Climate Projections & Scenario Development

Climate Change Vulnerability Assessment

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City of Cambridge,
Massachusetts

Acknowledgements

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

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Climate Scenarios

To conduct the vulnerability assessment, it was necessary to understand how future climate conditions might be different in terms of temperature, humidity, precipitation, and sea level. Since there is no way to know the future precisely, the assessment uses scenarios as the basis for the "climate stress test." Based on the best available science, the scenarios represent plausible future conditions that are different than the present.

The assessment used climate projections that were generated specifically for Cambridge. The customized projections take into account the City's location near the ocean, the urban heat island effect, and other local factors. The projections are based on sets of global climate model simulations that were downscaled using statistical methods and calibrated with historic data from local weather stations. The output from the projections provided temperature, humidity, and precipitation projections for Cambridge. Sea level rise assumptions were drawn from the 2012 NOAA Global Scenarios SLR Report in the 2014 U.S. National Climate Assessment, prepared by the U.S. Global Change Research Program.

Planning horizons: The City chose three planning horizons: present day, 2030, and 2070. Each of these planning horizons used thirty-year averages for temperature and precipitation data. Present day numbers are based on data from 1971 to 2000, which serves as a reference period to compare future climate change projections. The 2030 planning horizon uses climate projections from 2015 to 2044, and the 2070 planning horizon uses climate projections from 2055 to 2084.

Bounded uncertainty: In addition to using a variety of global climate models, uncertainty was bounded by adopting both low and high greenhouse gas (GHG) emission scenarios for both the temperature and precipitation parameters. The low emission scenario assumed that some significant mitigation measures were adopted that would reduce future levels of GHG emissions, and therefore lessen the overall intensity of events. The high emissions scenario modeled a future where there was no such mitigation and the ever-increasing GHG emissions resulted in greater impacts. Climate science, like all fields of science, is constantly evolving. The scenarios were developed using the latest available information with the understanding that assumptions, methodologies, and resultant projections will need to be revised in light of new data or technologies or changes in the environment itself.

Professional judgment: The climate projections generated ranges of values for climate parameters. The expertise of City staff, consultants, and outside experts was used to select values to use in heat and flood models based on experience and technical judgment.

Sea Level Rise and Coastal Storm Surge

Cambridge is unlikely to be impacted by sea level rise or storm surge in the immediate future due to flood protection from both the Charles River and Amelia Earhart dams.

Communities on and near the coast face the dual risk of rising sea levels and more intense coastal storms. Cambridge's geography affords some level of protection from coastal impacts, and the Charles River and Amelia Earhart (on the Mystic River) Dams act as storm surge barriers under current conditions. However, as the sea rises and coastal storms become stronger, risks will gradually increase to a point where the effectiveness of the dams as barriers diminishes and storm surges are able to flow overland around the dams and eventually overtop them, first with larger flooding events (e.g., the "100-year" or 1% probability of flooding), and then gradually over an extended period of time with smaller, more frequent flooding events.

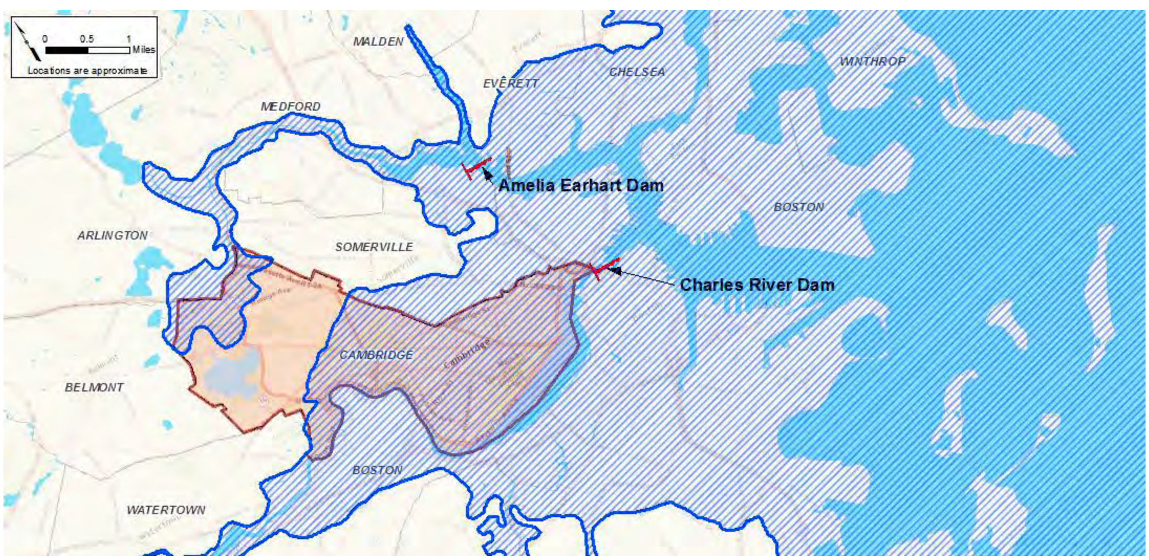


Figure 1: Boundaries of MassDOT study: Shaded area in blue indicates the extent and location of the project area that were included in this analysis. (Source: MassDOT, Woods Hole Group, UMass Boston, November 2015)

The City partnered with the Massachusetts Department of Transportation (MassDOT) to invest in detailed modeling of the flood impacts that would result from sea level rise and more intense and frequent storm events (Figure 1). The model uses thousands of historic and simulated future storms, including hurricanes and nor'easters, to estimate the probability of flooding in the Inner Core of the Boston area, including Cambridge. The model predicts up to 8 inches of sea level rise by 2030, and up to 3.4 feet by 2070 in this area. The results for 2030 indicate that the risk of storm surge flooding reaching Cambridge is less than 0.1%. This includes risks from both overtopping and flanking of the dams and incorporates factors such as increased river flows from runoff, increased pumping operations at the dams, and the twice-daily tide cycle. The 2070 modeling is still in progress, the results of which will be reported in the forthcoming Part 2 of this report. Ultimately, the inland flooding projections will be combined with the storm surge and sea level rise results to produce a holistic, integrated view of projected flood risks in Cambridge. The completed flooding projections will be used in the Climate Change Preparedness and Resilience Plan.

Precipitation

Precipitation driven flooding is likely to increase in frequency, extent, and depth.

The intensity of the heaviest rain and snowfall events in the Northeast U.S. has increased by 71% over the last half-century (Figure 2). As air temperatures rise, the atmosphere can hold more water, leading to more intense precipitation events. Over time such extreme events will become increasingly frequent.

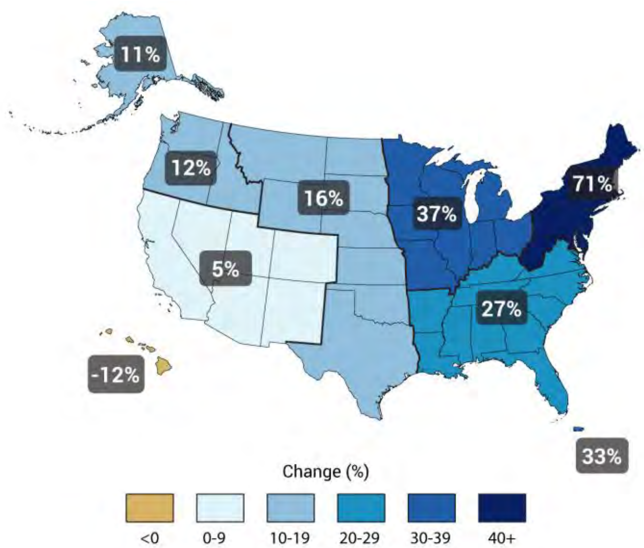


Figure 2: Observed change in very heavy precipitation events (defined as the heaviest 1% of all daily events) from 1958 to 2012. (Source: National Climate Assessment, Walsh et al. 2014)

Rainfall intensity affects the volume of water that flows across land, in rivers, and through stormwater systems. It is projected that extreme rain events will increase in frequency and intensity. The projected future rates of rainfall are shown in Figure 3.

The flood volume generated by the future 10-, 25-, and 100-year storm events – which are relatively large and infrequent storms – is unlikely to be adequately mitigated by increasing physical storage and conveyance capacity. It may be necessary to consider how best to deal with periodic flooding in some areas.

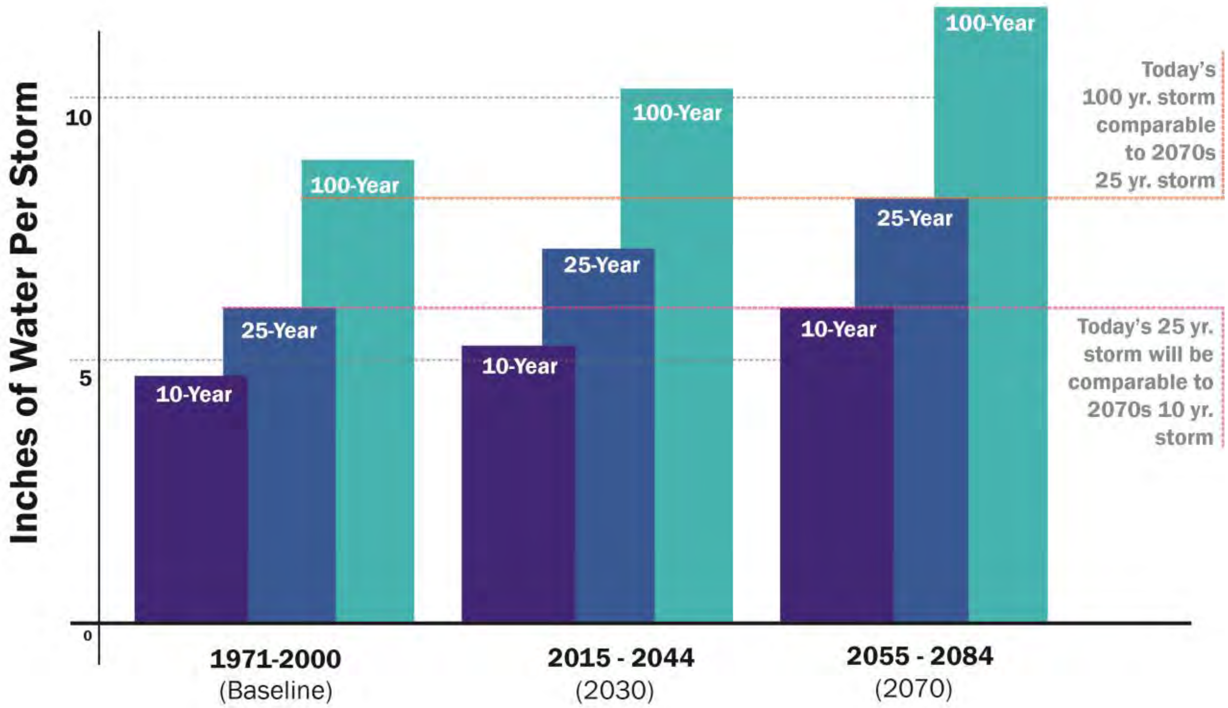


Figure 3: Precipitation projections (Source: Kleinfelder based on ATMOS projections November 2015)

Instead of the term "100-year storm," a hydrologist would rather describe this extreme hydrologic event as a storm having a 100-year recurrence interval. What this means is that a storm of that magnitude has a 1% chance of happening in any year. One-hundred-year storms can happen two years in a row. A 1% annual probability translates to a one in four chance of being flooded over a period of 30 years.

The projected rainfall rates, illustrated in Figure 3, were used for modeling storm overland run-off, river flow, and drainage through pipes. Integrated maps of inland flooding were developed for the entire City under different storm types and intensities.

The flooding scenarios assume that the pumps on the Charles River and Amelia Earhart Dams are functioning at full capacity to drain stormwater downstream and away from the City.

If those pumps fail, flooding, especially in the Alewife Brook area, would be substantially worse. Maintaining and increasing the pumping capacity of the Mystic River's Amelia Earhart Dam, which is located between Somerville and Everett and owned by the Commonwealth, will be essential to prevent or minimize flooding in northern Cambridge. This will require close cooperation among neighboring cities and state agencies.

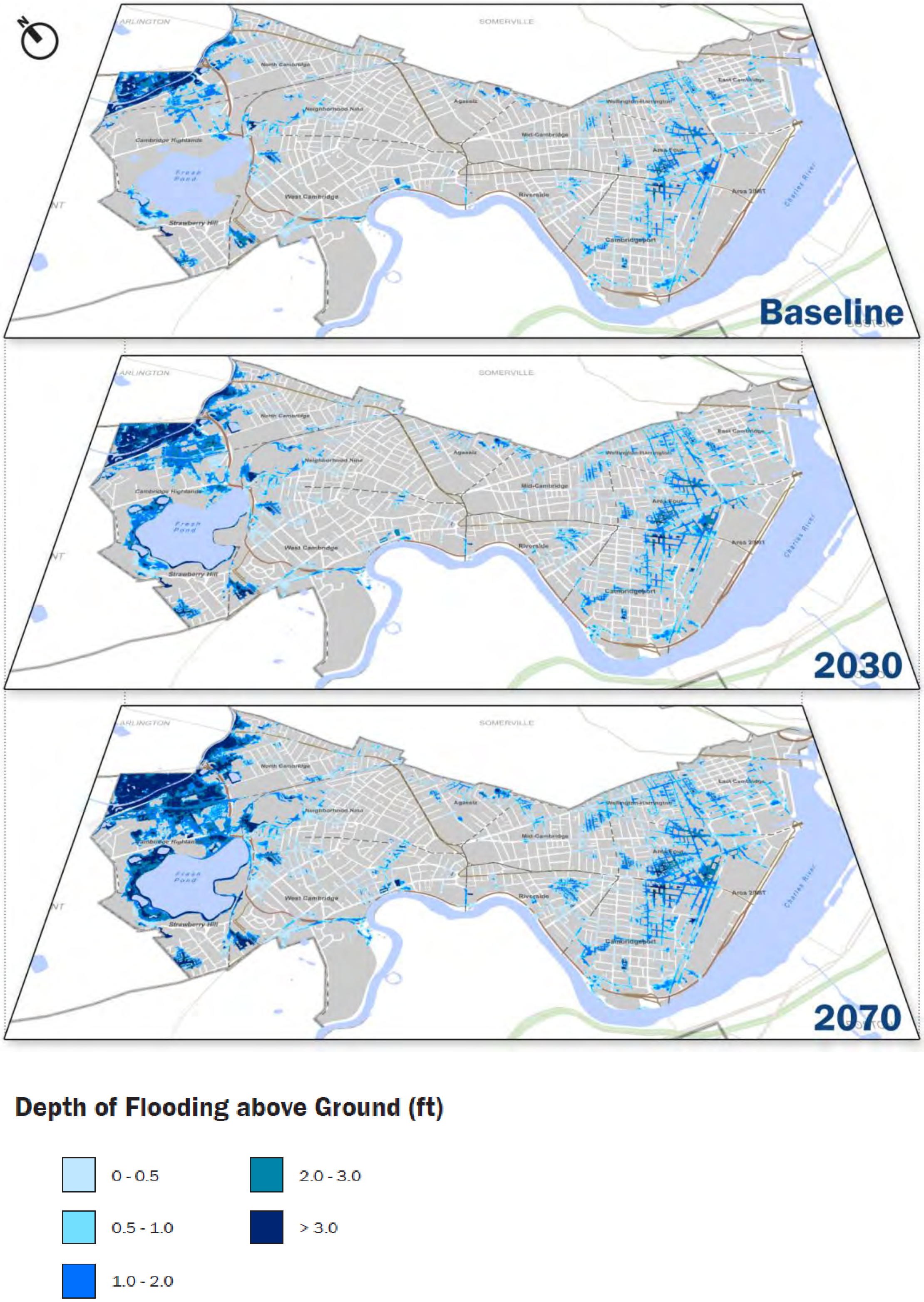


Figure 4: Inland flooding – 100-year 24-hour storm (Source: Kleinfelder with manhole flooding by MWH, riverine flooding by VHB, November2015)

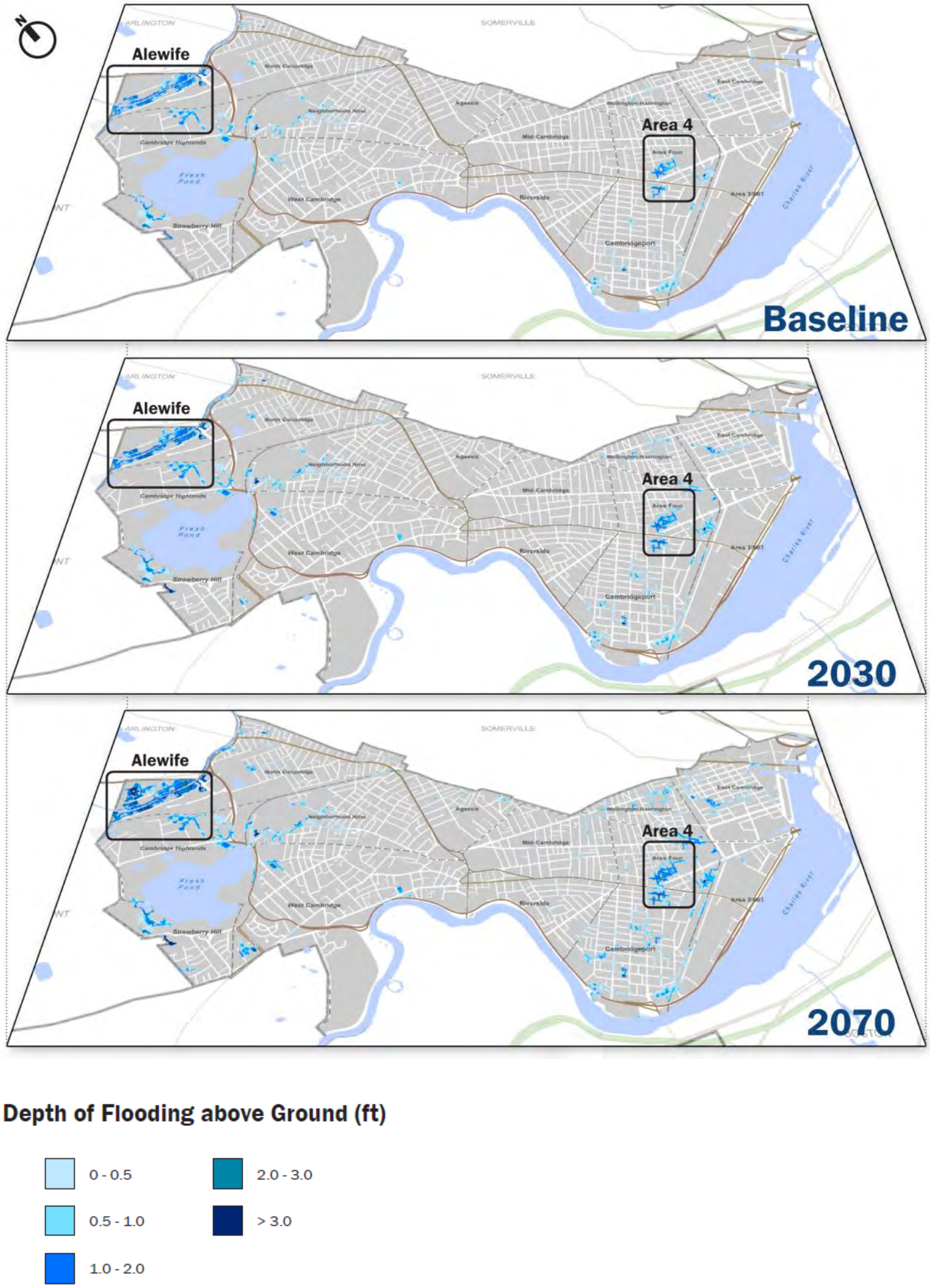


Figure 5: Inland flooding – 10-year 24-hour storm (Source: Kleinfelder with manhole flooding by MWH, riverine flooding by VHB, November 2015)

The Baseline map in Figure 4 illustrates potential flooding from a 100-year 24-hour storm under current conditions with an estimated rainfall of 8.9 inches over 24 hours. The 2030 map in Figure 4 illustrates potential flooding from a projected 100-year 24-hour storm with climate change and an estimated rainfall of 10.2 inches over 24 hours. The 2070 map in Figure 4 illustrates potential flooding from a projected 100-year 24-hour storm with climate change and an estimated rainfall of 11.7 inches over 24 hours.

The Baseline map in Figure 5 illustrates potential flooding from a 10-year 24-hour storm under current conditions with an estimated rainfall of 4.9 inches over 24 hours. The 2030 map in Figure 4 illustrates potential flooding from a projected 10-year 24-hour storm with climate change and an estimated rainfall of 5.6 inches over 24 hours. The 2070 map in Figure 4 illustrates potential flooding from a projected 10-year 24-hour storm with climate change and an estimated rainfall of 6.4 inches over 24 hours.

The three maps shown in Figure 4 depict “100-year” (i.e., a 1% chance of occurring in a given year) 24-hour rainfall events today and in 2030 and 2070. Over these three time periods, the area of the City projected to flood increases from 13% to 18% by 2030 and 23% by 2070. That is, the additional 2.5 inches of rainfall expected in a 2070 100-year 24-hour storm would flood an area almost twice the size of what would be flooded today.

The flooding projected to occur in northern Cambridge would result primarily from Alewife Brook overflowing its banks. The flooding projected for eastern Cambridge is a function of insufficient capacity in the area’s stormwater and combined sewer systems and the inability of the piped infrastructure to convey the water away, resulting in water backing up and ponding around manholes and catch basins. Although flooding in eastern Cambridge appears less severe, the building character and socio-economic make-up of the affected neighborhoods make these areas very vulnerable. Also, while 100-year flood events are more severe in extent and depth, events such as a 10-year flood are relatively more frequent, so the cumulative damages can be significant.

Flood risks do not fall into neat categories. In addition to the 10- and 100-year events, there are also risks posed by short-duration (1 or 2 hours) intense storms and long-duration (48 to 72 hours) storms and events in between. Cambridge has already experienced flooding from these types of storms. For example, on July 10, 2010, 3.6 inches of rain fell in a single hour, exceeding the capacity of Cambridge’s stormwater system and resulting in significant flooding in several neighborhoods (Figures 8 and 9). These types of storms are projected to become more frequent.

The future rainfall projections were used in hydrologic/hydraulic models to create the maps of projected flooding in Figure 4. The maps show where flooding from extreme rainfall events, shown as the 100 year or 1% probability storm of 24-hour duration, would occur based on current land conditions and stormwater infrastructure.

The flooding maps help identify the neighborhoods, streets, and individual structures most at risk of flooding. The 100-year storm event flood maps (Figure 4) depict a larger at-risk area compared to the 10-year storm flood maps (Figure 5). However, while the 10-year storm flood covers a less extensive area, the flooding from this type of event will be more likely and frequent for those areas affected because it has a 10% chance of occurring every year.

This is an important factor in certain neighborhoods, such as Area 4 and Alewife, which have already experienced repeated flooding.

In a related concern, in certain parts of Cambridge, stormwater and sewer pipes are still combined and connected to twelve (12) combined sewer overflow (CSO) locations. These discharge combined sewage into the Charles River and Alewife Brook (rather than allowing it to back up into buildings) when flow exceeds the system’s capacity. Measures to alleviate combined discharges will be developed in the Climate Change Preparedness and Resiliency Plan.

Flooding transcends municipal boundaries. Recognizing this, the City of Cambridge, Boston Water and Sewer Commission (BWSC), MassDOT, the Massachusetts Department of Conservation and Recreation (DCR), Massachusetts Water Resources Authority, and City of Boston are collaborating on a regional approach to identify and decrease regional flood risks. One outcome is that Cambridge and BWSC are partnering on developing design storm criteria that will improve infrastructure to manage future extreme storm events.

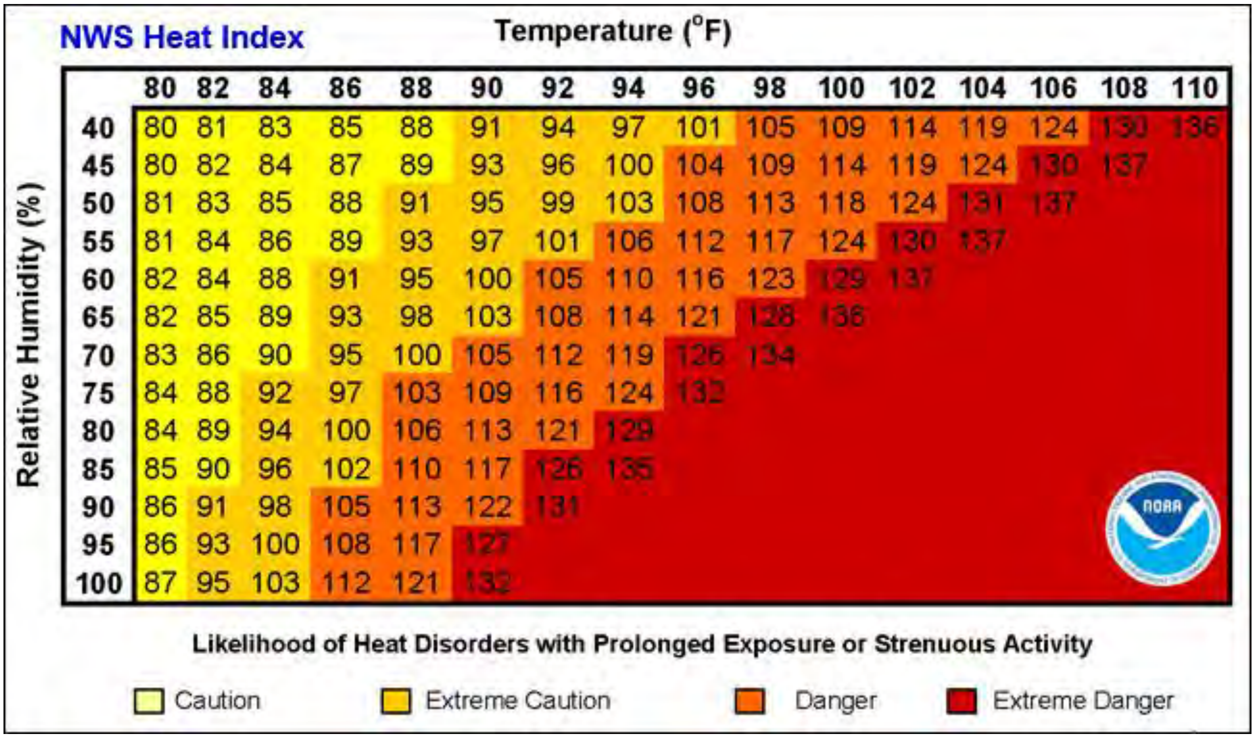
Heat

Both annual temperature and heat waves are likely to increase

Temperatures are expected to rise through 2070 and beyond. This trend will be experienced both as increasing average or “new normal” temperatures and as more extreme, less predictable heat events. It is very likely that Cambridge will experience heat waves of greater frequency and duration and that this shift will have implications for both human health and the built environment. Northern cities are less adapted to extreme heat because of little historical need to do so. The ability to increase our resilience to heat is a matter of behavioral adaptation (e.g., personal preparedness, active support networks), effective management of chronic disease, and selective modifications to the built environment (e.g., green roofs, cool shelters, water spray facilities). This report outlines anticipated increases in average temperature and extreme heat events and the impact these changes will have on residents, businesses, institutions, City services, and critical networks.

This project reports probable heat changes in three different ways:

- **Ambient air temperature** is the measured air temperature. Climate projections track how ambient air temperature might change moving forward. This important indicator establishes overall baseline and trends, as well as provides some indication of whether there may be impacts to heat-sensitive infrastructure and population.
- **Heat index** is a more accurate indicator of heat stress in humans. The heat index combines both temperature and relative humidity data to determine the "feels like" temperature that people experience. A day with lower temperatures combined with higher humidity can produce the same level of heat stress as a day with a higher temperature and lower humidity. The Heat Index Chart, as published by the National Oceanic and Atmospheric Administration (NOAA), in Figure 6 below, illustrates that relationship. Heat stress affects the body's ability to maintain its normal temperature and may damage vital organs. Extreme heat causes more deaths in the U.S. than floods, hurricanes, lightning, tornadoes, and earthquakes. But heat-related deaths are preventable. Physical assets, such as electrical substations, are not generally affected by humidity. Therefore, heat index was not considered to assess the vulnerability of the built infrastructure.
- **Heat wave** is an extended period of very high temperatures. The extended period of heat has significant implications for public health because human physiology is quite sensitive to long periods of sustained heat exposure. Locally, heat waves have been defined most often as three or more days in a row with ambient temperatures greater than 90°F.



Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Figure 6: Heat index chart (Source: National Weather Service NWS, National Oceanic and Atmospheric Administration NOAA)

This assessment projects that the numbers of days over 90°F will nearly triple by 2030 from the current annual average of 11 days and that there may be 4 to 6 times more days by 2070 (see Figure 7). Considering historic data, these scenarios may under-predict both the duration of heat waves and their frequency. For example, there was a recorded 8-day heat wave throughout the Boston metropolitan area in August 2002. A similar event happened in 1944. More recent events include a 5-day heat wave in 2010 (August 29 - September 2) and a series of 4-day heat waves in June 2008, July 2008, July 2010, and July 2012. The projections used in the assessment indicate heat waves will become more likely and frequent.

The duration and intensity of heat waves have significant implications for public health – especially for vulnerable populations that do not have access to sufficient cooling options. Each passing day of extreme heat decreases a person's ability to cope with the heat stress. This is especially threatening for the very young, the elderly, and those with existing health challenges like cardiovascular, circulatory, and respiratory conditions.

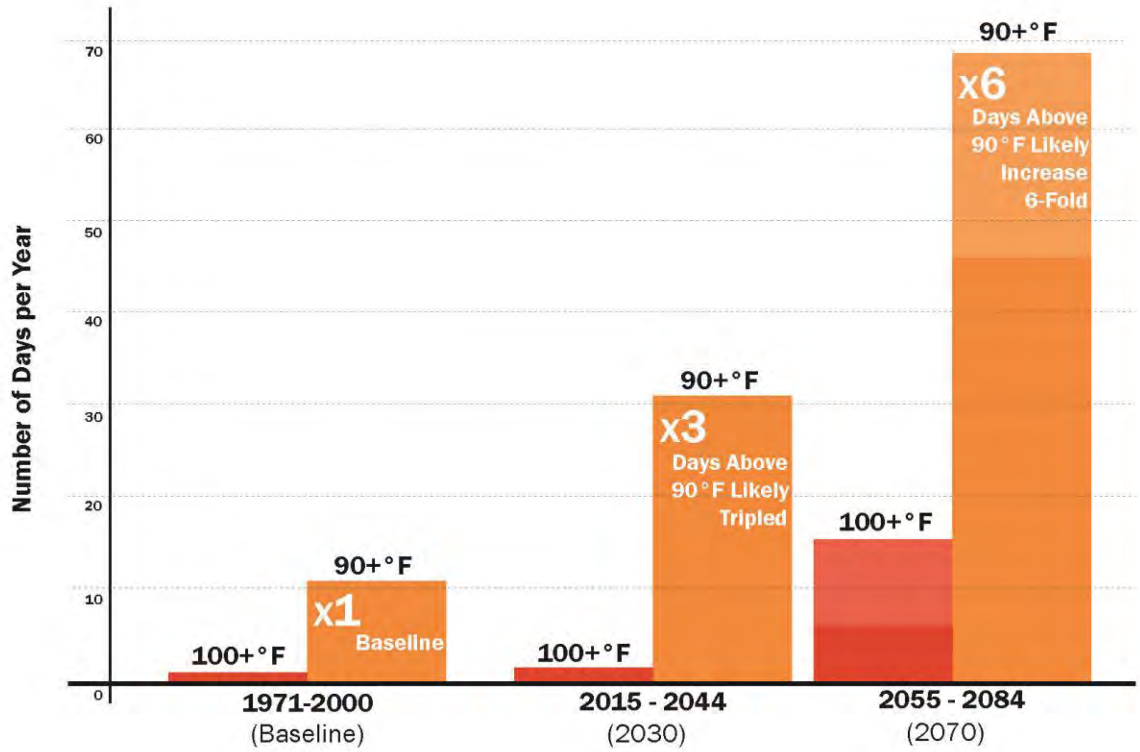


Figure 7: Number of days above 90°F (Source: Kleinfelder based on ATMOS research, November 2015)

This assessment further evaluates the role of the **urban heat island effect**, where heat absorbing surfaces and lack of shading exacerbate temperatures and are likely to result in an uneven heat burden across the City.

Heat waves in the Boston area are broadly defined as periods of unusually hot weather (over 90°F) over at least 3 consecutive days. Heat wave frequency and duration are expected to increase. Currently, the hottest days of the year usually occur during the summer months of June, July, and August. As the number of days with extreme heat increases, the likelihood of heat waves also increases, since there is a greater chance that those days will occur in succession. Likewise, those hotter days are associated with particular weather patterns that will likely last more than one day. The graphic below (Figure 8) illustrates what the relative change in heat patterns might be in the future. By 2070, there could be as many as 68 days per year greater than 90°F, of which there could be as many as 16 days greater than 100°F. While these days may be spread out over more than three months (as shown in Figure 8), the calendar illustrates the possibility that temperatures in Cambridge could exceed 90°F for most of summer if all of the year's warmest days fell in the summer months of June through August.

Heat impacts are not evenly distributed throughout the City. The following maps (Figure 9) illustrate the current distribution of heat throughout the City and how that might evolve by 2030 and 2070. These maps are based on heat index to take humidity into account. According to these scenarios, the entire City could be experiencing dangerous levels of heat stress by 2070.

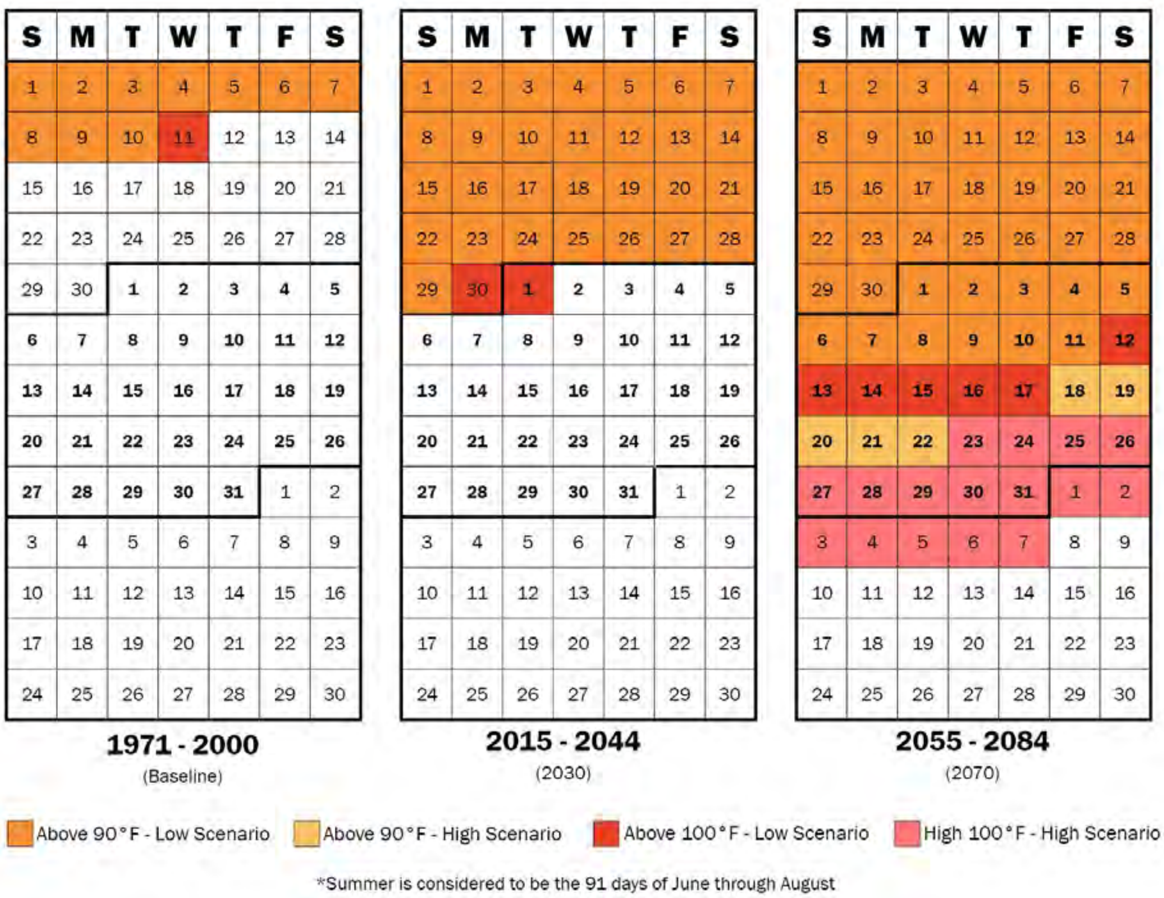


Figure 8: Relative increase in possible projected days above 90°F and 100°F over a 3-month period
(Source: Kleinfelder based on ATMOS research, November 2015)

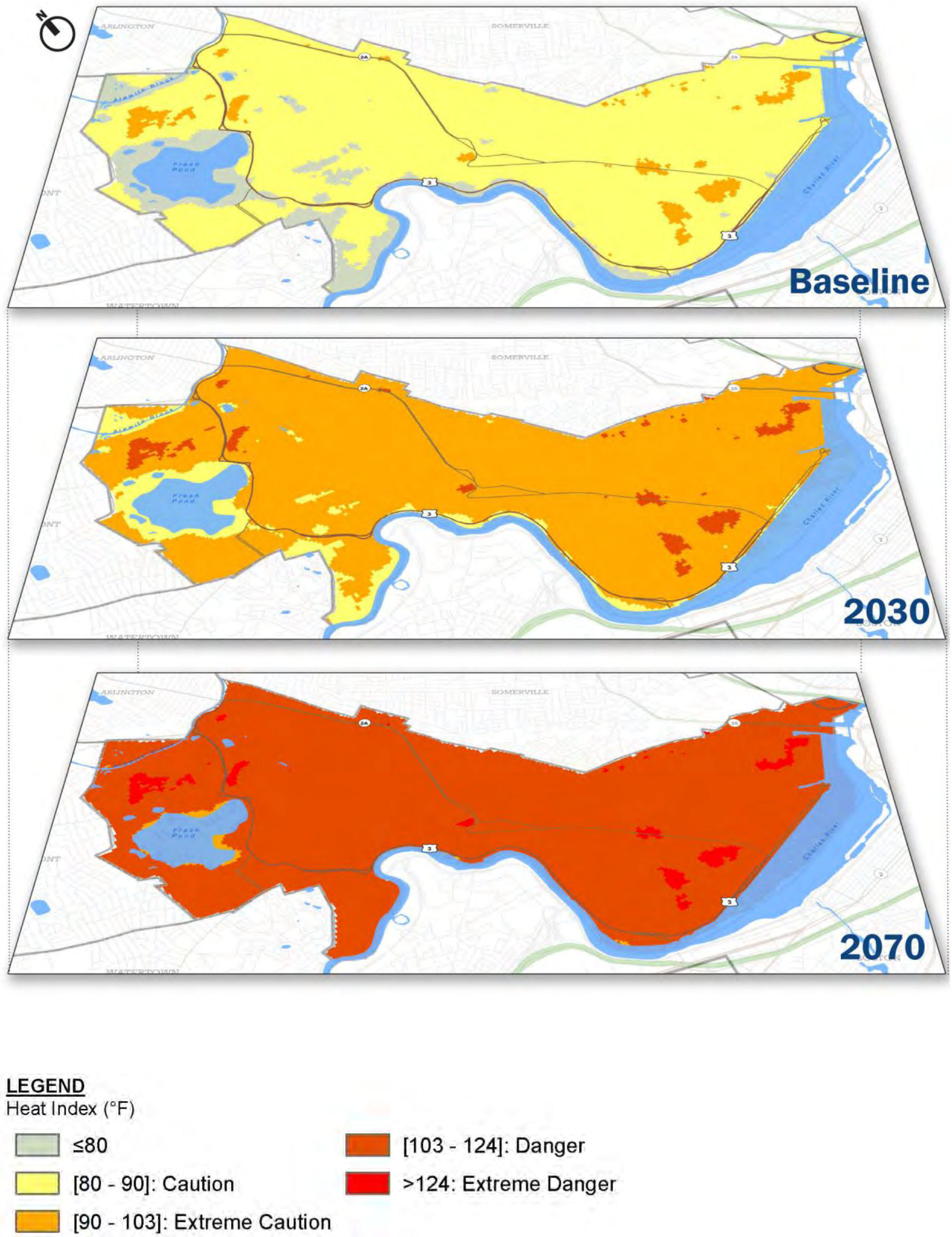


Figure 9: Heat island maps (heat index) (Source: Kleinfelder based on ATMOS research, November 2015)

The Baseline map in Figure 9 illustrates the variability in “feels-like” temperature across the City under present conditions with localized heat islands above 100ºF when average heat index for the City is 85ºF (based on available recorded data). The 2030 map in Figure 9 illustrates the variability in “feels-like” temperature across the City by 2030 with localized heat islands above 100ºF when average heat index for the City is 96ºF (90ºF ambient temperature with relative humidity of 50-55%). The 2070 map in Figure 9 illustrates the variability in “feels-like” temperature across the City by 2070 with localized heat islands above 120ºF when average heat index for the City is 115ºF (100ºF ambient temperature with relative humidity of 45-50%).

Next Steps

The climate impacts identified here were used to inform the vulnerability assessment and will be the baseline against which the City conducts its climate “stress test.” It is recognized that climate science, as all other science disciplines, is a constantly evolving field with new information being released on a daily basis. The City is committed to keeping abreast of these changes and updating its assumptions in light of major shifts. However, the City also understands the urgency to move to adaptation and implementation. The scenarios established here represent robust and thoughtful baselines against which the City can start to plan for both mitigation and adaptation.

Why Climate Change?

Climate is changing across the globe with palpable effects at the regional and local level. Over the last 50 years, changing patterns in temperature, precipitation and other climate parameters have been recorded attesting to the increasing frequency and intensity of climate change related weather events. Massachusetts average temperatures have increased by 0.4°F per decade, and winter temperatures by twice that, 0.8°F per decade[1]. Annual average precipitation has been increasing at more than 2 inches per decade, with greatest increases in spring, summer and fall[1]. (NOAA, 2013). Across the Northeast, the frequency of heavy precipitation, including both rain and snow events, has increased by 74% from 1958 to 2011, accompanied by an increase in the magnitude of floods[2]. The average length of the growing season in the Northeast increased by 10 days from 1901-1960 to 1991-2011[2], while extreme heat days are becoming more frequent and extreme cold days less frequent across the entire U.S. [2]

A comparison, in Figure 10, between observed global CO2 emissions and the various emissions scenarios used in recent national and international climate change assessments shows that observed emissions have so far exceeded projected trends for even the highest emissions scenarios. This provides a warning that projections might actually underestimate the magnitude and rate of future climate changes. (See Figure 10 below.)

[1] National Oceanic and Atmospheric Administration (NOAA) 2013. Updated Mean Sea Level Trends – 8443970 Boston, Massachusetts. http://tidesandcurrents.noaa.gov/sltrends/sltrends_update.shtml?stnid=8443970

[2] *Walsh et al., 2014a refers to* Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. http://nca2014.globalchange.gov/report/our-changing-climate/introduction

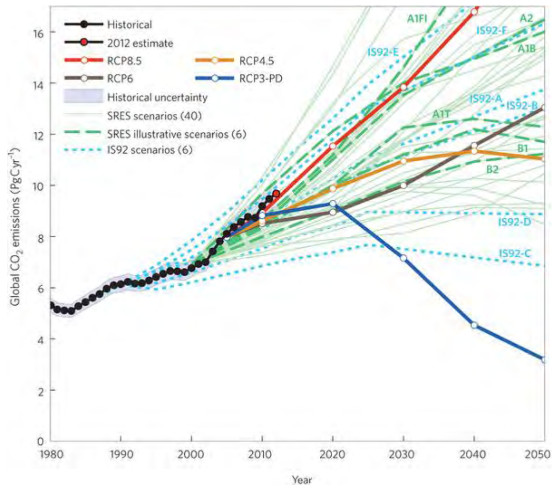


Figure 10: Observed global CO2 emissions compared with various emissions scenarios, including the RCP scenarios used for Cambridge [3]

What Climate Change Means for Cambridge

While global averages provide generalized trends, more localized projections are required to make informed planning, policy, design and investment decisions. The City of Cambridge decided to use a combination of historic data, downscaled projections and professional judgment to develop climate scenarios against which to assess the vulnerability of key assets and community resources.

Planning Horizons

One of the first parameters to establish is the span of years over which the climate change projections will be analyzed. For the Cambridge study, the years 2030 and 2070 were the two planning horizons selected: 2030 (15 years from present) provides a nearer-term target that can easily be incorporated into existing planning horizons, while 2070 (55 years from present) provides a longer-term vantage that aligns well with the life expectancy of built infrastructure and a longer-range forecast on shifts in climate. 2070 provides an upper bound of what might be expected by that time horizon. However, it is important to mention that climate change projections associated with 2030 and 2070, particularly for temperature and precipitation, are based on a 30-year averaging period around each planning horizon. This averaging is important to nullify the year-to-year and decadal variations that can occur from natural cycles, such as El Nino, La Nina and North Atlantic Oscillation effects. Also, the 30-year averaging period smooths out some of the uncertainty in the science of climate change projections and indicates that the projections for

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[3] Peters, Andrew, Boden, Canadell, Ciais, Le Quere, Marland, Raupach, and Wilson (2013). The challenge to keep global warming below 2°C. Nature Climate Change, 3, 4-6. Online at: http://www.nature.com/nclimate/journal/v3/n1/full/nclimate1783.html?WT.ec_id=NCLIMATE-201301

no single year in that time frame is exactly the same as the average. To consider this averaging period, the planning horizons for Cambridge are referred to as 2030s and 2070s.

Emissions Scenarios

Climate projections are calculated based on numerous assumptions among which the concentrations of greenhouse gases within the atmosphere under future scenarios is key. The Intergovernmental Panel on Climate Change (IPCC) has put forth various emission scenarios to capture a wide range of projections for future population, demographics, technology and energy use and estimate changes in greenhouse gas concentrations over time. Higher scenarios of GHG emissions assumed continued dependence on fossil fuels such as coal, gas, and oil as the primary energy source (Figure 11, orange and red lines). Lower emissions scenarios envision a transition from fossil fuels to non-carbon-emitting renewable energy sources (Figure 11, green and blue lines). The emissions scenarios used for Cambridge are from a family of scenarios called the Representative Concentration Pathways (RCP), which were also used in the most recent U.S. National Climate Assessment (2014), as well as in IPCC's Fifth Assessment Report (2014). Climate projections for Cambridge are based on the highest emissions scenario (RCP 8.5, red line in Figure 11) and a lower emissions scenario (RCP 4.5, blue line in Figure 11). These two scenarios were selected in order to provide a bounded range of "plausible" scenarios for projected changes in temperature, precipitation, sea level rise (SLR), and storm surge.

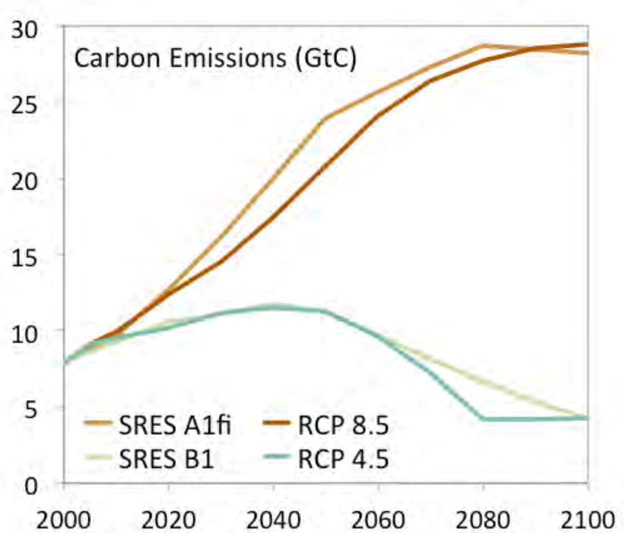


Figure 11: Emission scenarios for Cambridge: highest scenario (RCP 8.5), where human emissions of carbon dioxide and other heat-trapping gases continue to rise, and lower scenario (RCP 4.5), where emissions peak and then begin to decline by mid-century.[4]

[4] Source: Inman, Mason (2011). Opening the Future. Nature Climate Change 1, 7-9. Online at: http://www.nature.com/nclimate/journal/v1/n1/box/nclimate1058_BX1.html

Global Climate Models

Future emission scenarios are used as input to global climate models (GCMs). GCMs are complex, three-dimensional models that are continually evolving to incorporate the latest scientific understanding of the atmosphere, oceans, and Earth's surface. Global climate models incorporate many other facets of the Earth's climate system, including chemistry, biospheric processes, land use, etc. As output, GCMs produce geographic grid-based projections of temperature, precipitation, and other climate variables at daily and monthly scales. The GCMs used for the City of Cambridge consist of a more recent set of models that have contributed to to phase 5 of the Coupled Model Intercomparison Project[5]. These models have been used to project climate change and corresponding impacts in the IPCC Fifth Assessment report and 2014 U.S. National Climate Assessment. Climate Change projections for Cambridge were derived from 9 CMIP5 GCMs with daily temperature and precipitation outputs for the RCP 8.5 and 4.5 scenarios. The names of the 9 GCMs are derivied from the institutions running the models: CCSM4, CNRM-CM5, CSIRO-Mk3.6.0, MPI-ESM-LR, HadGEM2-CC, INMCM4, IPSL-CM5A-LR, MIROC5 and MRI-CGCM3.

Methodology

The methodology for calculating climate change projections for precipitation and temperature in Cambridge relied on the downscaling work of Dr. Katharine Hayhoe, which was performed specifically for this study. (Refer to Appendix B for more detailed analysis). This work was vetted by an Expert Advisory Panel consisting of members from academia (Daniel Schrag, Department of Earth and Planetary Sciences at Harvard University; Joyce Rosenthal, Graduate School of Design at Harvard University; Peter Frumhoff, Union of Concerned Scientists; Henry Jacoby, Sloan School of Management at MIT; Bruce Anderson, Department of Geography and Environment at Boston University; Stephen Hammer, MIT; John Spengler, Harvard University), and has been subsequently cross-checked with work by other climatologists working with Boston Water and Sewer Commission.

GCMs provide climate change projection outputs at a coarse resolution, with geographic grid cells so large that just three cells cover the entire New England region. These model outputs are not sufficient to capture local climate variations that would be important to consider at the scale of a city. The methodology used to transform the GCM outputs from coarse-resolution grids into high-resolution (tens rather than hundreds of square miles) locally-calibrated temperature and

[5] *CMIP5; Taylor et al. 2012 refers to* Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl, 2012: An overview of cmip5 and the experiment design. *Bull. Amer. Meteor. Soc.*, 93, 485–498.

precipitation projections is called downscaling. The climate projections for the City of Cambridge were downscaled using a statistical approach called the Asynchronous Regional Regression Model (ARRM) . ARRM established a statistical relationship between GCM ouputs (simulated temperature and precipitation data) and weather station data from in and around Cambridge over a long historical period (30 to 40 years). This downscaling method, also called "training", was used to calibrate GCM outputs to better reflect local climatic conditions. Using a long time period for this calibration helped capture a representative range of variability in the statistical relationship and protected the relationship from being overly influenced by fluctutations of a particular year or short time period. This historic relationship was then applied to future GCM projections to produce a local distribution of temperature and precipitation that changes over time.

For this project, high-resolution projections were developed for the three long-term (records longer than 40 years) weather stations nearest to Cambridge, located in Jamaica Plain, Boston Logan Airport and Reading. In addition, precipitation projections were calibrated against observational data from three closer, short-term (records less than 5 years) weather stations in Cambridge, Brighton, and Belmont and Boston Logan. Relative humidity projections were determined for only Boston Logan, since this was the only station with long-term relative humidity observations available.

Regional Coordination

Climate projection data, methods, and results developed for this study have been shared with various state and municipal agencies including Massachusetts Department of Transportation (MassDOT), Massachusetts Department of Conservation and Recreation (DCR) managing the operations of the Charles River and the Amelia Earhart dams, Massachusetts Port Authority (Massport), Massachusetts Executive Office of Energy and Environmental Affairs (EEA), Boston Water and Sewer Commission (BWSC), and the City of Boston. Revised projected rainfall depths associated with 24-hr and 48-hr duration design storms with recurrence intervals of 10-, 25- and 100-years were jointly estimated for mid-century and late-century time frames. For these design storm estimates, the City of Cambridge and BWSC reached consensus on using the same design values, thus building regional consistency and ensuring compatibility between systems that intersect across municipal boundaries.

The type of comprehensive regional coordination approach set forth in this project is a pioneering step, and one that facilitates multiple entities to share data and results across a common platform. Findings from the Cambridge project will be updated as new data and studies are made available for further regional coordination.

Uncertainty and Likelihood in Climate Change Projections

Climate projections are characterized by large uncertainties. The sources of these uncertainties at the global scale can be primarily from two sources:

- Uncertainties in future greenhouse gas emission scenarios and other climate drivers which alter the global energy balance, such as aerosols and land-use changes
- Uncertainties in how sensitive the climate system as reflected in the global climate models will be to greenhouse gas concentrations and other climate drivers

In addition to the sources of uncertainty at the global scale, uncertainties in climate change projections at the local and regional scale, as for the City of Cambridge, can arise from two additional sources:

- Uncertainties in downscaling methods used to transform global climate model output to local scales since changes in local physical processes that operate at fine scales, such as land/sea breezes, may not be fully captured by the global climate models used to make projections
- Uncertainties in choice of weather stations that suitably capture climate variability, which can be especially large over small regions, partially masking more uniform effects of climate change

The uncertainties at the global scale in climate change projections for the City of Cambridge have been reduced by using a range of greenhouse gas emission scenarios and by using an ensemble of nine global climate models. Using a lower and a higher emission scenario reduces uncertainties by providing a range of "plausible" future scenarios under different projections for future population, demographics, technology and energy use, rather than relying on one single such scenario. This causes the results to be bound by best- and worst-case scenarios, with the intent that possible futures would be contained within them. Using model output from an ensemble of nine GCMs, and then selecting the median values for these GCMs for temperature and precipitation projections reduces the uncertainty related to relying on one or two GCMs that may be either highly sensitive or relatively insensitive to greenhouse gas concentrations and other climate drivers.

Uncertainties in downscaling methods have been addressed for design storm projections by using results from two different downscaling methods (station-based statistical downscaling for the City of Cambridge and grid-based statistical downscaling for the City of Boston). Since it was not possible to do the same for all other temperature and precipitation projections, inherent uncertainties from downscaling still remain. The uncertainties from choice of weather stations that capture climate variability have been reduced by using the projections from multiple weather stations in and around Cambridge.

According to the IPCC uncertainty guidance document, likelihood, as defined in Table 1 below, provides calibrated language for describing quantified uncertainty. It can be used to express a probabilistic estimate of the occurrence of a single event or of an outcome (e.g., a climate parameter, observed trend, or projected change lying in a given range). Likelihood may be based on statistical or modeling analyses, expert views, or other quantitative analyses.

Likelihood Scale	
Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33-66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

Table 1: Likelihood Scale[6]

*Additional terms that were used in limited circumstances in the AR4 (*extremely likely* 95-100% probability, *more likely than not* - >50-100% probability, and *extremely unlikely* – 0-5% probability) may also be used in AR5 when appropriate.

[6] Guidance Note for Lead Authors of the **IPCC** Fifth Assessment Report on Consistent Treatment of Uncertainties IPCC, July 2010. http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

Climate Change Scenarios for Cambridge

Climate change projections for Cambridge, historic extreme weather observations and expert judgement, were used to determine the most plausible climate change scenarios for Cambridge for the 2030s and 2070s planning horizons. The sections below presents the key findings for each climate parameter and the respective scenarios used for 2030s and 2070s. In many cases, the scenarios have an an upper and lower bound to explain the range of plausible future scnearios that may occur in the City under climate change conditions. These future scenarios served as “stress-test” conditions for assessing impacts to built infrastructure, as well as to the social environment in the City.

Temperature Scenarios for 2030s and 2070s

Over the coming century, mean annual and seasonal temperatures in Cambridge are expected to increase. Historically, annual temperature (night + day) averaged around 50^{o}F in Cambridge. Annual temperature is projected to be around 53^{o}F by 2030s, and as much as around 56-59^{o}F by 2070s, as reported in Table 2. For extreme temperature indicators, days per year with maximum air temperature greater than 90^{o}F and 100^{o}F were used. By 2030s, it is likely that days above 90^{o}F per year will triple and, by 2070s, days above 90^{o}F per year will increase six fold, with 6-15 days per year above 100 F. Historically, there have been less than 1 day per year above 100^{o}F in the Cambridge region.

A critical measure for temperature is the heat index, which combines ambient air temperature and relative humidity to determine the “feels-like” or the human-perceived temperature. Heat index is a key indicator for reporting public health concerns since heat index exceeding 91^{o}F is considered to be in the “extreme caution” zone from prolonged exposure to heat or strenuous activity. Historically, average daily summer heat index in Cambridge hovered around 85^{o}F. By the 2030s, summer heat index is projected to average around 95^{o}F, and by the 2070s, it is projected to exceed 100^{o}F for the lower scenario and 115^{o}F for the higher scenario.

Temperature Changes	Baseline	2030s (2015-2044)		2070s (2055-2084)	
	1971-2000	Lower	Higher	Lower	Higher
Annual Temperature (ºF)	50	53.3	53.5	55.8	58.7
Summer Temperature (ºF)	70.6	74.5	74.8	77.4	80.6
Winter Temperature (ºF)	29.8	32.2	33	34.6	38
Days > 90ºF (days/year)	11	29	31	47	68
Days > 100ºF (days/year)	<1	2	2	6	16
Heat Index (ºF)	85	94.75	96	101	115.5

Table 2: Temperature projections [7]

The temperature scenario used to assess impacts on the built environment in this project corresponds to heat wave scenarios. Four consecutive days with maximum ambient air temperature at 90ºF by 2030s was selected as a highly plausible scenario since by then approximately 30 days per year are projected to be above 90ºF. The heat wave scenario selected for 2070s corresponds to five consecutive days with maximum ambient air temperature at or above 90ºF, which includes three consecutive days at 100ºF, also a highly plausible scenario considering that it is projected that 68 days per year might be at or exceeding 90ºF by 2070s.

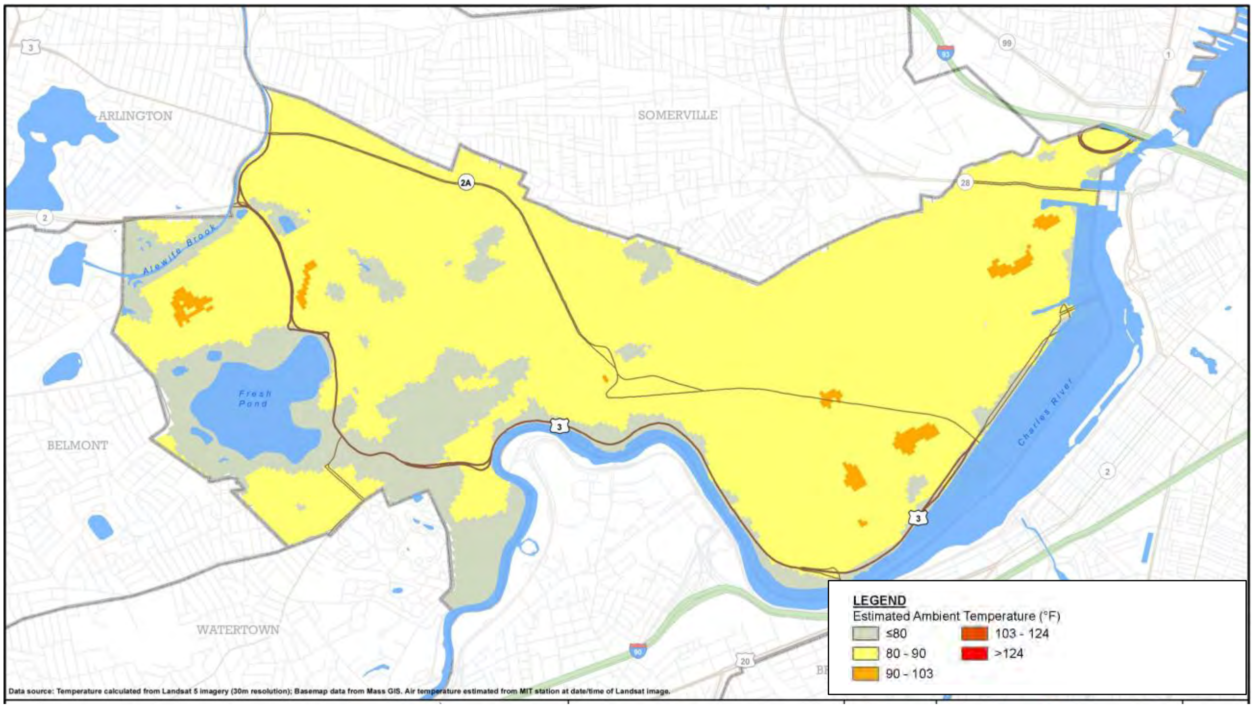
The temperature scenario used to assess impacts on the social environment or health impact corresponds to a heat wave scenario by 2030s with four consecutive days of maximum heat index at 96ºF. The 2070s scenario corresponds to a longer more intense heatwave: five consecutive days with maximum heat index at or above 100ºF, including three consecutive days with heat index at 115ºF.

Mapping Temperature Scenarios for 2030s and 2070s

The heat wave scenarios for Cambridge were mapped in GIS using Landsat data and other information such as tree canopy cover, LiDAR elevation data, and percent urban. The maps are used to illustrate how localized heat island impacts in the City are projected to increase in both extent and intensity by 2030s and 2070s. The heat island map for assessing the impact on vulnerable populations (part of the social environment) was modified to include the heat index impacts. The figures below present the heat island maps for ambient temperatures for present conditions, 2030s and 2070s that were used to assess heat impact on the built environment (Maps 1 through 3). Urban heat islands maps factoring in heat index/relative humidity (Maps 4 through

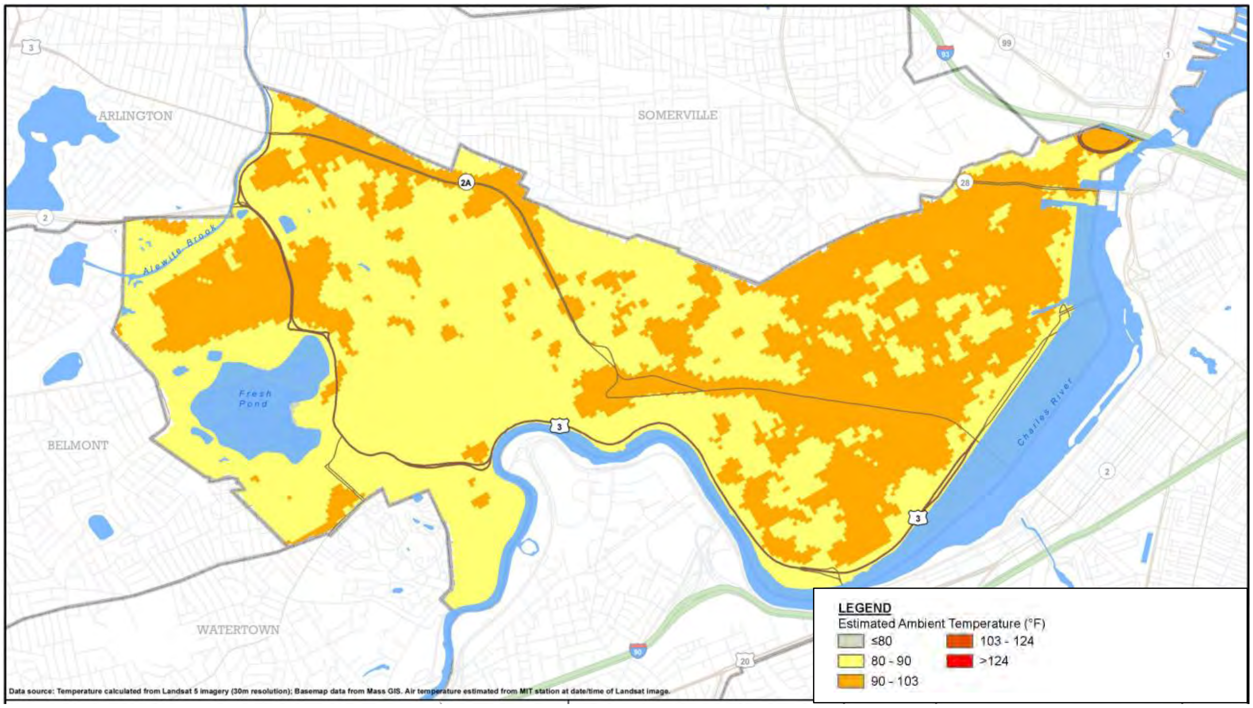
[7] Source: ATMOS Report, CCVA, October 2013.

6) were used to assess heat impact on vulnerable populations. A limitation of future scenario maps is that they are only snapshots of conditions at a particular moment and do not depict temporal aspects of heat waves. For example, heat can build up in the environment over the duration of a multi-day heat wave, preventing nighttime temperatures from dropping back to safer levels and elevating heat stress. Heat island effects are expected to be more intense if the longer duration of future heat waves could be factored into these maps (Appendix D for detailed report on methodology for developing the heat index maps.).

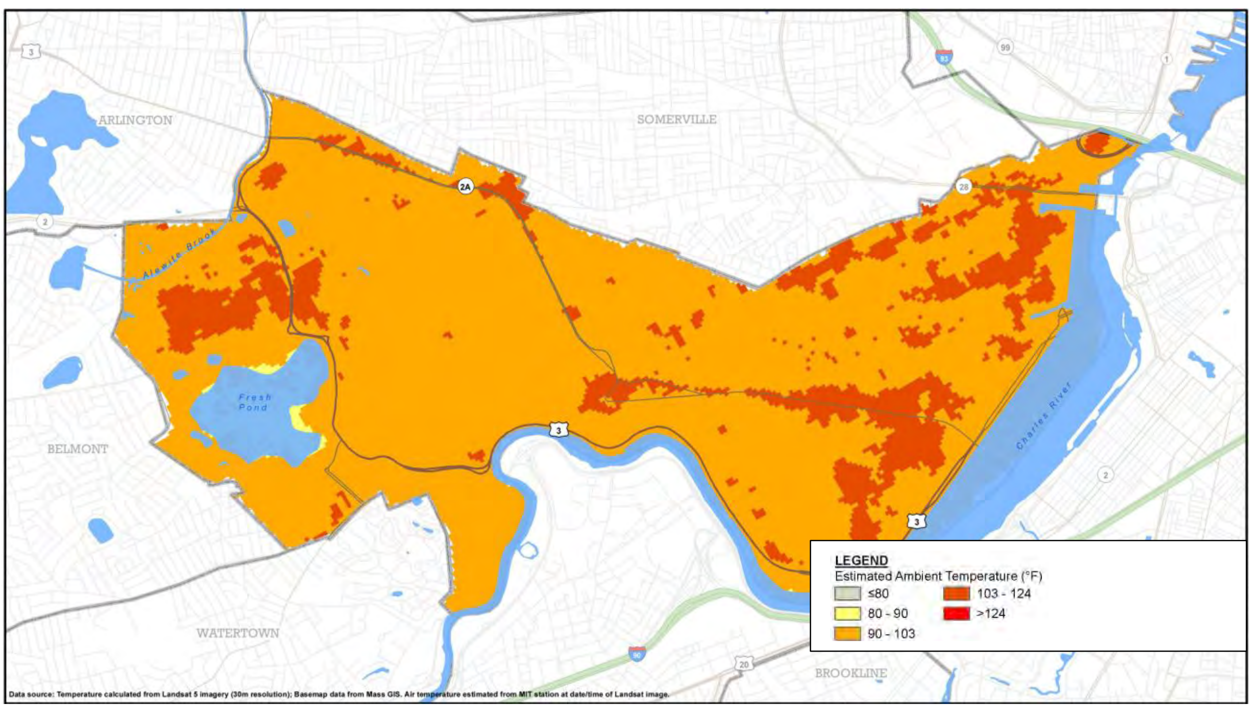


Map 1: Ambient air temperature variability under present conditions on an 83°F day (based on available recorded data)[8] with localized heat islands above 100°F.

[8] Source: Kleinfelder, November 2015

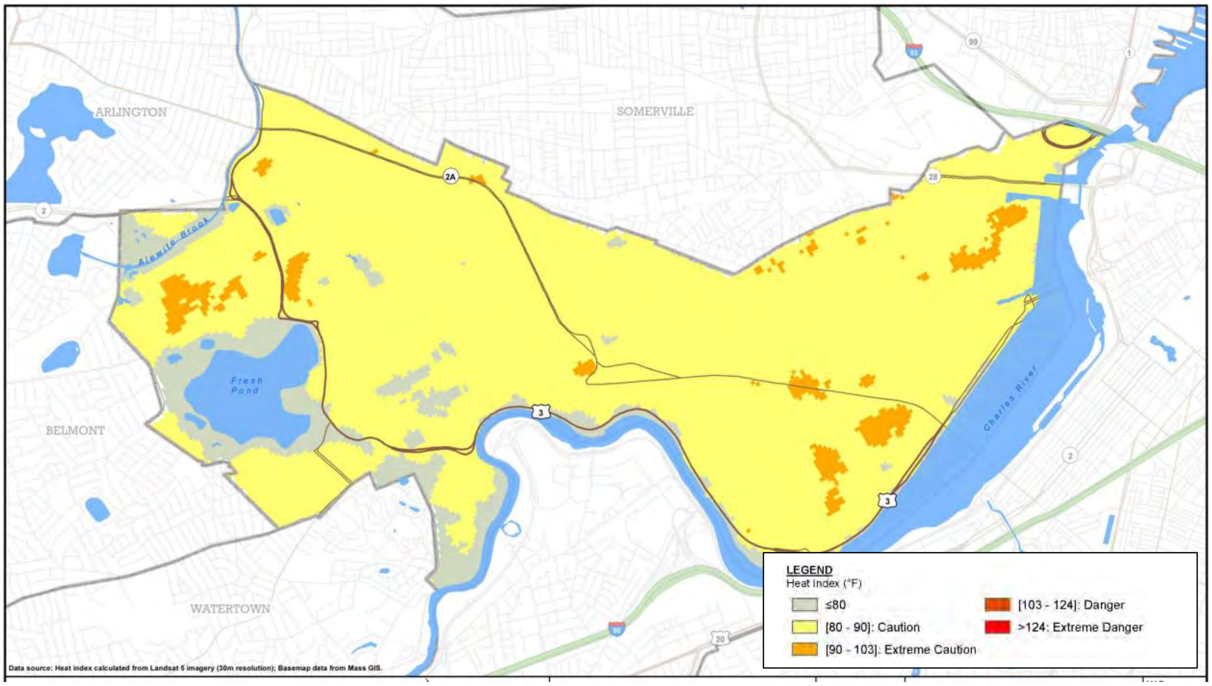


Map 2: Ambient air temperature variability by 2030s on a 90ºF day with localized heat islands above 100ºF.[9]

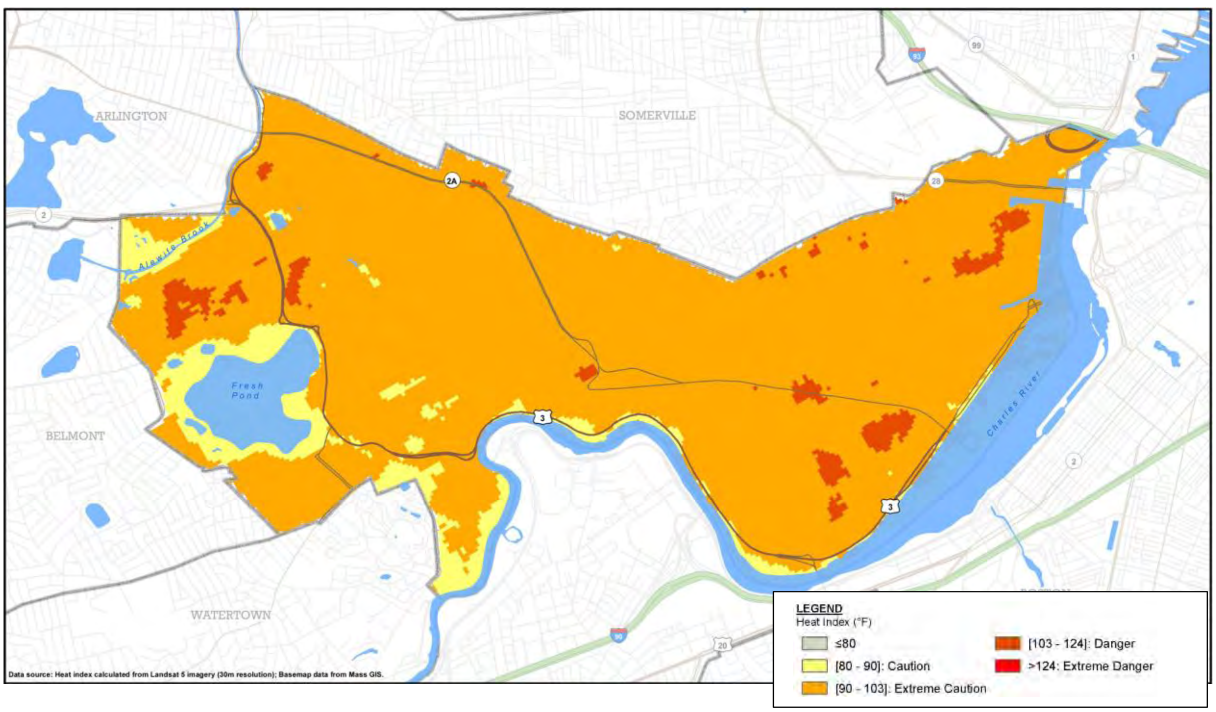


Map 3: Ambient air temperature variability by 2070s on a 100ºF day with localized heat islands above 100ºF[9].

[9] Source: Kleinfelder, November 2015

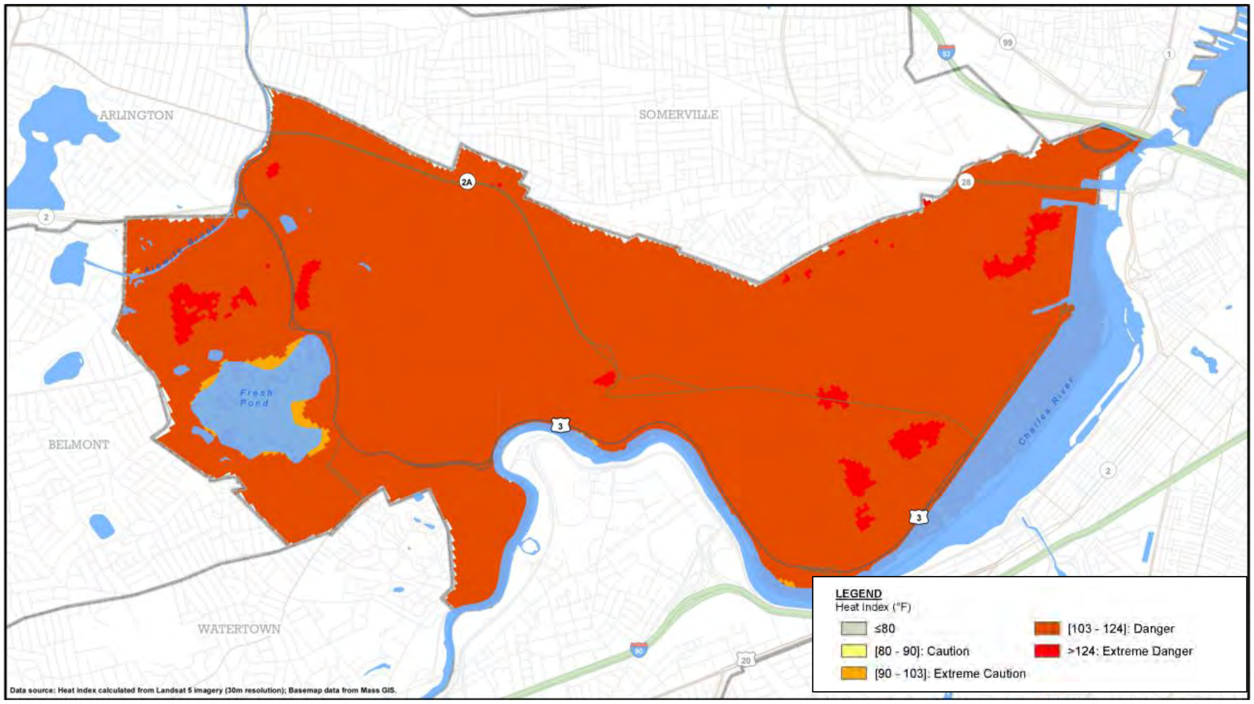


Map 4: Heat index variability under present conditions on a day when average "feels-like" temperature is 85ºF (based on available recorded data) with localized heat islands above 100ºF [10]



Map 5: Heat index variability by 2030s on a day when average "feels-like" temperature is 96ºF (90ºF ambient temperature with relative humidity of 50-55%) with localized heat islands above 100ºF[10].

[10] Source: Kleinfelder, November 2015



Map 6: Heat index variability by 2070s on a day when average "feels-like" temperature is 115ºF (100ºF ambient temperature with relative humidity of 45-50%) with localized heat islands above 120ºF[11].

Precipitation Scenarios for 2030s and 2070s

Annual precipitation is projected to remain fairly constant through the 2030s and increase by approximately 6 to 10 inches or 15-20% by the 2070s compared to the historical period. These increases are projected to occur primarily in winter and spring (Table 3). Precipitation intensity (a measure of the total annual average amount of precipitation falling per day, defined as total annual precipitation divided by the number of wet days per year) is expected to increase by around 5% by the 2030s and 15% by the 2070s. In the future, the projected increase in precipitation intensity is expected to continue, with greater changes by 2070s. The same holds true for the extreme precipitation events.

For the extreme precipitation projection, the City of Cambridge and Boston Water and Sewer Commission collaborated on development of design storm 'values' that take into consideration projected climate change for planning purposes. Design storms are used to assess carrying capacities and level of service associated with drainage systems, as well as to determine flooding/overflows associated with stormwater/sewer infrastructure. Estimating rainfall depths

[11] Source: Kleinfelder, November 2015

associated with design storms for future planning horizons is important since historic precipitation patterns are already changing and projected to further change in terms of both intensity and frequency. Therefore, new construction projects designed to alleviate flooding and/or upgrades to existing stormwater/wastewater infrastructure to mitigate flooding impacts need to be evaluated in terms of their performance under future rainfall depths. The main objective of the collaborative effort was to address this very issue. The projected rainfall depths associated with 24-hour and 48-hour duration design storms with recurrence intervals of 10, 25, and 100 years were estimated for mid-century and late-century time frames (Table 3). For these design storm estimates, local and state government agencies reached consensus on using the same design values, thus building regional consistency and ensuring compatibility between systems that intersect across municipal boundaries.

It can be observed from the results in Table 3 that for the 24-hour duration storms, the 25-year storm of today will be the 10-year storm by 2070s, and the 100-year storm of today will be the 25-year storm by 2070s. The recurrence interval for a storm refers to its probability of occurrence. Therefore, a "10-year storm", or a 1-in-10-year storm, is a storm that has a 10% probability of its rainfall amount being equaled or exceeded in any given year, a "25-year storm" is one that has a 4% annual probability of occurrence and a "100-year storm" is one that has a 1% probability of this occurring in any given year.

Precipitation Changes	**Baseline**	**2030s (2015-2044)**		**2070s (2055-2084)**	
	1971-2000	**Lower**	**Higher**	**Lower**	**Higher**
Annual Precipitation (in.)	45	48	48	51.5	54
Summer Precipitation (in.)	9.5	9.8	9.8	10.1	10.3
Winter Precipitation (in.)	11.4	12.6	12.7	14.1	15.4
# days per year > 2 in. rain in 24 hrs (days)	2	3	3	3	3
Max. 5-day precipitation per year (in.)	6	6.5	6.6	7	7.2
24-hr design storms					
10yr	4.9	5.6		6.4	
25 yr	6.2	7.3		8.2	
100 yr	8.9	10.2		11.7	
48-hr design storms					
10yr	5.5	6.4		7.2	
25 yr	7	8.6		9.8	
100 yr	10	13.2		15.7	

Table 3: Precipitation projections [12]

[12] Source: ATMOS Report, CCVA, October 2013, BWSC Climate Projections

The precipitation scenarios that were used for assessing the impacts on Cambridge for both the built and social environment corresponded to the extreme precipitation events defined by the 24-hour duration storms. For both 2030s and 2070s, the 10-year event was selected as the "lower scenario" since it has a higher probability of occurrence (10%) in any given year, and the 100-year event was selected as the "higher scenario" since it has a lower probability of occurrence (1%) in any given year.

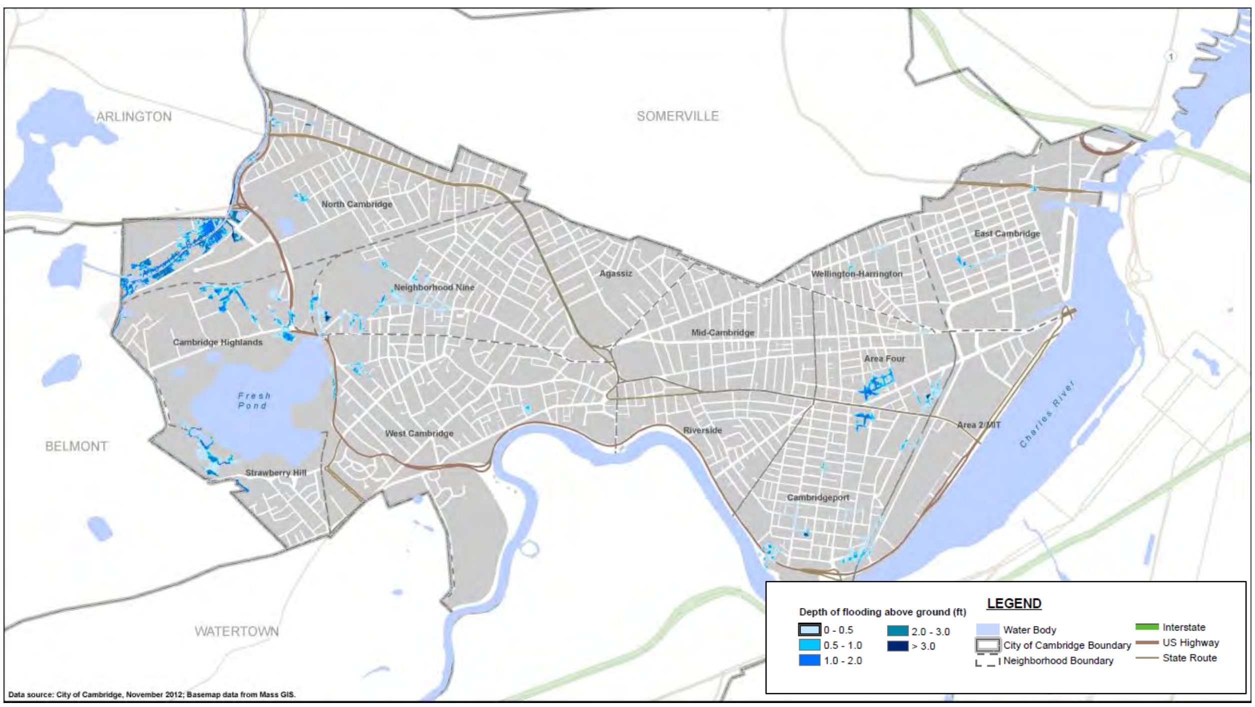
Modeling and Mapping Precipitation Scenarios for 2030s and 2070s

One of the unique aspects of this project is the development of a linked precipitation model that takes into account overland/surface flooding, both in the Charles River and Alewife Brook watersheds, and flooding from the piped infrastructure (e.g., manholes flooding, pipes surcharging, overflows at outfalls, etc.) due to capacity issues in the City's stormwater and combined sewer collection systems. The integration of the precipitation modeling results with sea level rise and storm surge modeling will be conducted in Part 2 of the Vulnerability Assessment. The development of this overarching model relied on integrating the studies, models, and information from numerous regional stakeholders including municipal and state agencies (City of Cambridge, Boston Water and Sewer Commission, MA Department of Conservation and Recreation), academia (Paul Kirshen, University of New Hampshire and Ellen Douglas, University of Massachusetts, Boston) and consultants (MWH, VHB, Woods Hole Group).

The overland flooding from the upper Charles River basin, which is upstream of the Watertown Dam, and hence upstream of Cambridge, was estimated using a unit hydrograph model. The overland flooding and piped infrastructure flooding for areas in Cambridge in the lower Charles River basin (downstream of the Watertown Dam to the New Charles River Dam) have been modeled using the ICM-2D model. The overland flooding and piped infrastructure flooding for areas in Cambridge in the Alewife Brook sub-basin have been modeled using a combination of the HEC-RAS model and the ICM-2D model.

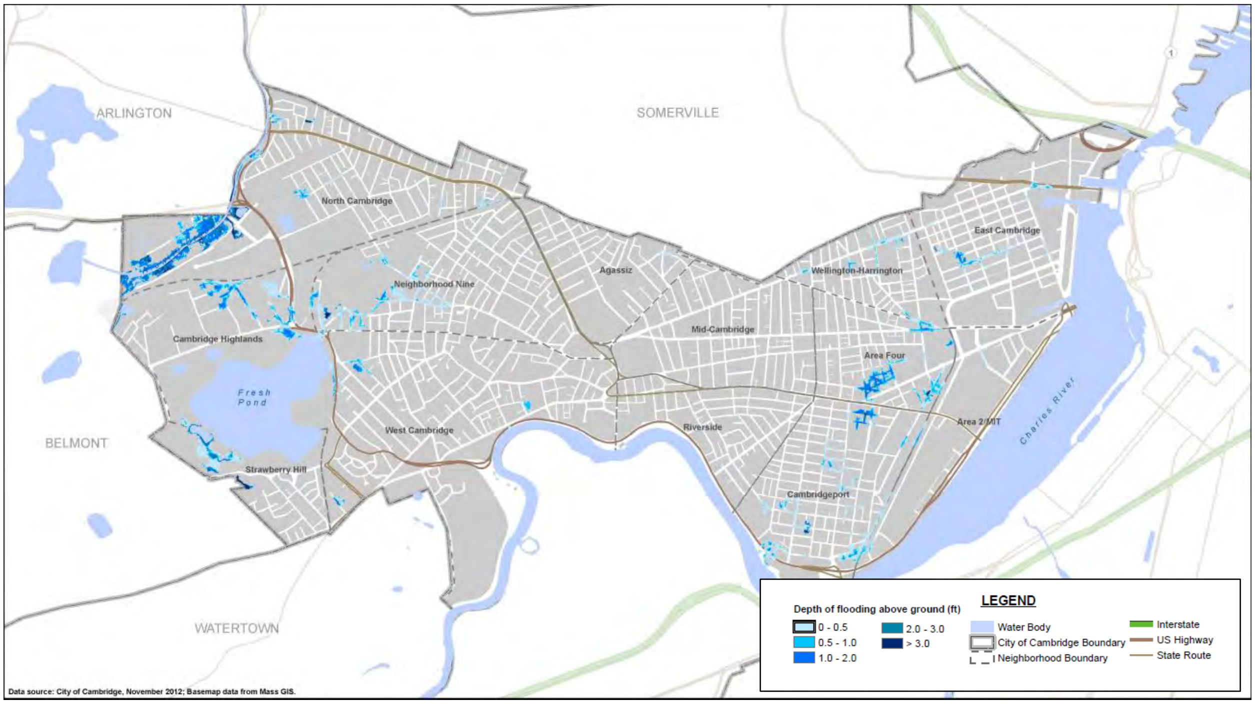
The models also considered assumptions on the operations of the Charles River Dam and the Amelia Earhart Dam (e.g. pumps, lock gates operations, etc.) in maintaining their respective basin elevations in response to "stress" from extreme precipitation events. It is important to report that the operations of the dams play a critical role in limiting flooding impacts both upstream and downstream of the dam. For example, if all three pumps at the Amelia Earhart Dam were assumed to be operational in the precipitation models, the projected extent and depth of flooding in the north and west of Cambridge for present and future 100-year storm events by 2030s and 2070s were less when compared to the scenario when only two of those pumps are operational. The two-pump scenario was considered in the FEMA maps, which consequently report greater extent of flooding under a similar storm event.

The precipitation scenarios for Cambridge were mapped in GIS using the integrated output from the different models. The impact of these probable scenarios were assessed in the vulnerability and risk assessment task to understand the impacts of both flooding extent and depth on specific assets and systems in the built and social environment. The figures below present the precipitation flooding maps for present conditions, 2030s, and 2070s for the “lower” scenario 10-year storm event (Maps 7 through 9), and for the “higher” scenario 100-year event (Maps 10 through 12), respectively.

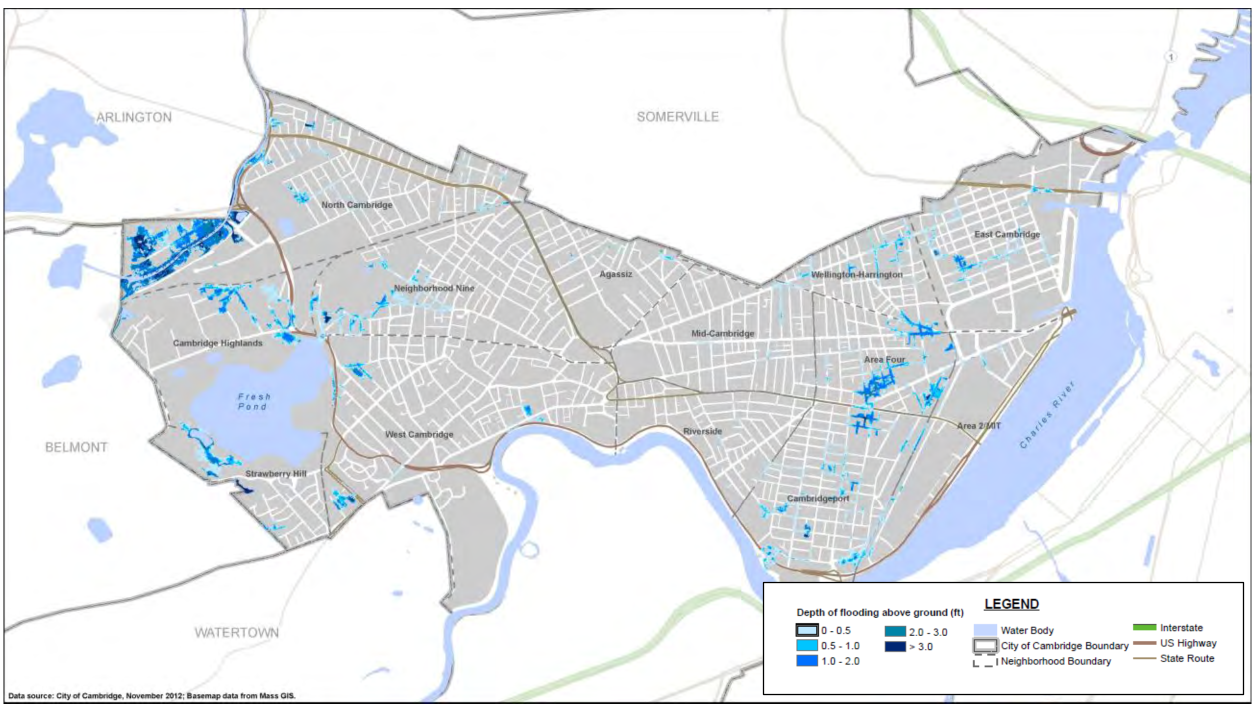


Map 7: Present conditions precipitation flooding – current 10-yr 24-hr storm (4.9 inches over 24 hours) [13]

[13] Source: Kleinfelder, November 2015, informed by MWH (manhole) and VHB (riverine) models

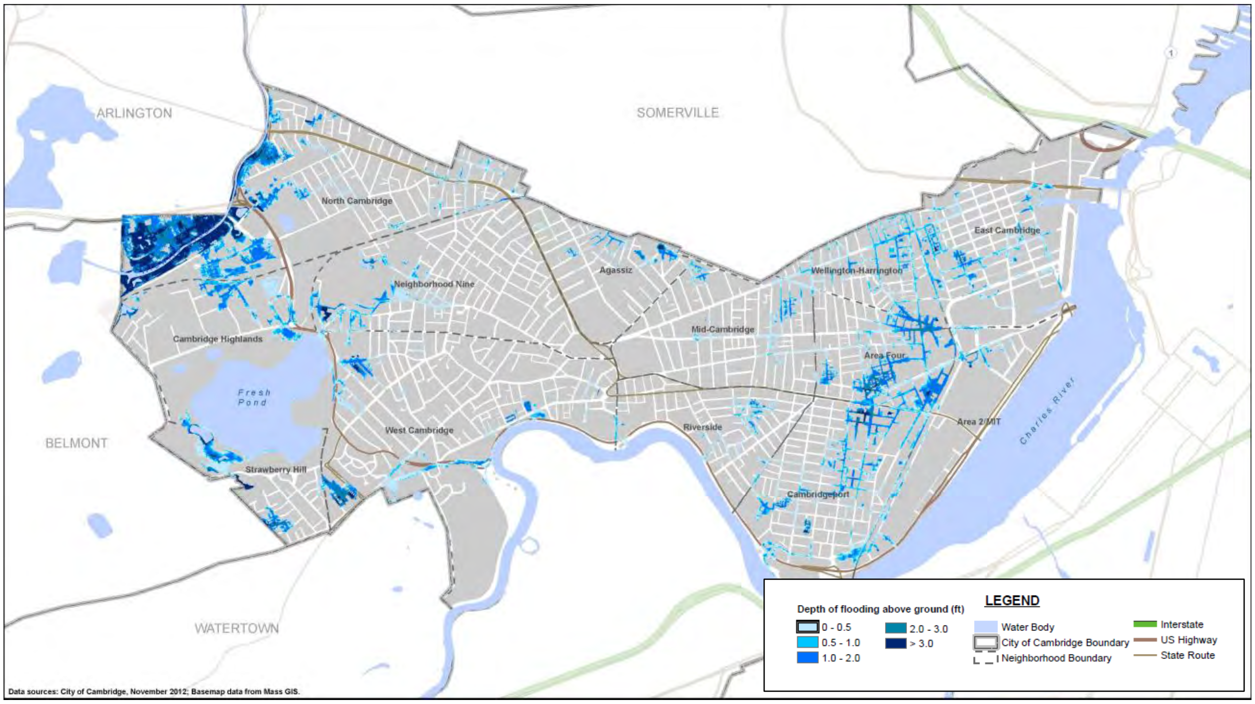


Map 8: Precipitation flooding scenario – 10-yr 24-hr storm by 2030s (5.6 inches over 24 hours) [14]

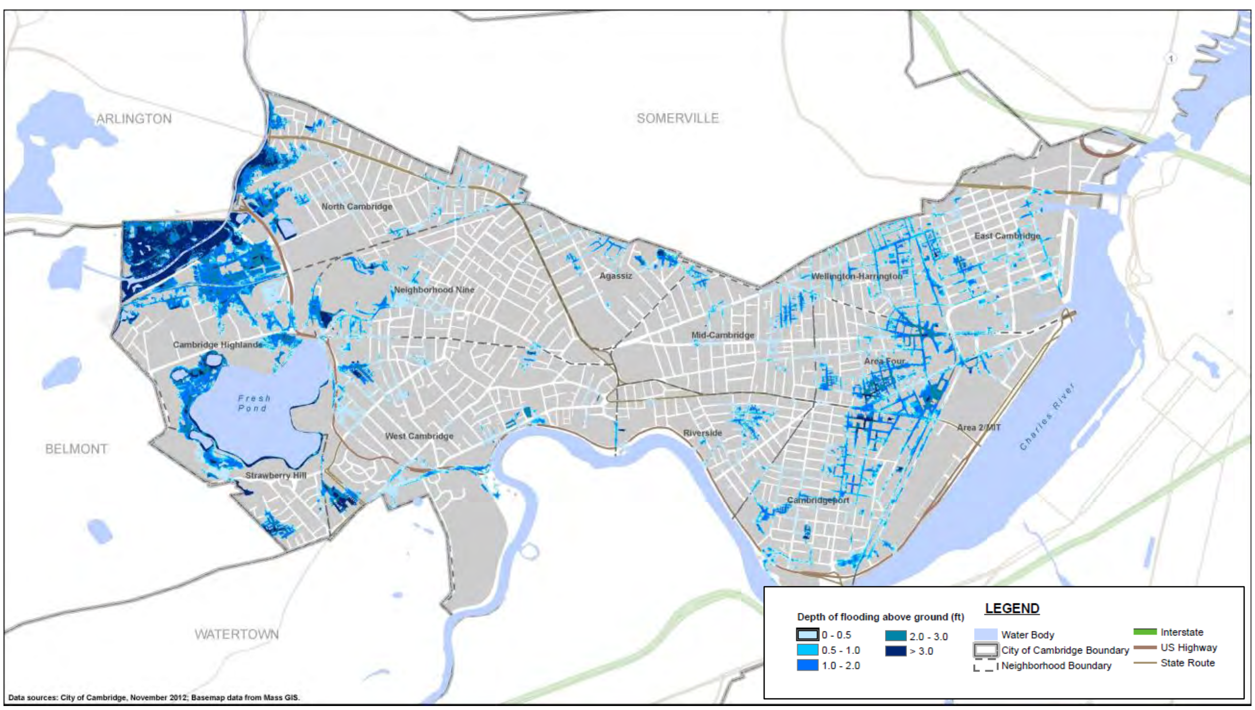


Map 9: Precipitation flooding scenario – 10-yr 24-hr storm by 2070s (6.4 inches over 24 hours). [14]

[14] Source: Kleinfelder, November 2015, informed by MWH (manhole) and VHB (riverine) models

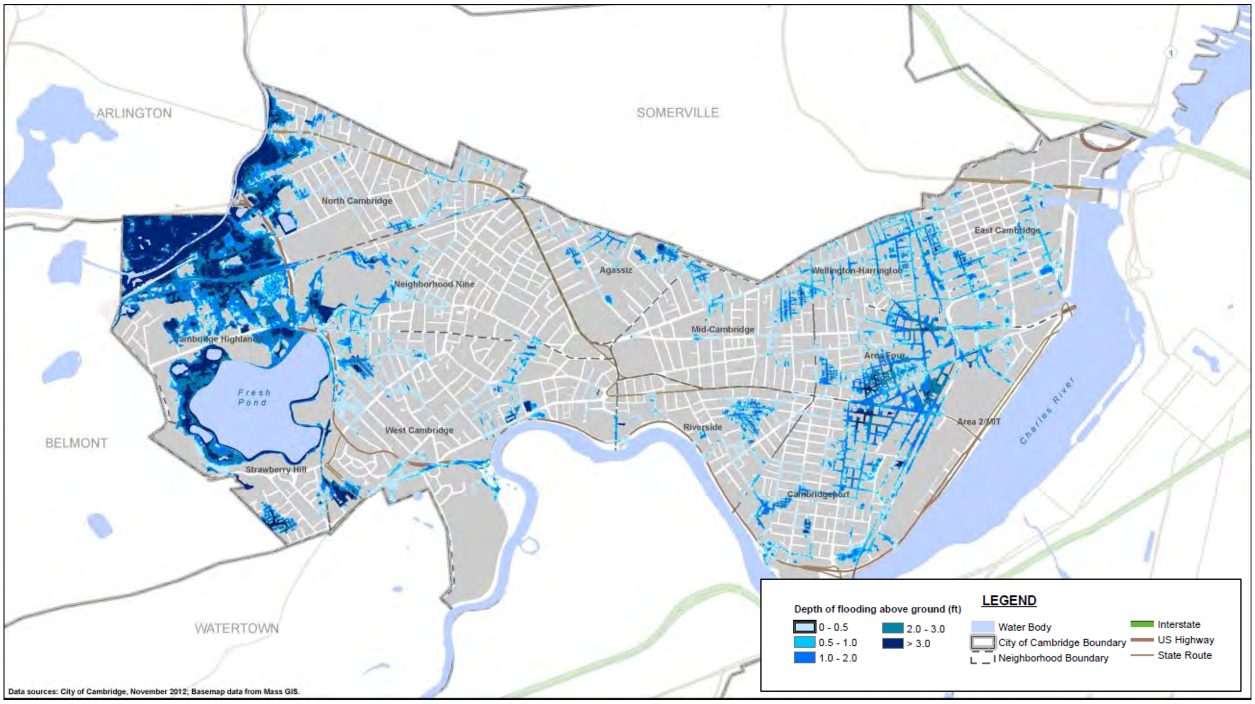


Map 10: Present conditions precipitation flooding – current 100-yr 24-hr storm (8.9 inches over 24 hours) [15]



Map 11: Precipitation flooding scenario - 100-yr 24-hr storm by 2030s (10.2 inches over 24 hours) [15]

[15] Source: Kleinfelder, November 2015, informed by MWH (manhole) and VHB (riverine) models



Map 12: Precipitation flooding scenario –100-yr 24-hr storm by 2070s (11.7 inches over 24 hours) [16]

Sea Level Rise and Storm Surge Scenarios for 2030s and 2070s

Over the past century, sea levels have been rising as a result of climate change. Oceans have warmed, causing their volumes to expand, and glaciers and land-based ice have melted, contributing additional fresh water to the oceans' volumes. Global sea level rise (SLR) and relative SLR in Boston have been respectively occurring at average rates of 0.07 inches per year[17], and 0.11 inches per year[18] (NOAA 2013). Relative SLR in the Boston area has been higher than global SLR because the local landmass in Boston has been sinking at an estimated rate of 0.04 inches per year (the result of long-term geological processes). Sea level rise is expected to continue, and even accelerate in the future, due to climate change.

To provide the City of Cambridge with reasonable estimates of future sea levels, relative SLR in Boston Harbor has been projected up to the year 2100 from the baseline year of 2013. The projections are based on the "Highest" and "Intermediate High" scenarios for global SLR recommended by NOAA (2012), as well as the estimated rate of local land subsidence in Boston (0.04 inches per year). Estimates of total relative SLR in Boston Harbor are listed in Table 4, in

[16] Source: Kleinfelder, November 2015, informed by MWH (manhole) and VHB (riverine) models
[17] Global sea level rise scenarios: National Oceanic and Atmospheric Administration (NOAA). 2012. Technical Report: Global Sea Level Rise Scenarios for the United States National Climate Assessment. http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf
[18] National Oceanic and Atmospheric Administration (NOAA) 2013. Updated Mean Sea Level Trends – 8443970 Boston, Massachusetts. http://tidesandcurrents.noaa.gov/sltrends/sltrends_update.shtml?stnid=8443970

increments of 10 years from 2020 through 2100. According to this, the relative mean sea level is projected to rise by 0.66 ft. by 2030 and by 3.39 ft. by 2070 according to the “Highest” scenario.

Scenarios	2020	2030	2040	2050	2060	2070	2080	2090	2100
Global SLR (from 2013-2020) "Highest" (feet)	0.21	0.61	1.10	1.70	2.40	3.21	4.11	5.12	6.23
Global SLR (from 2013-2020) "Intermediate-High" (feet)	0.14	0.38	0.68	1.04	1.46	1.93	2.46	3.05	3.69
Land subsidence (feet) @ 0.04 in./yr.	0.02	0.06	0.09	0.12	0.15	0.19	0.22	0.25	0.29
Total Relative SLR - "Highest" (feet)	0.24	0.66	1.19	1.82	2.56	3.39	4.33	5.37	6.52
Total Relative SLR – "Intermediate-High" (feet)	0.16	0.44	0.77	1.16	1.61	2.12	2.68	3.30	3.98

Table 4: "Highest” and “Intermediate-High” scenario projections for relative SLR in Boston (2013-2100) [19,20]

Modeling and Mapping Sea Level Rise and Storm Surge Scenarios for 2030s and 2070s

The impacts of sea level rise and storm surge by 2030 and 2070 for the City of Cambridge were modeled using the Boston Harbor Flood Risk Model (BH-FRM) that is currently being developed by the Woods Hole Group for the greater Boston area including Cambridge and surrounding communities in Massachusetts. The BH-FRM has been 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 modeling system 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 relevant for Cambridge extends to the Watertown Dam,

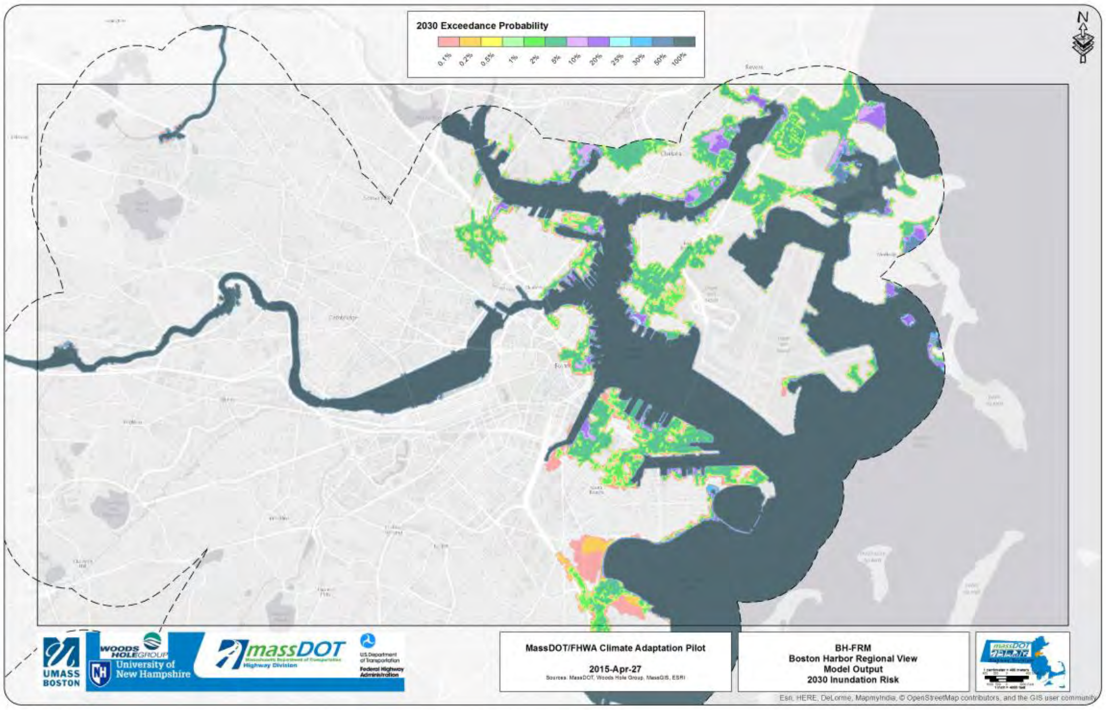
[19] Source, global sea level rise scenarios: National Oceanic and Atmospheric Administration (NOAA). 2012. Technical Report: Global Sea Level Rise Scenarios for the United States National Climate Assessment. Online at: http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

[20] Source, local land subsidence rate: Massachusetts Executive Office of Energy and Environmental Affairs (EEA) and Massachusetts Climate Change Adaptation Advisory Committee. 2011. Massachusetts Climate Change Adaptation Report. Online at: http://www.mass.gov/eea/waste-mgnt-recycling/air-quality/green-house-gas-and-climate-change/climate-change-adaptation/climate-change-adaptation-report.html

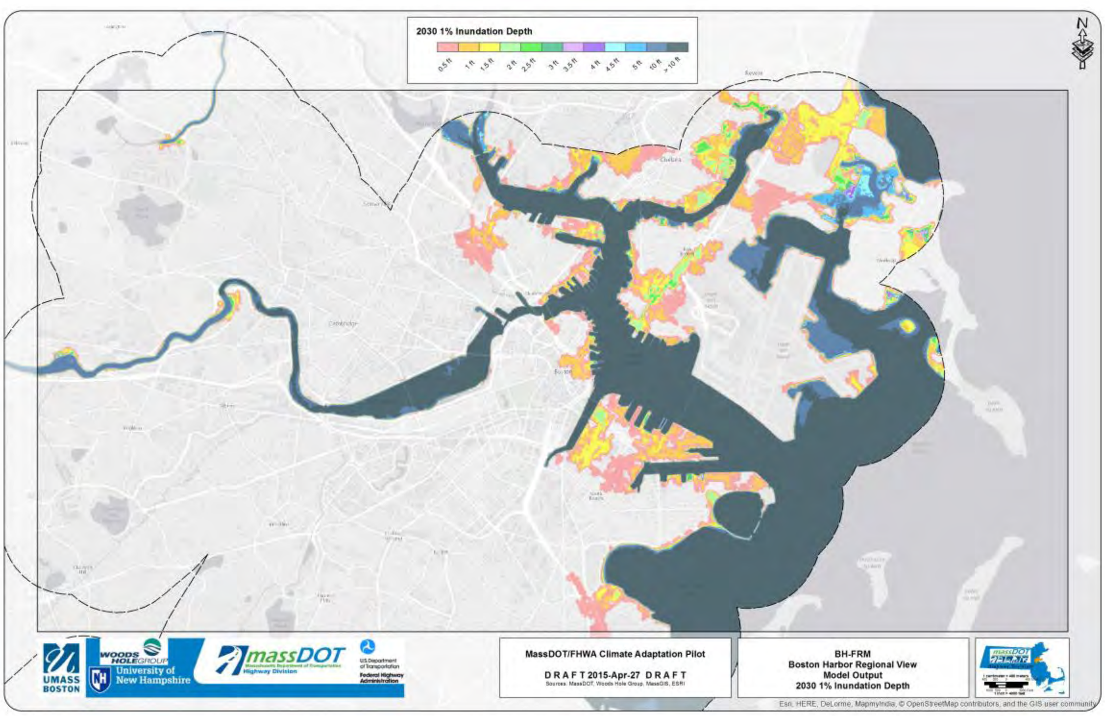
for the Charles River basin side, and upstream of the Amelia Earhart Dam and downstream of the Alewife Brook, for the Alewife Brook sub-basin side.

The sea level rise scenarios for 2030 and 2070 presented in Table 4 were considered in the BH-FRM. The modeling approach is risk-based, which uses a fully optimized Monte Carlo approach, simulating a statistically robust set of storms (both tropical storms such as hurricanes and extra-tropical storms such as nor'easters) for each sea level rise scenario. The storm climatology for the hundreds of different types of storms are all factored in the Monte Carlo simulations of these storm events. The storm climatology is based on present climate for planning horizons until 2050, but for storm simulations beyond 2050, the 21st century climatology is used to simulate the storms.

Results of the Monte Carlo simulations are used to generate Cumulative probability Distribution Functions (CDFs) of the storm surge water levels at a high degree of spatial precision, which will be beneficial to the City to assess the vulnerability and risk for infrastructure, and develop its climate change preparedness plan. The BH-FRM results for 2030 for the greater Boston area including Cambridge are illustrated in Maps 13 and 14. Map 13 presents the percent probability of flooding by 2030, with different colors corresponding to different probability levels of flooding. Map 14 presents the depth of flooding above existing ground by 2030s under a 1% probability level, which is similar to the 100-year flood event.



Map 13: Inundation risk map for 2030s[21]



Map 14: Depth of flooding map at 1% risk for 2030s[21]

[21] Massachusetts Department of Transportation (MassDOT). 2015. FHWA Climate Adaptation Pilot, Draft BH-FRM Model Output for 2030

Key findings from the sea level rise and storm surge model for Cambridge for the 2030s:

- There is very low risk (no coastal flooding at reasonable probability levels) for Cambridge up to 2030s.
- Both the Charles River Dam and the Amelia Earhart Dam provide protection up to 2030s and are not overtopped or flanked for a reasonable risk level, which implies that the probably to overtop the dams is infinitesimal. This may change with 2070s conditions.
- There is a flooding pathway towards Cambridge from the Schrafft's City Center area in Somerville, but it does not propagate far enough south to cross into Cambridge up to 2030s. This may also change in 2070s.
- Flooding does occur on the south side of the Charles River Dam during storm events, but does not actually flank the dam. The wall along I-93/Beverly Street keeps the water on the east side, which may also change in 2070s results.
- Up to 2030s, no coastal storm surge will propagate upstream of the Mystic River in the Alewife Brook area as long as the Amelia Earhart Dam is functional and is operated correctly. The small pockets of flooding shown in Maps 13 and 14 are due to overbank flooding. These estimates of overbank flooding are approximate since river discharge-based dynamic flooding was not the main focus of the BH-FRM model.
- The heavy river discharge does cause some flooding along the banks of the Charles and Mystic Rivers just due to the extreme discharge flow (e.g., the Oxbow region of the Charles River), but this is not coastal-based, rather just heavy discharge down the river interacting with a reduced flow capacity in the region.

Assumptions used in the BH-FRM model for Charles River Dam operations:

- The model keeps the upstream basin between 108.5 feet MDC (2.07 feet NAVD88) and 106.5 feet MDC (-0.07 feet NAVD88), just like the actual operations. When the water in the basin reaches the 108.5 feet MDC level, all six pumps turn on in the model and pump water downstream of the dam. When the water elevation is lowered to 106.5, the pumps turn off. In the model, this is a simple binary operation: either all six pumps are on, or they are all off. However, in real life, there may be a management/human element involved, and all six pumps may not be turned on/off at the same time.
- In all coastal storm scenarios, the 100-year 24-our duration discharge hydrograph for 2030s at Charles River has been applied such that the peak discharge approximately aligns with the peak of the storm surge. The probability that they would align is low, but

this conservative scenario was selected to understand the impacts from the worst case for flooding.

- All six pumps at the dam are assumed to be operational and have full capacity if needed. Scenarios when pumps fail or are inoperable are not part of the current model.
- Each of the six pumps has a maximum capacity of 1400 cfs.

Assumptions used in the BH-FRM model for Amelia Earhart Dam operations:

- The model keeps the upstream basin between 106.5 feet MDC (-0.07 feet NAVD88), and 104.5 feet MDC (-1.93 feet NAVD88), just like the actual operations. When the water in the basin elevation reaches 106.5 feet MDC, all three pumps turn on in the model and pump water downstream of the dam. When water elevation is lowered to 104.5 feet MDC, the pumps turn off. In the model, this is a simple binary operation: either all six pumps are on, or they are all off. However, in real life, there may be a management/human element involved, and all three pumps may not be turned on/off at the same time.
- In all coastal storm scenarios, the 100-year 24-hour duration discharge hydrograph for 2030s at Alewife Brook has been applied such that the peak discharge approximately aligns with the peak of the storm surge. The probability that they would align is low, but this conservative scenario was selected to understand the impacts from the worst case for flooding.
- All three pumps at the dam are assumed to be operational and have full capacity if needed. Scenarios when pumps fail or are inoperable are not part of the current model.
- Each of the three pumps has a maximum capacity of 1400 cfs.

Next Steps

It is important to emphasize that the proposed climate scenarios present a permutation of possible flood and heat events illustrating “probable futures” as guidance for preparedness planning. These projections are meant to be reviewed and updated as the science of climate change evolves with new tools and informed by revised observed trends.

The vulnerability and risk assessments for the City’s critical assets and resources was performed using the projected “exposures” recorded as increase in temperature in degree Fahrenheit and depth of flooding as measured in the probable scenarios.

Demographic Projections – 2030s

In evaluating impacts, the City of Cambridge Vulnerability Assessment takes into account climate projections for the 2030 and 2070 scenario. As part of this assessment, we propose that the City incorporate the MAPC dynamic modeling of population projections as developed in the ‘Population and Housing Demand Projections for Metro Boston: Regional Projections and Provisional Municipal Forecasts’ report (Metro Future)[22]. The vulnerability of the Cambridge social environment will be shaped by the demographic and housing landscape projected under the 2030 and 2070 scenarios and will determine the degree of vulnerability based on factors such as age.

Regional population growth projections have been developed up to 2040 and can be used for the 2030s scenario development. We recommend a qualitative approach to predict anticipated population growth for the 2070s scenario, based on the projected growth rates described below.

The MAPC Metro Future report provides regional population projections for two growth scenarios up to 2040 (2010–2040). The two growth scenarios ‘Status Quo’, and ‘Stronger Region,’ represent 6.6% and 12.6% growth, respectively, over the next 30 years. The ‘Status Quo’ scenario is based on current birth, death, migration, and housing occupancy trends, which are key drivers in predicting population growth. The ‘Stronger Region’ scenario assumes a shift in these trends based on key developmental policies to attract and retain a younger population to the urban hubs of the region and affordable city living through job creation and multi-family housing developments. As the City seems to be moving toward this in its policies, and as the region as a whole is experiencing an increase in-migration documented in the American Community Survey report[23], we are recommending the use of the ‘Stronger Region’ scenario as a more representative scenario for Cambridge in 2040.

Tables 5a and 5b below from the Population and Housing Demand Projections for Metro Boston Executive Summary summarize the housing and population increases projected for 2040 under both scenarios.

Status Quo: 6.6% over the next three decades, accompanied by an expanding aging population, which is expected to grow by approximately 36%. The population age group 25 to 64 is anticipated to remain the same[20]. Children under age 15 are projected to increase by almost 30%.

[22] Metropolitan Area Planning Council (MAPC). 2014. Population and Housing Demand Projections for Metro Boston, Regional Projections and Municipal Forecasts. Online at: http://www.mapc.org/data-services/available-data/projections
[23] https://www.census.gov/how/infographics/foreign_born.html

Stronger Region*:* 12.8% over the next three decades with a 7% increase in the population group aged 25 to 64[22] and 40% increase in children under 15. A similar trend is observed with a growing aging population experiencing a marginal increase (38% instead of 36%) as compared to projections under the Status Quo scenario.

No impacts are expected to the labor force unless projects aimed at increasing employment are implemented within the Stronger Region Scenario, which can add 7% growth to the workforce. Based on these projection assumptions, the municipal forecast for Cambridge population growth between 2010 and 2030 is charted in the following tables.

Cambridge 2010 - 2030	**Present**	**Status Quo 2010 - 2030**	
	2010	2030 Projection	Percent Projected Change
Total Population	105,162	110,623	5.19%
Population < 5 years	4,526	5,744	26.91%
Population < 15 years	10,324	13,370	29.50%
Population > 65 years	9,988	13,566	35.82%

Cambridge 2010 - 2030	**Present**	**Stronger Region**	
	2010	2030 Projection	Percent Projected Change
Total Population	105,162	118 625	12.80%
Population < 5 years	4,5 26	6,210	37.21%
Population < 15 years	10,3324	14.508	40.53%
Population > 65 years	9, 988	13,749	37.66%

Tables 5a and 5b: Population and demographic projections based on the Status Quo and Stronger Region scenarios developed by MAPC for 2010 – 2030.[24]

Based on these projections, the City of Cambridge anticipates the population to increase by over 12% under the Stronger Region scenario. Increased population diversity, particularly under the Stronger Region scenario, resulting from higher in-migration rates and an increase in aging population, is anticipated to be similar between the Status Quo and Stronger Region scenarios.

Currently, population below age of 5 or above 65 represents about 13% of the total population. As projected in 2030s, these two age groups combined represent about 17% of the population

[24] Metropolitan Area Planning Council (MAPC). 2014. Population and Housing Demand Projections for Metro Boston, Regional Projections and Municipal Forecasts. Online at: http://www.mapc.org/data-services/available-data/projections

which therefore changes the profile of the City's demographics on how best address public health issues related to climate change, for example heat waves where these two groups are vulnerable.

Since population projections have not been developed past 2040, we recommend the qualitative assessment of vulnerability based on the Stronger Region Scenario using the 12.8% growth rate. We have not yet assessed the demographic shifts likely to occur in this phase of growth (2040 – 2070).