inundation map for the City of Cambridge and surrounding area in 2030 (from Bosma et al., 2015).

Figure 2 presents an inundation probability of exceedance map for the City of Cambridge, as well as for the surrounding river basins. The color scale corresponds to the probability of occurrence for inundation in the 2070 timeframe. For example, an area shaded in dark purple represents a 20% annual chance of being inundated, or a 5-year return period water surface elevation (expected to occur once every 5 years). Figure 2 indicates that a majority of the areas adjacent to the Mystic River and Alewife Brook have a 10-20% annual flooding probability (5-10 year return period water surface elevations) in 2070, while the areas adjacent to the Charles River have 0.2-1% annual flooding probabilities (100-500 year return period water surface elevations) in 2070. In Cambridge specifically, the upper Ponds adjacent to Alewife Brook are flooded significantly, with most of the area experiencing a 10-20% inundation probability. Along the north bank of the Charles River, flooding probabilities are approximately 0.5% (200-year return period water surface elevation), with an increased probability of flooding (2-5%) in the area between the new and old Charles River dams in the North Point area of Cambridge.

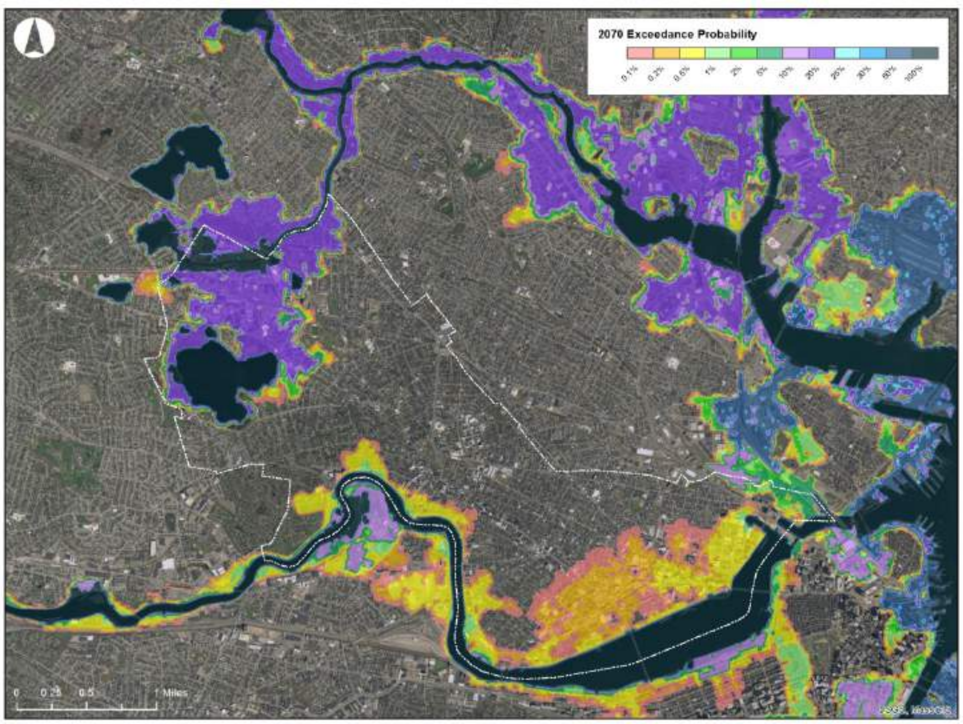


Figure 2. Probability of inundation map for the City of Cambridge and surrounding area in 2070.

Water depths associated with any inundation probability level can also be extracted from the BH-FRM. Figure 3 presents the depth of flooding associated with the 1% annual chance probability (100-yr return period water surface elevation), while Figure 4 presents the depth of flooding associated with the 0.1% (1000-yr return period water surface elevation). Flood depths along the Mystic River and Alewife Brook generally are between 1-10 feet, with the upper Ponds within Cambridge having significant areas of 10 foot depths. The areas adjacent to the Charles River also range between 1-10 feet with much greater spatially variability. However, along the north bank of the Charles River, in Cambridge, depths associated with the 0.1% chance event are less than 3 feet, with the exception of the Longfellow Park area, which experiences depths of up to 10 feet (Figure 4). The results presented herein, with refined focus in the Cambridge areas were also included in the MassDOT report, so they are consistent with those intended for the CCVA.

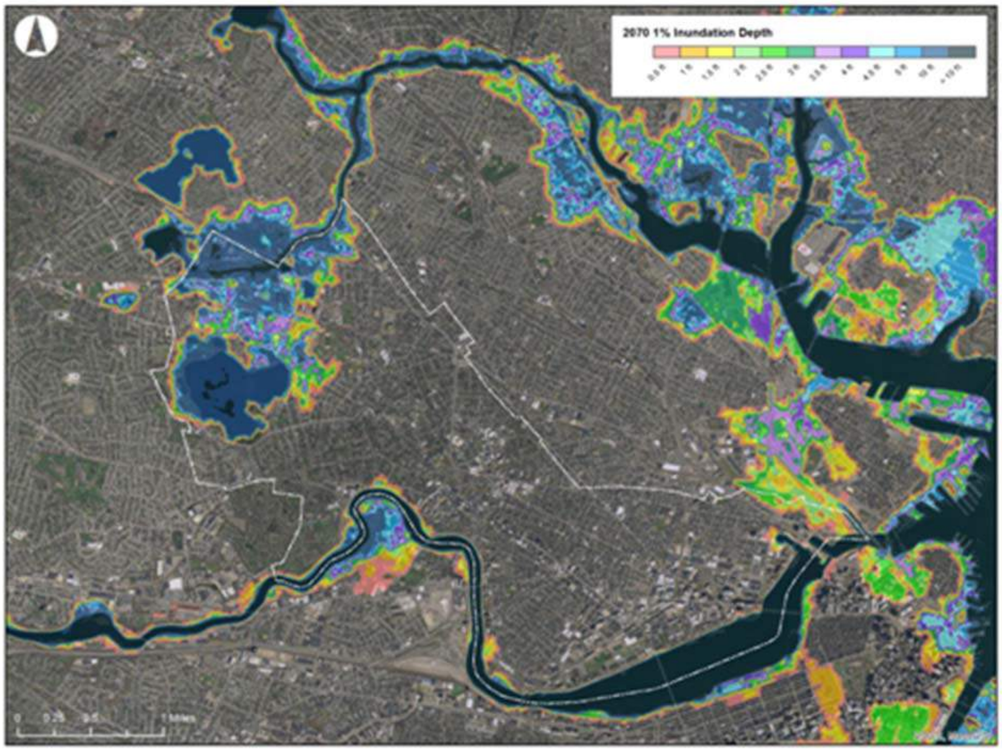


Figure 3. Inundation depths associated with the 1% inundation probability in 2070.

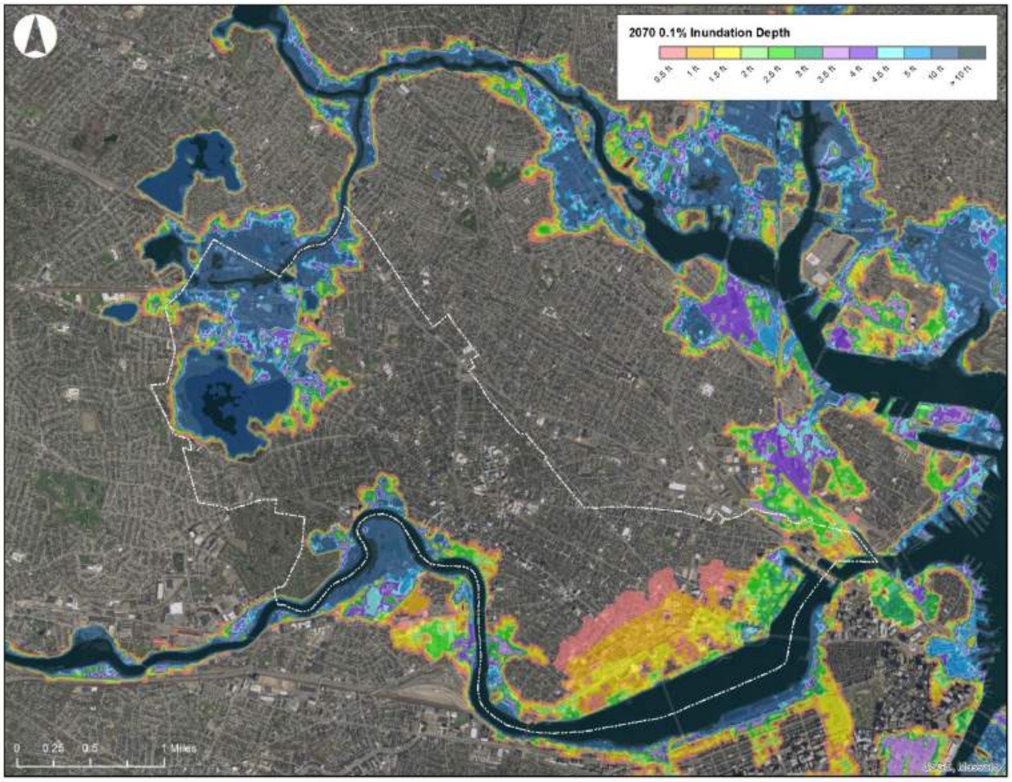


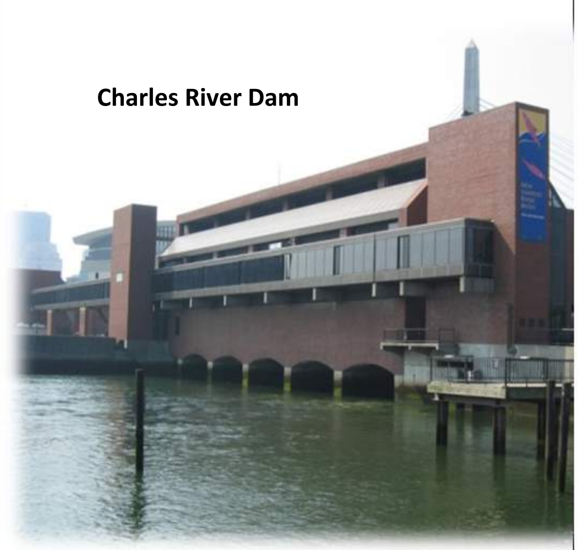
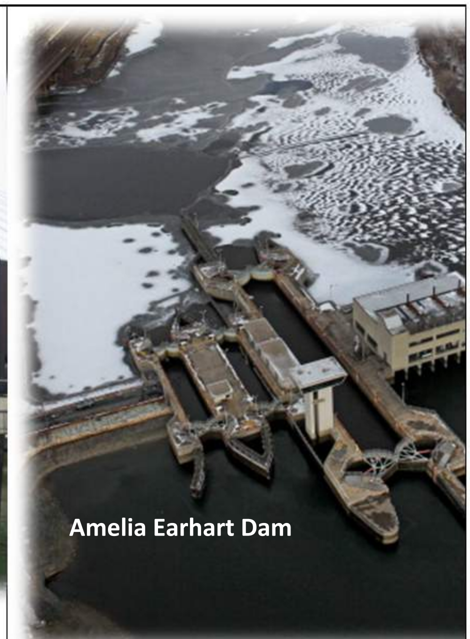
Figure 4. Inundation depths associated with the 0.1% inundation probability in 2070.

TASK 2 – Timing and probability of Dam Flanking/Overtopping

As presented in the MassDOT report (Bosma et al., 2015), the BH-FRM indicated that both the Charles River Dam and the Amelia Earhart Dam have an insignificant probability of being overtopped or flanked in the 2030 timeframe. However, by 2070, BH-FRM indicated that both dams have the potential to be overtopped and/or flanked under various extreme storm events. Therefore, in order to further evaluate the potential flanking and overtopping associated with increased water levels (due to SLR and storm surge) on the downstream side of the Charles River and Amelia Earhart dams, the BH-FRM result for 2030 and 2070 were evaluated in concert with the projected SLR rates to refine the timeframe associated with potential compromises of the dams. Table 1 presents the results of this assessment for both dams and for projected water surface elevation return periods of 100-years (1% annual chance of occurrence) and 500-years (0.2% annual chance of occurrence). Reasonable time ranges for the potential flanking or overtopping of each dam are presented.

Both dams are estimated to be flanked before they are overtopped by approximately 10-15 years, indicating that the local crest elevations and pump systems are more resilient to flood potential than the surrounding landscape. Flanking of the Amelia Earhart dam occurs directly adjacent to the dam, more significantly on the west side of the dam near the Assembly Row area (Figure 2), as well as a larger flood pathway initiated in the Chelsea region. The Charles River dam is flanked directly south of the dam, as well as via a significant flood pathway that initiates from the Mystic River and advances through Somerville and the Sullivan square area (Figure 2). The Amelia Earhart dam is flanked and overtopped before the Charles River dam by approximately 15-20 years.

Table 1. Timing estimates of potential flanking and overtopping of the Charles River and Amelia Earhart dams.

Dam	 *Charles River Dam*		 *Amelia Earhart Dam*	
Flood Probability	**1% (100-yr)**	**0.2% (500-yr)**	**1% (100-yr)**	**0.2% (500-yr)**
Overtopping	2065	2050	2055-2060	2040
Flanking	2055-2060	2045	2045-2050	2030-2035

TASK 3 – Sensitivity of storm surge results to river discharge

The BH-FRM was used to simulate the water levels in the rivers (Charles and Mystic) upstream of the dams (CRD and AED) with and without river discharge for cases when the dams are flanked/overtopped (2070 timeframe). As such, the increased influence of the river discharge combined with the upriver propagating storm surge was examined. Coastal storms that were simulated represented events that produced water surface elevations high enough to flank and/or overtop the dam and produced water surface elevation levels associated with a 0.2 to 1% probability. All results used site-specific river discharge associated with a 24-hour 100-year event under 2070 climate conditions as fully explained in Bosma et al. (2015). This discharge represents the water that arrives to the rivers from the watershed. As a conservative assumption, the peak discharge was aligned with the peak of the storm surge to create the greatest water interaction, although in reality the concurrence of these two conditions would be rare. Using this approach, the sensitivity of the flooding water surface elevations and extents to a combined discharge and storm surge occurrence could be evaluated. Results were evaluated for the

Charles River, as well as the Mystic River and Alewife Brook area. It should be noted that these results do not include the influence of (1) precipitation falling directly on the Cambridge area that may have a difficult time draining, or (2) any backup of underground piped infrastructure that may occur due to elevated water levels at outfall locations.

Figure 5 presents the results of the comparison for the Charles River. The darker shaded blue-green area represents the extent of flooding for a storm surge with normal river discharge conditions (average daily flow). The lighter shaded blue-green represents the extent of flooding for a storm surge with increased river discharge (24-hour, 100-year precipitation event by 2070). Similarly, Figure 6 represents the increase in water surface elevations throughout the Charles River region when considering the combined precipitation induced discharge and storm surge scenario compared to the surge only scenario. The color scale in Figure 6 represents a distribution of this increase in water surface elevation (in inches) due to the combined discharge and surge scenario. Cooler colors (blues and greens) represent smaller increases in water surface elevation, while hotter colors (yellows and reds) represent larger increases in water surface elevation between the combined discharge and storm surge scenario compared to the surge only scenario.

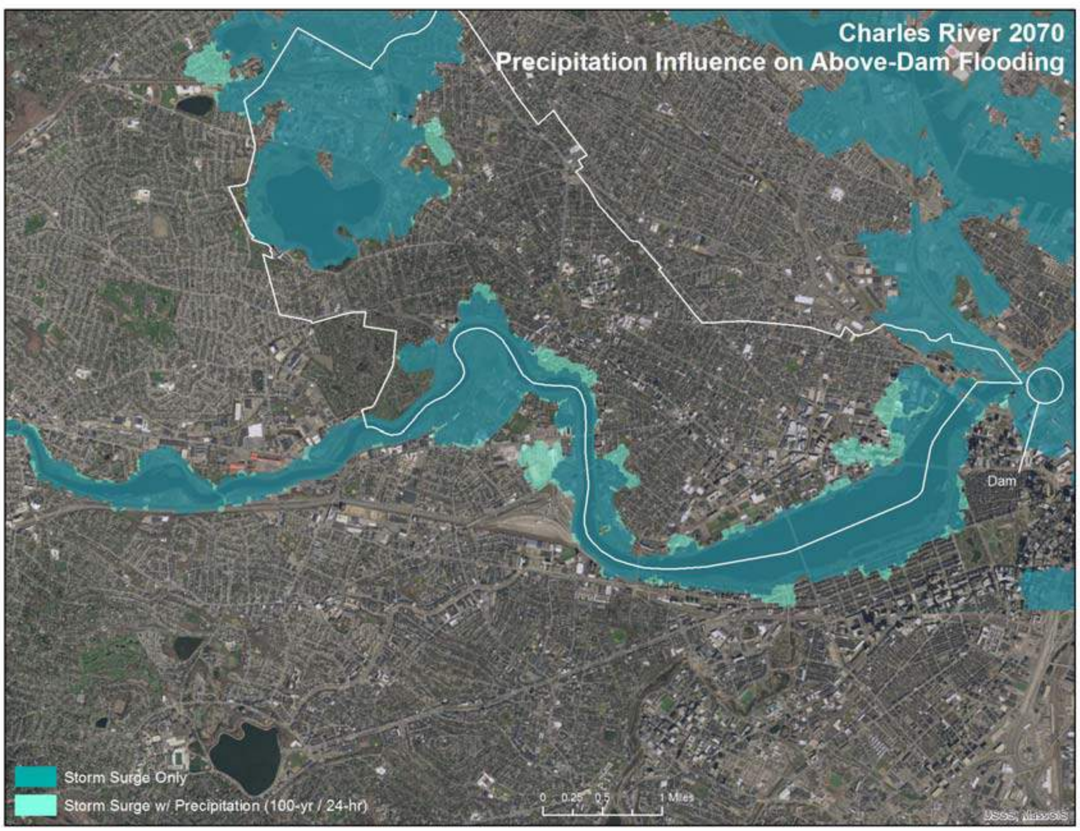


Figure 5. Increases in flooding extent due to a combined discharge (100 year-24 hour storm by 2070) and storm surge conditions in 2070 compared to a storm surge only condition in 2070 for the Charles River area.

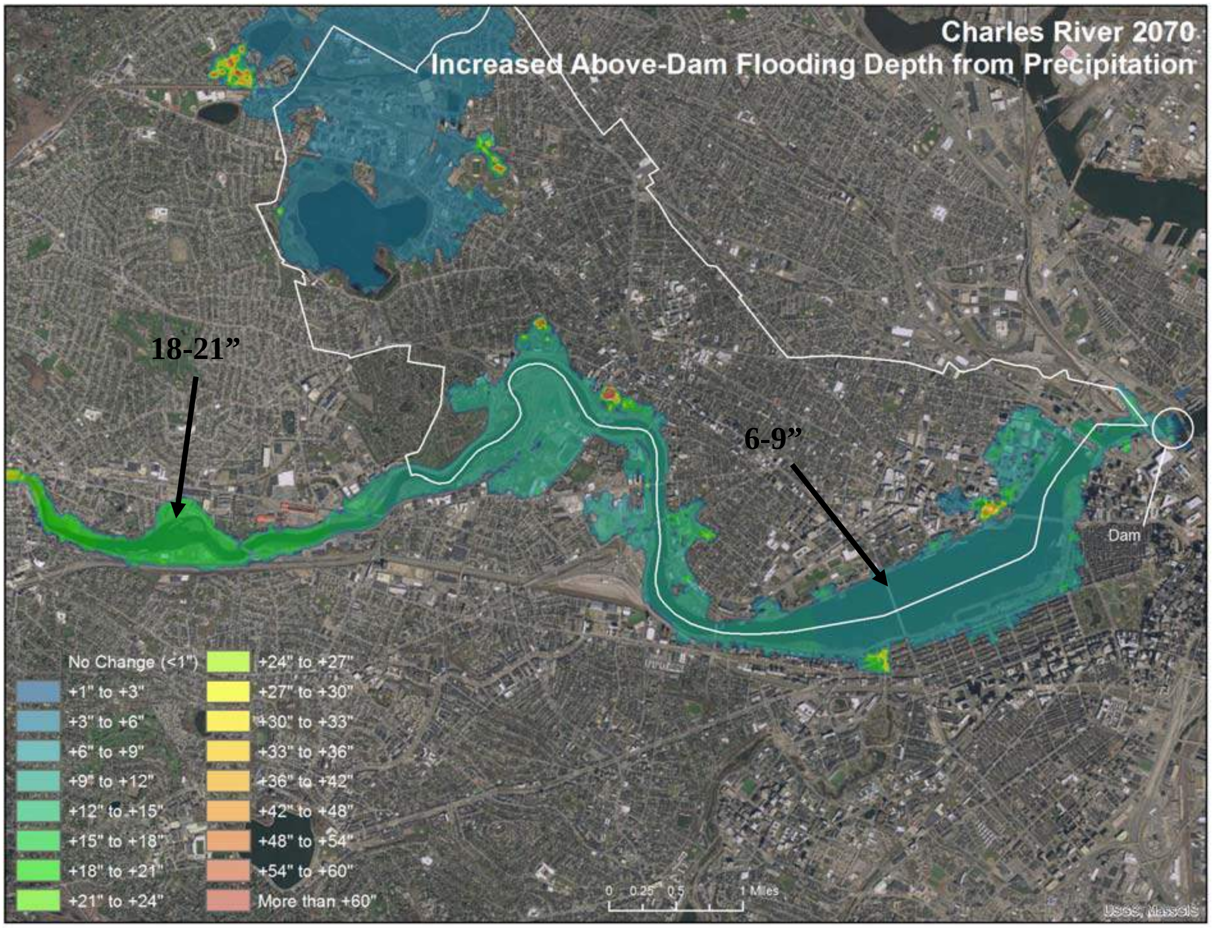


Figure 6. Increases in water depths due to a combined discharge (100 year 24-hour storm by 2070) and storm surge conditions in 2070 compared to a storm surge only condition in 2070 for the Charles River area.

The figures indicate that there are only minor expansions to the flooding in the City of Cambridge due to the joint discharge and surge when compared to surge only, and in general these expanded areas only represent 1-3” in depth (Figure 6). While the expansion of the flood area is relatively minor due to the dominance of the overall volume of water that arrives from the ocean during a storm surge event, the combination of the two conditions does result in a back up of water in the Charles River. The freshwater discharge is not able to flow downstream as easily due to the increased tail water conditions caused by the storm surge. This produced increases in water levels in the areas just downstream of the Watertown Dam of 18-21 inches in the Charles River. These increased depths were reduced proceeding downstream with water levels in the upper pool of the lower Charles River Basin between the Massachusetts Avenue Bridge and the Longfellow Bridge increasing by 6-9 inches, and by only a few inches in the vicinity of the Charles River dam. These increased water levels in the river itself, while not significantly increasing the extent of overland flooding (Figure 5), may have an impact on the ability of water to drain through the piped infrastructure due to increased tail water at outfall locations.

Figure 7 and 8 present similar flooding extent and changes in depths, respectively, for the Mystic River and Alewife Brook region. The increases in the extent of flooding in the City are mostly insignificant, except for a small expansion to the northeast of Fresh Pond that is flooded only under the combined discharge and storm surge scenario (Figure 7). The increases in water surface elevation for the combined discharge and storm surge conditions are also minor (Figure 8), primarily due to the smaller discharge and watershed associated with the Mystic River system. Much of the downstream portion of Alewife Brook does not experience any significant increases, while the depths in the vicinity of Alewife Brook increases 3-6 inches due to the combined discharge and surge conditions.

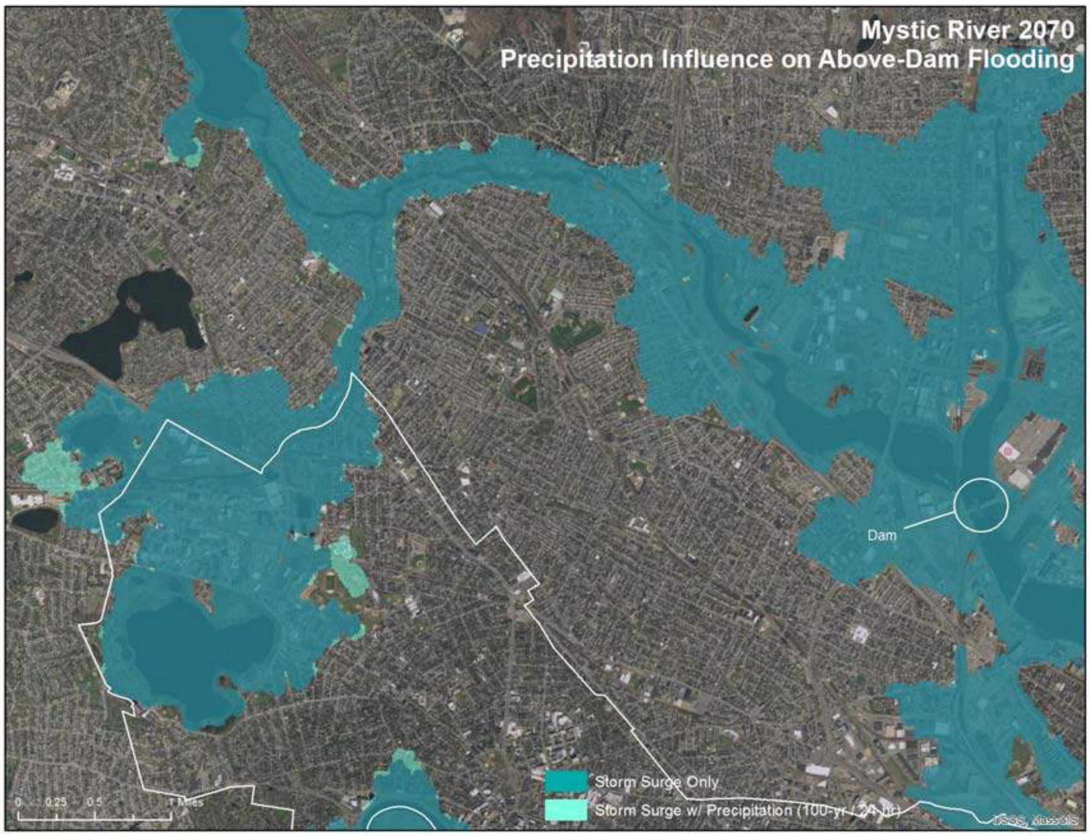


Figure 7. Increases in flooding extent due to a combined discharge (100 year 24 hours storm by 2070) and storm surge conditions in 2070 compared to a storm surge only condition in 2070 for the Mystic River and Alewife Brook area.

Since the Amelia Earhart dam is overtopped and flanked for higher probability and less extreme events than the Charles River Dam in 2070. Therefore, additional simulations were conducted that evaluated the combination of increased discharge with smaller, more frequent storm surge conditions. Specifically, 5-10 year (10-20% probability) events were considered with and without the 24-hour, 100-year discharge conditions to determine if smaller, potentially less dominating surge event would results in increased sensitivity to the discharge. Figure 9 presents the increased depths throughout the Mystic River region when considering the combined discharge and storm surge scenario compared to the surge only scenario using a smaller surge that compromises the Amelia Earhart dam. The results indicated that there remains no significant increase in flooded extent, and the reduced storm surge elevation lessens the level of backup in the upstream portions of the piped infrastructure system that drains to Alewife Brook compared to the larger storm surge scenario. For example, Alewife Brook only increases by an elevation of 1-3 inches under this combined scenario.

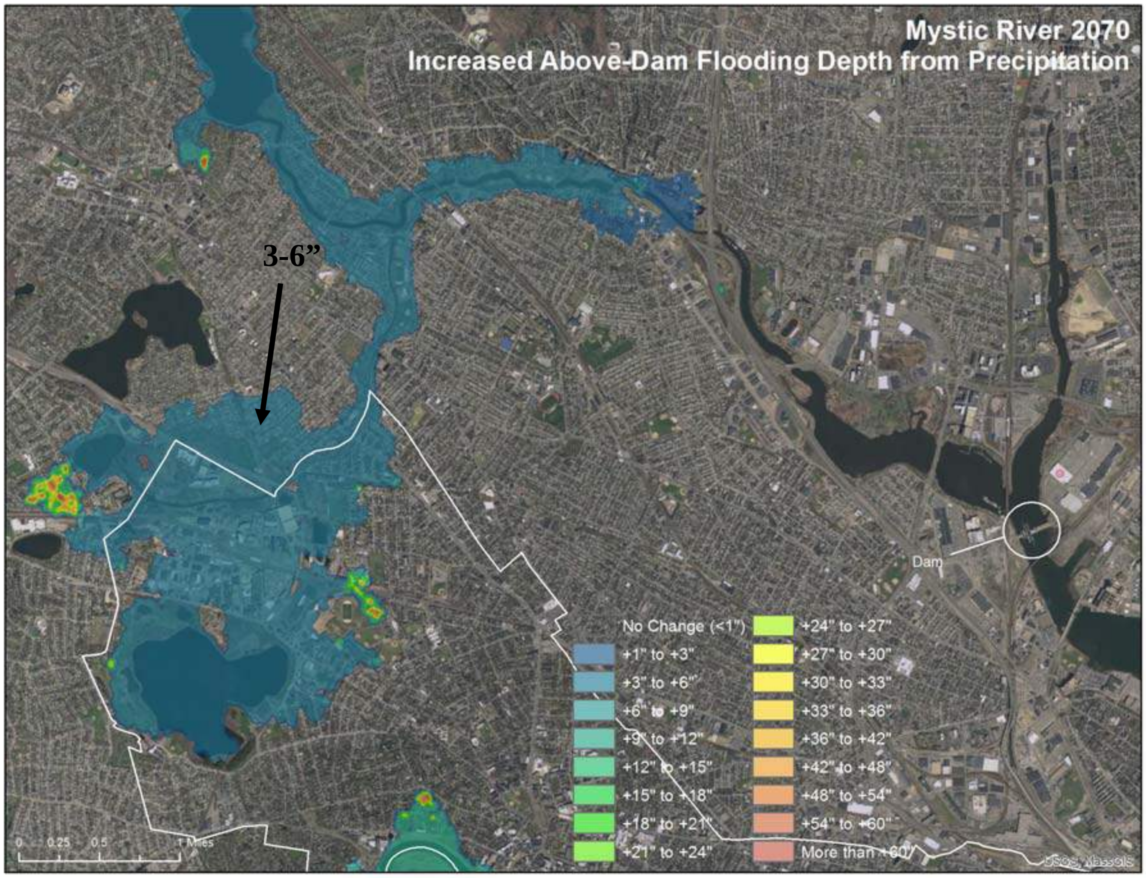


Figure 8. Increases in water depths due to a combined discharge (100 year 24 hour storm by 2070) and storm surge conditions in 2070 compared to a storm surge only condition in 2070 for the Mystic River and Alewife Brook area.

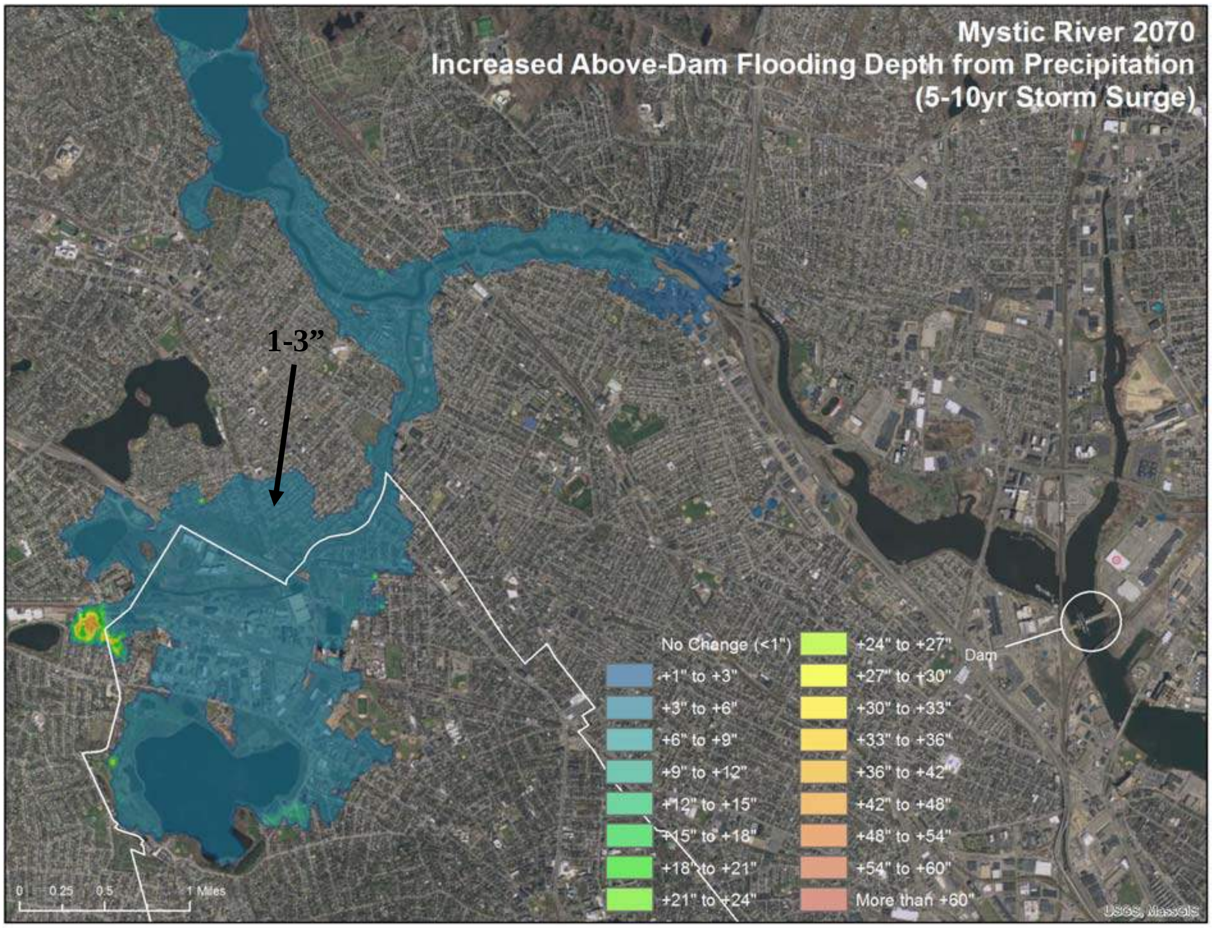


Figure 9. Increases in water depths due to a combined discharge (100 year 24 hour storm by 2070) and storm surge conditions in 2070 compared to a storm surge only condition in 2070 for the Mystic River and Alewife Brook area.

Summary and Key Findings

- In the 2030 timeframe and associated climate, there is an insignificant probability that the Charles River dam or Amelia Earhart dam is flanked or overtopped.

- The Amelia Earhart dam is flanked and overtopped by potential storm surge events approximately 15-20 years sooner than the Charles River dam. Both the Charles River dam and Amelia Earhart dam are flanked before they are overtopped and significant regional flood pathways develop that flank the dams through Somerville and Sullivan Square (flanking of the Charles River dam to the north), and through Chelsea (flanking of the Amelia Earhart dam to the north).

- The Charles River dam is flanked as soon as 2045 by a 500-year water surface elevation and by 2055-2060 by a 100-year water surface elevation. The Amelia Earhart dam is flanked as soon as 2030-2035 by a 500-year water surface elevation and by 2045-2050 by a 100-year water surface elevation.

- The Charles River dam is overtopped by 2050 by a 500-year water surface elevation and by 2065 by a 100-year water surface elevation. The Amelia Earhart dam is overtopped by 2040 by a 500-year water surface elevation and by 2055-2060 by a 100-year water surface elevation.

- In Cambridge under the 2070 climate conditions, the upper Ponds adjacent to Alewife Brook are flooded significantly, with most of the area experiencing a 10-20% inundation probability. Along the north bank of the Charles River, flooding probabilities are approximately 0.5% (200-year return period water surface elevation), with an increased probability of flooding (2-5%) in the area between the new and old Charles River dams in the North point area of Cambridge.

- Under 2070 climate conditions, food depths along the Mystic River and Alewife Brook generally are between 1-10 feet, with the upper Ponds within Cambridge having significant areas of 10 foot depths. The areas adjacent to the Charles River also range between 1-10 feet with much greater spatial variability. In Cambridge, along the north bank of the Charles River, depths of flooding above ground associated with the 0.1% chance event are less than 3 feet, with the exception of the Longfellow Park area, which experiences depths of up to 10 feet.

- Flooding extents are relatively insensitive to the river discharge, meaning adding a significant river discharge (e.g., associated with a 100-yr, 24-hr precipitation by 2070) does not substantially increase the flooding extent compared to the storm surge only condition. This is primarily due to the significant volume of water flanking/overtopping the dam in these scenarios. The freshwater river discharge volume is relatively small compared to the storm surge ocean volume. While there were minor areas where the spatial extent of flooding was increased; however, these areas were relatively limited and typically consisted of shallow depths. These results were consistent for various storm surge occurrences that overtop and/or flank the dams. For example, a 100-year to 200-year storm surge water surface elevation, and a 5-year to 10-year storm surge water surface elevation that overtopped/flanked the Amelia Earhart dam were both relatively insensitive to the discharge of the Mystic River.

- While the extent of spatial flooding was not substantially increased due to combining storm discharges with storm surge, the water surface elevation in the rivers themselves were increased. Water surface elevations increased during the combined discharge and storm surge scenarios as freshwater backed up in the rivers due to the increased tail water caused by the storm surge. For the Charles River, this resulted in increases in the water surface elevations of 3-21 inches, with the greatest increases occurring the furthest distance from the CRD. For the AED, this consisted of increases in water levels of approximately 3-6 inches in the vicinity of Alewife Brook, but with no significant changes in the downstream portions of the Mystic River.

References

Bosma, K, E.Douglas, P Kirshen, K.McArthur, S.Miller, and C.Watson, 2015. *MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery*. Falmouth, MA, Woods Hole Group, Inc.

Appendix 3

Drainage Infrastructure Propagation Assessment during SLR/SS Events With and Without Concurrent Precipitation

Climate Change Vulnerability Assessment

Part 2 – Sea Level Rise and Storm Surge

City of Cambridge, Massachusetts

February 2017

Disclaimer: The CCVA Part 2 Vulnerability Assessment is based on best available information for sea level rise and storm surge projections at the time the analysis was conducted. Updates will be provided as new information is made available and key findings re-assessed accordingly.

TO: Kleinfelder
ORIGINAL ISSUE DATE: December 22, 2015
REVISED ISSUE DATE: April 19, 2016
FROM: David Bedoya, William C. Pisano, MWH
RE: Drainage infrastructure flood propagation assessment during SLR/SS events with and without concurrent precipitation

Introduction

This memorandum presents key findings of a flood risk sensitivity analysis for the Alewife and Lower Charles River basins. This analysis evaluated flood risk generated in drainage infrastructure due to increased river water surface elevations (WSE) caused by flanking and/or overtopping of the New Charles River Dam (CRD) or the Amelia Earhart Dam (AED) under predicted sea level rise and storm surge (SLR/SS) conditions. According to the Boston Harbor-Flood Risk Model (BH-FRM) results reported in the MassDOT's climate change vulnerability assessment of the central artery(Bosma et al., 2015) and used for the Cambridge Climate Change Vulnerability Assessment (CCVA), both the CRD and the AED are at significant risk of being breached between 2045 and 2050 (AED) or between 2055 and 2060 (CRD). Forecasted peak river WSE in the Lower Charles River and the Alewife Brook are 21.1 ft-CCB and 23.41ft-CCB, respectively for the 1% probability SLR/SS event (no rain) in the 2070 time horizon. To put these WSE in prospective, forecasted peak levels generated by the 100-year, 24-hour storm event for the same time horizon and without SLR/SS influence are 14.8ft-CCB and 19.8ft-CCB for the Lower Charles River and the Alewife Brook, respectively.

Modeled Scenarios

Due to the forecasted increase in river WSE, the City of Cambridge proceeded with an evaluation of flood risk caused by pipe flow propagation for SLR/SS scenarios capable of breaching the dams. This assessment was performed with and without concurrent precipitation using the Infoworks ICM model. The 1% probability SLR/SS event for the 2070 time horizon as generated by the BH-FRM was used for this analysis. Modeled scenarios are described below:

1. **Model runs with SLR/SS without precipitation:** The goal of this scenario was to compare (a) the extent and depth of flooding propagated inland via piped infrastructure during the 1% probability SLR/SS event with no precipitation in the 2070 time horizon with (b) the extent of flooding in precipitation-only scenarios reported in the memorandum "*Infoworks ICM Modeling of the Alewife Brook and Charles River Systems in Cambridge, MA*" of September 2014 supporting Cambridge's CCVA.

2. **Model runs with SLR/SS with concurrent precipitation:** The goal of this model runs was to compare (a) the extent and depth of flooding generated by a 10-year, 24-hour rainfall combined with a 1% probability SLR/SS event in 2070 with (b) the extent of flooding generated by the 2070, 1% probability SLR/SS event (no rain) and the precipitation-only (no SLR/SS) scenarios.

In both cases, it was assumed that the dams were operating in the same conditions assumed in the precipitation-only scenarios (i.e. 3 and 6 operational pumps at the AED and the CRD, respectively). It is important to note that the precipitation-only scenarios described in the memorandum "*Infoworks ICM Modeling of the Alewife Brook and Charles River Systems in Cambridge, MA*" of September 2014 assumed no breaching of the dams. Conversely, for both scenarios described above, the dams were flanked and overtopped per results from the BH-FRM.

For both scenarios, dynamic river WSE curves with a duration of 12.5 hours were provided for all Charles River outfalls and the Prison Point pump outlet by the Woods Hole Group (WHG), who developed the BH-FRM. An example of one of these curves is depicted in Figure 1 (left side). For the Alewife Brook outfalls, only peak WSE were provided by the WHG.

For scenario 1, the river WSE were input into the Infoworks ICM model as outfall boundary conditions and the model was run with no rainfall for 12.5 hours (red line in Figure 1). The duration of these runs captured the peak WSE in the Charles River outfalls, which occurs at 10.5 to 11 hours from the beginning of the SLR/SS event (Figure 1). Table 1 presents a comparison of peak WSE in selected outfalls of the Alewife Brook (CAM004 outfall) and the Charles River (Western Avenue outfall) for precipitation-only scenarios and the 1% probability SLR/SS event (no rain) in 2070.

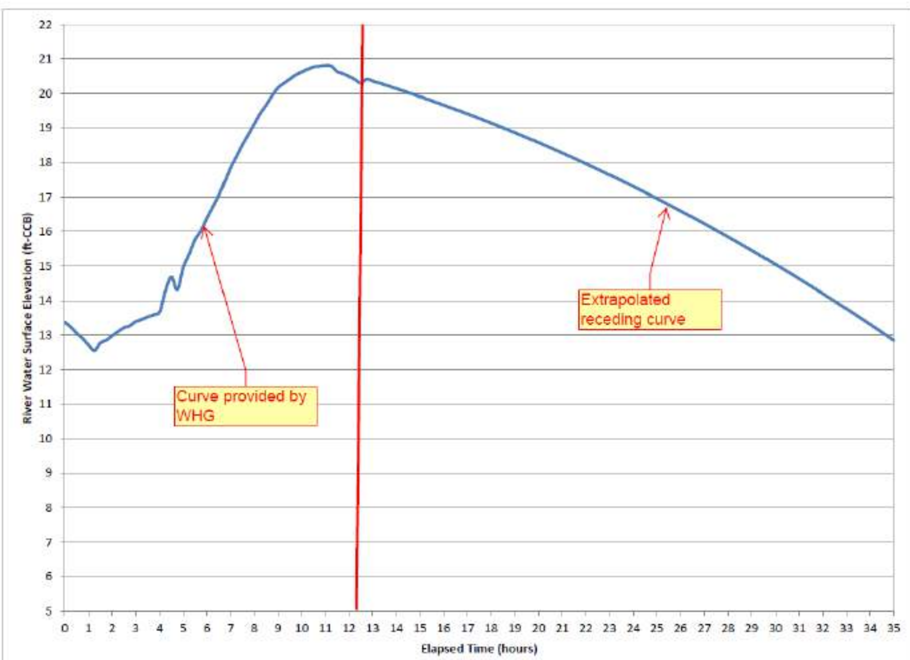


Figure 1. Example of a WSE curve used in the SLR/SS analysis for one of the Charles River outfalls

Scenario 2 was run with the same outfall boundary conditions as scenario 1 but the simulation included concurrent precipitation as well (10-year, 24-hour rainfall forecasted for year 2070). For this scenario, the following assumptions were made:

1. Duration of the WSE curves: Since the design rainfall event had a total duration of 24 hours and the provided WSE curves for the Charles River basin only lasted 12.5 hours, the WSE curves were expanded assuming that the WSE recession time was 24 hours after the peak, which occurred at approximately 11 hours. A quadratic, polynomial fit was used to compute the outfalls' receding WSE curves as shown in Figure 1.

2. Concurrence of WSE and precipitation peaks: It was assumed that the peak WSE occurred one hour before the peak rainfall intensity to reflect a potential worst case scenario. The reason why the peak rainfall was delayed one hour with regards to the peak WSE was to allow enough travel time of backflows from the river to the most upstream system points via conveyance conduits. Therefore, once the peak rainfall intensity occurs at 12 hours, the conveyance conduits have the smallest possible available capacity.

Table 1. Peak WSE in the Charles River and Alewife Brook basins per scenario

Scenario	Time Horizon (year)	Charles River peak WSE at Western Avenue outfall (ft-CCB)	Alewife Brook peak WSE at CAM004 outfall (ft-CCB)
100y, 24hr precipitation only	Present	14.3	17.1
	2030	14.5	18.2
	2070	14.8	19.8
10y, 24hr precipitation only	Present	13.6	13.9
	2030	13.8	14.4
	2070	14.0	14.9
1% Probability SLR/SS (no rain)	2070	20.8	23.4

Model Results

Scenario 1: 2070, 1% probability SLR/SS event with no precipitation

Charles River and Alewife Brook areas flood extent and flood depth maps are provided in Figures 2 to 4. Flood volumes per reporting area are provided in Table 2.

Scenario 2: 2070, 1% probability SLR/SS event with concurrent precipitation (10yr, 24hr storm)

Charles River and Alewife Brook areas flood extent and flood depth maps are provided in Figures 5 to 7. Flood volumes per reporting area are provided in Table 2.

Table 2. Flood manhole volumes (in MG) for SLR/SS scenarios and precipitation-only scenarios

	Precipitation-only scenarios						SLR/SS scenarios	
	10-year, 24-hour			100-year, 24-hour			1% SLR/SS with 10y, 24hr precip.	1% SLR/SS w/o precip.
	Time Horizon							
System Area	Present	2030	2070	Present	2030	2070	2070	2070
Area 13+ De Wolfe St	0.00	0.01	0.25	6.06	11.78	19.49	0.34	0.02
Harvard Sq. + CAM005/ CAM007/ Sparks St	0.08	0.32	1.32	6.39	10.14	15.33	4.03	1.47
Western Ave + Flagg St	0.00	0.00	0.03	1.11	2.26	3.95	3.03	1.07
CAM017+ Ames Wadsworth	2.19	4.42	8.33	25.31	34.50	46.23	45.46	6.68
Broad Canal System	0.31	0.84	1.53	4.16	5.66	7.44	3.63	1.73
Cambridgeport	1.56	2.76	4.46	12.24	16.87	22.46	17.05	5.66
Lechmere Canal drain system	0.31	0.84	1.53	4.17	5.66	7.44	4.00	1.87
Golf Couse + May Street	1.85	2.89	4.50	9.27	11.70	14.88	12.53	4.41
CAM004	3.48	4.60	5.85	11.13	14.87	23.74	28.80	14.61
401A/B	0.61	0.95	1.36	3.17	5.57	7.59	2.28	0.02
CAM400	0.00	0.00	0.00	0.18	0.32	0.43	0.95	0.65
CAM002	0.01	0.06	0.17	0.85	1.24	1.77	0.66	0.26
CAM001	0.15	0.35	0.49	0.90	1.07	1.30	1.45	0.19

Conclusions

<u>SLR/SS events with no precipitation:</u>

Results from the BH-FRM in combination with results from Infoworks ICM make it clear that the Charles River and the Alewife River basins have different flood mechanisms during SLR/SS events. The Cambridge side of the Lower Charles River is not expected to experience major overbank flooding at the 1% probability in the 2070 time horizon as reported in the "*BH-FRM model simulations and assessments to support the CCVA"* Technical Memorandum of December 2015. However, during this event, the substantial increase in peak river WSE due to breaching of the CRD causes substantial inland flooding in upstream, low-lying areas due to propagation of the flood wave through piped infrastructure. The Western Avenue and Flagg Street catchments, Broadway, Green Street, parts of Lechmere, Pleasant Street, and Albany at Portland streets seem to be the most vulnerable to SLR/SS events as shown in Figures 2 and 3. This type of flooding could potentially be prevented by installing flap valves or any means of backflow prevention at stormwater outfalls.

On the other hand, SLR/SS-included flooding in the Alewife is mostly driven by overbank flooding as the extent of flooding provided in the BH-FRM maps for this area encompass most of the flood extent generated by pipe flood propagation shown in Figure 4.

<u>SLR/SS combined with concurrent precipitation events:</u>

Model runs combining SLR/SS and precipitation resulted in a very significant increase in flood extent and flood depths within the Charles River areas with respect to the SLR/SS, no rain events (compare Figures 2 and 3 versus Figures 5 and 6). This is also true when compared to the previously provided, precipitation-only flood maps in the Cambridge CCVA for the same precipitation design event (i.e. 10-year, 24-hour, 2070 storm). Therefore, it appears that piped infrastructure is highly sensitive to increased river WSE when it comes to the ability to convey new flows generated by precipitation. In some areas, the flood extent and flood volumes for the 1% probability SLR/SS event combined with the 10-year, 24-hour storm event in 2070 is roughly equivalent to the precipitation-only 100-year, 24-hour rainfall event in 2030 (Western Avenue and Cambridgeport) or 2070 time horizon (CAM017) (Table 2).

Similar to the SLR/SS events without precipitation, the City could benefit from the installation of backflow preventers in its stormwater outfalls to (1) prevent backflows from the river due to increased WSE and (2) maximize storage capacity in its conveyance conduits before the rain event affects the area.

References

Bosma, K., Douglas, E., Kirshen, P., McArthur, K., Miller, S., Watson, C. (2015). *MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery.* Falmouth, MA, Woods Hole Group, Inc.

Figure 2. Charles River Northern Tributary Catchments

2070, 1% Probability SLR/SS event without precipitation

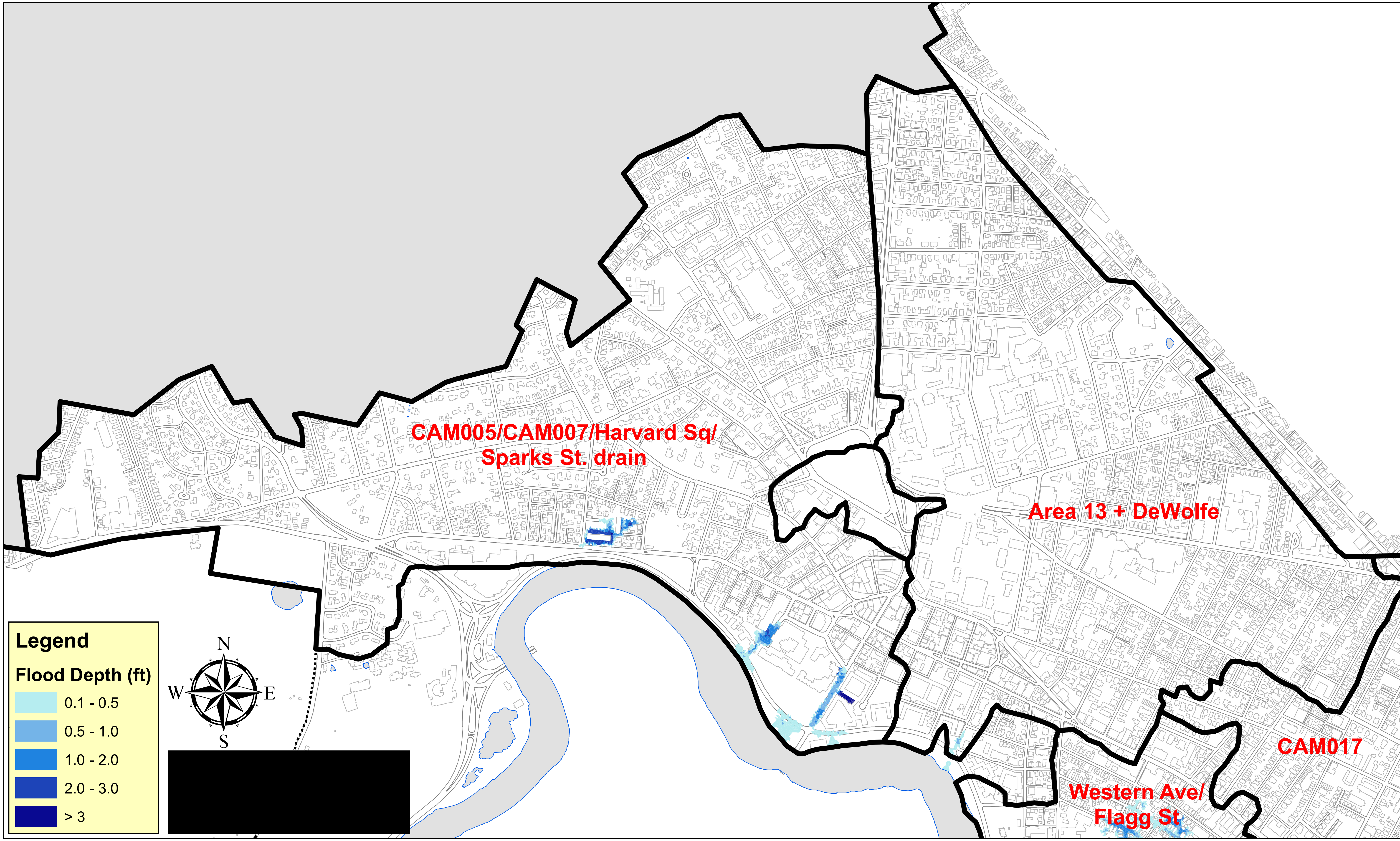


Figure 3. Charles River Southern Tributary Catchments

2070, 1% probability SLR/SS event without precipitation

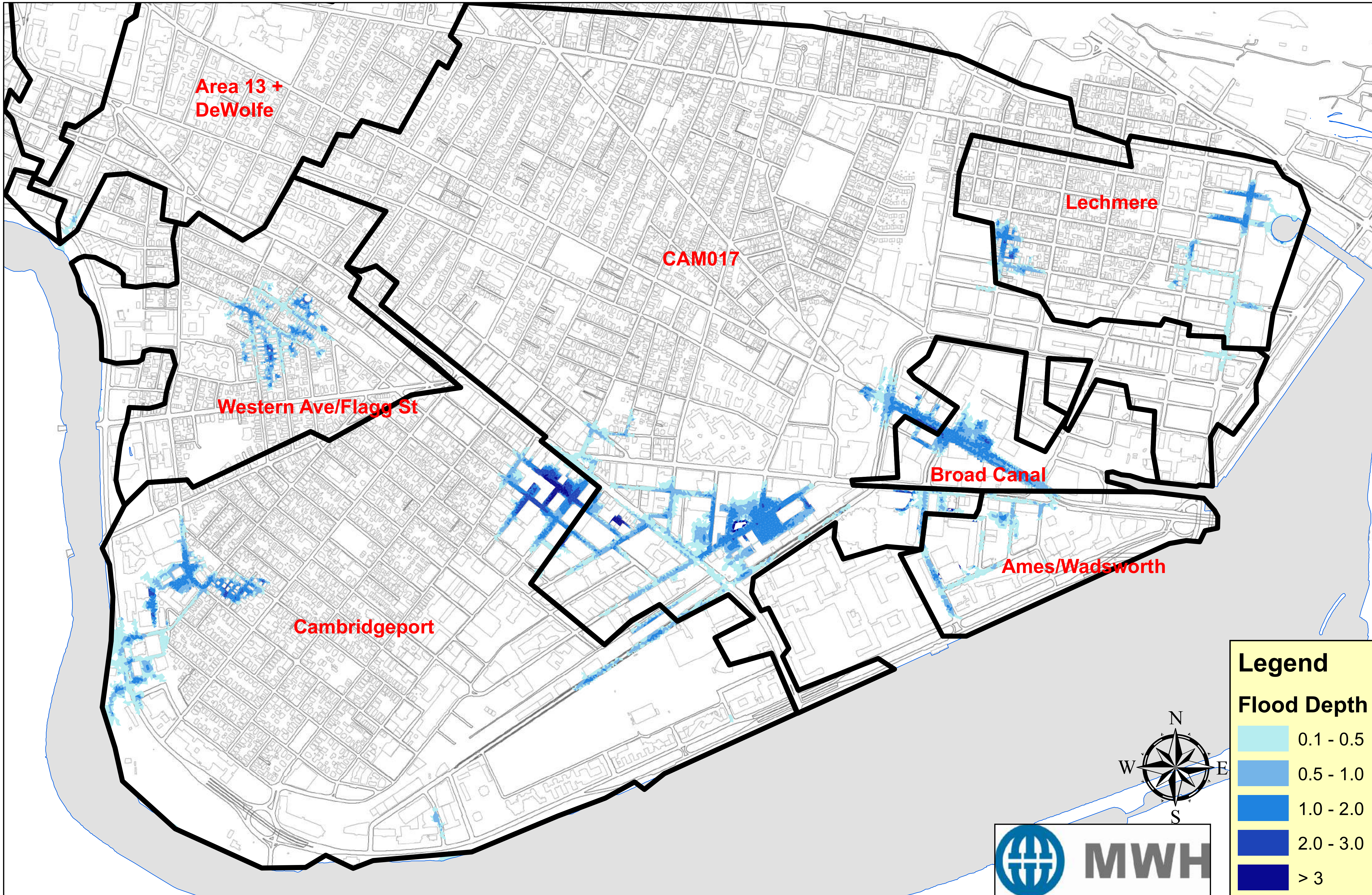


Figure 4. Alewife Tributary Area

2070, 1% probability SLR/SS event without precipitation

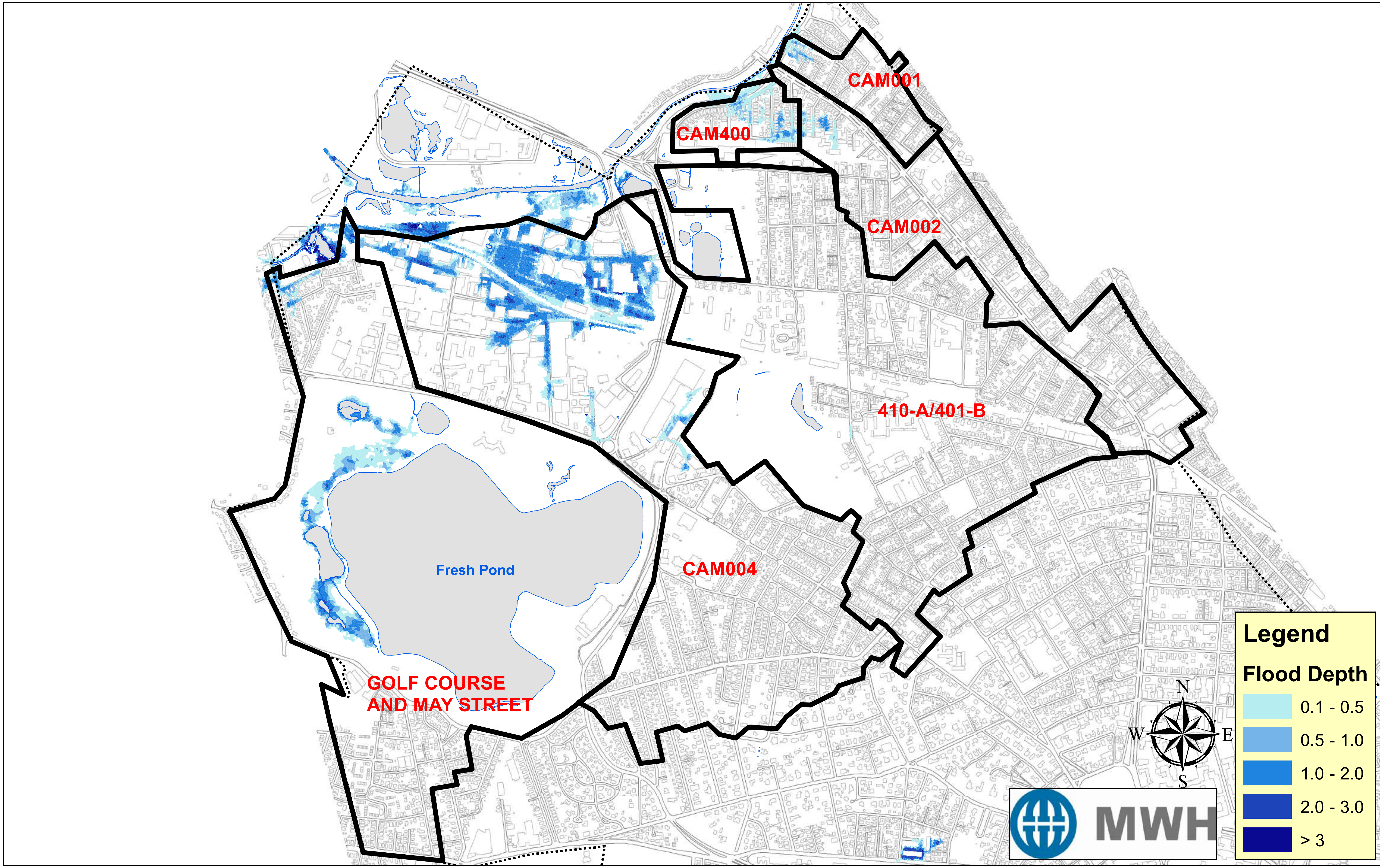


Figure 5. Charles River Northern Tributary Catchments

2070, 1% Probability SLR/SS event with 10-yr, 24-hr precipitation

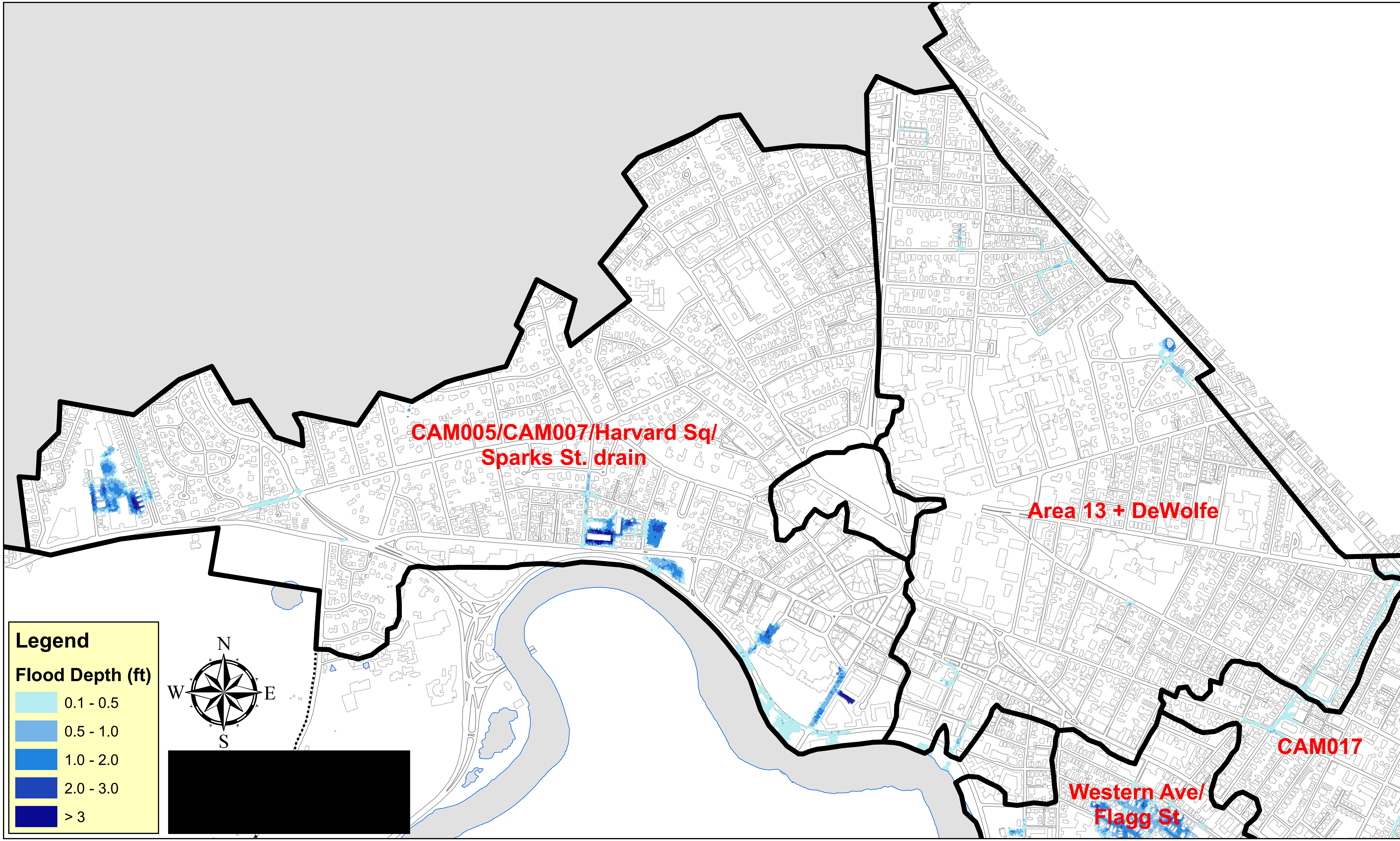


Figure 6. Charles River Southern Tributary Catchments

2070, 1% probability SLR/SS event with 10-yr, 24-hr precipitation

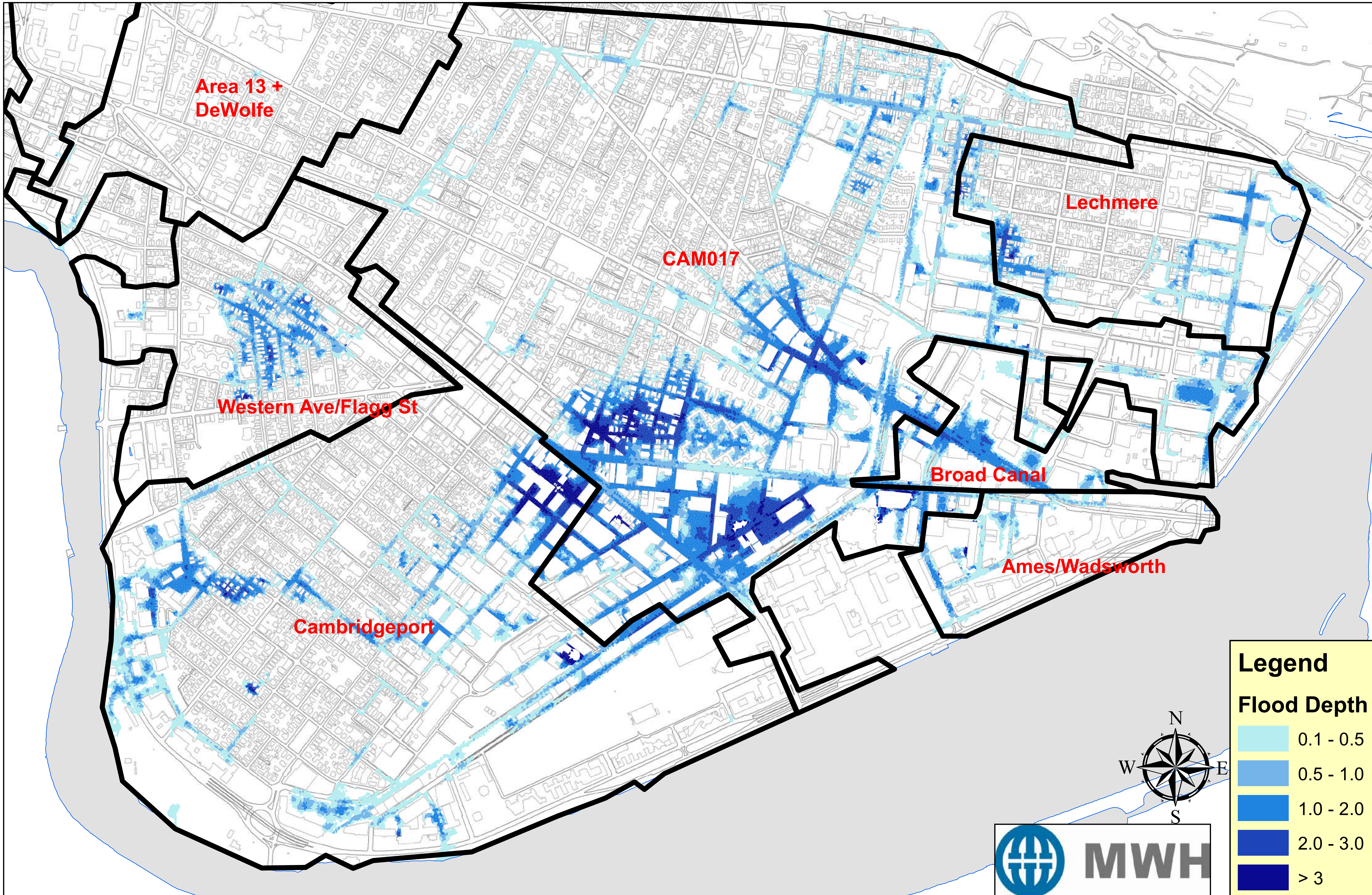


Figure 7. Alewife Tributary Area

2070, 1% probability SLR/SS event with 10-yr, 24-hr precipitation