Climate Change Vulnerability Assessment

November 2015

City of Cambridge,
Massachusetts

The CCVA Report

1
Part

ADDITIONAL RESOURCES

The following reports were produced as part of this project and will provide more information on the topics covered in this report:

- ***Climate Projections & Scenario Development***
- ***Critical Assets & Community Resources***
- ***Vulnerability & Risk Assessment Technical Reports***
    - ***Ranking Reports for Critical Assets & Community Resources***
    - ***Climate Change Vulnerability Assessment for the Urban Forest in Cambridge***
    - ***Vulnerable Population Ranking Memorandum***
    - ***Public Health Assessment***
    - ***Economic Vulnerability Assessment***

These technical reports are available online at:

http://www.cambridgema.gov/climateprep

November 2015

Dear Members of the Cambridge Community,

I'm pleased to issue Part 1 of the Cambridge Climate Change Vulnerability Assessment (CCVA) Report. This report is born from a recommendation by the Cambridge Climate Protection Action Committee and concerns expressed by the Cambridge community about the local implications of global climate change. The City recognizes the Intergovernmental Panel on Climate Change's finding that it is unequivocal that climate change is happening and that we are moving in the direction of a warmer planet. It is our responsibility to account for climate change in our planning and decision-making in order to sustain this vibrant City and its people.

The CCVA Report Part 1 makes clear that there will be real and significant risks to Cambridge over time – especially from increasing heat and precipitation-driven flooding – that will threaten public health and safety, our economy, and the City's quality of life if we do not act. This report provides a strong foundation for preparing our community for these risks through a Climate Change Preparedness and Resilience Plan that will be developed over the next few years and serve as a key underpinning for the Citywide Plan. While these planning initiatives move forward, the City will simultaneously pursue early actions. Part 2 of this report that addresses the risks from sea level rise and coastal storm surges will be issued in the next few months.

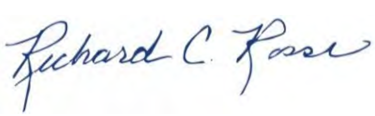
The CCVA Report is a beginning. It will necessarily be a continuous mission to update the vulnerability assessment as the science evolves and new observations are made. The assessment has deepened our understanding of how climate change affects the City. The process has also helped form new relationships among the City, community organizations, institutions, and the private sector within Cambridge and throughout the region that will support all of us in becoming better prepared and more resilient.

A great effort was made to conduct this assessment with the best available science and information and to be transparent and open. The detailed data and analyses behind the report are being publicly-shared to engage and support stakeholders in their own efforts.

The strong support of the City Council through its approval of funding and policy direction, for which I am thankful, has enabled the vulnerability assessment to be conducted. I appreciate all the input and support we have received from the members of the community, the Expert Advisory Panel, and the Technical Advisory Committee, which was critical to the development of this report.

Cambridge is planning ahead for climate change and treating this matter with urgency. I am gratified to see residents, businesses, community organizations, and institutions across the City joining the effort and working together. Making Cambridge better prepared and resilient requires a community-wide effort. The City looks forward to continuing this important work.

Very truly yours,



Richard C. Rossi
City Manager

Fig. 1 **Charles River Basin** (Source: City of Cambridge)

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Acknowledgments

PURPOSE

Heat vulnerability and inland flooding are more imminent concerns for Cambridge than sea level rise.

The City of Cambridge has been an early adopter of sustainability policies and practices. In 1999, the City joined ICLEI - Local Governments for Sustainability. ICLEI is the world's leading network of over 1,000 cities, towns and metropolises committed to building a sustainable future. In 2002, the Cambridge City Council adopted the *Cambridge Climate Protection Plan*, which focused on reducing greenhouse gas (GHG) emissions within the City. For many years, the City's primary focus was on GHG emissions reduction to minimize Cambridge's contribution to climate change. However, scientists tell us that even with reduction initiatives in place, some amount of climate change is "locked in" and will impact our future, and the *Climate Change 2007: Synthesis Report*, by the Intergovernmental Panel on Climate Change (IPCC) warned that climate changes may be irreversible. Based on this understanding, growing public concern, and a strong recommendation from the Climate Protection Action Committee (CPAC) — an advisory group to the City Manager — the City decided that it is necessary to prepare for climate change impacts while continuing to reduce emissions to avoid the worst effects.

Climate change is altering the climatic conditions upon which Cambridge historically developed. The patterns of temperature, precipitation, and sea level that were used to design buildings and infrastructure and locate critical facilities, are shifting to new patterns that will affect both the built environment and people. If left vulnerable, climate change poses significant threats to Cambridge's economy, quality of life, public health, and safety. The City recognizes this and commissioned a study to anticipate how our climate might shift, using the best available science, and to identify our vulnerabilities so that we can manage and protect Cambridge's future under climate change. The City believes it is better to plan ahead and be proactive, instead of trying to react after impacts occur.

The science of climate change is well established. Increasing global temperatures have led to rising sea levels, shrinking of the polar ice caps, receding glaciers, changes in seasonality, and shifting animal and plant populations, among other impacts. While it is scientifically accepted that the global climate is shifting towards warmer conditions, additional work is needed to translate how those changes will present at the local level. The Cambridge Climate Change Vulnerability Assessment (CCVA) provides some of the translation.

The assessment serves as a technical foundation for the Climate Change Preparedness and Resilience Plan that will follow, and for other preparedness initiatives. While we know that climate change is scientifically unequivocal and that the climate is shifting toward a warmer, wetter regime and higher sea levels, it is difficult to know exactly what the climate will be like in the future, and when the changes will occur. To account for this uncertainty, the climate change projections used in this assessment are based on a 30-year span around each planning horizon, 2030 and 2070. The projections used in this assessment should not be viewed as a precise prediction of the future. Instead, this vulnerability assessment should be viewed as a "climate stress test" for Cambridge. In other words, what would happen to the City's built environment and its people if we see higher temperatures and more flooding, and what would that mean to our economy, public health, and well-being?

This assessment was conducted in response to public concern and emerging scientific findings, and was initiated at the strong recommendation of the multi-stakeholder CPAC. It was conducted in a transparent, open manner and sought to engage the community and key stakeholders. The goal of this engagement was to bring everyone along with the City in understanding the local implications of climate change, and to support and spur preparedness discussion across the City.

Two advisory committees were formed: an Expert Advisory Panel of climate scientists and policy experts from local institutions to guide the assessment's methodologies, and a Technical Advisory Committee representing institutions, businesses, state agencies, and residents to provide input on various steps of the process. The community at large was engaged through over 40 meetings involving more than 900 people at neighborhood and other community venues. Participants at these meetings learned about the vulnerability assessment and gave their input on key concerns and hopes about what the City will do next to address what we have learned through the process. This extensive engagement with the community and key stakeholders has begun to develop a common understanding about what climate change means to Cambridge. Preparing Cambridge for climate change requires a community-wide effort. All the data and information developed for the assessment are being publicly-shared. The assessment enables the City and the community to start prioritizing the key vulnerabilities and establishes a foundation to plan for greater resilience and preparedness.

The assessment identifies Cambridge's key physical and social vulnerabilities based on an assumption that no action is taken. These results will inform the City's upcoming Climate Change Preparedness and Resilience Plan. Understanding possible consequences will hopefully also inspire action to reduce greenhouse gas emissions and reduce the likelihood of more extreme impacts. As a result of the extensive public engagement effort, a shared understanding of the local implications of climate change has begun to develop. This vulnerability assessment is the beginning of what will need to be a continuous process. Updates will be needed in response to new information.

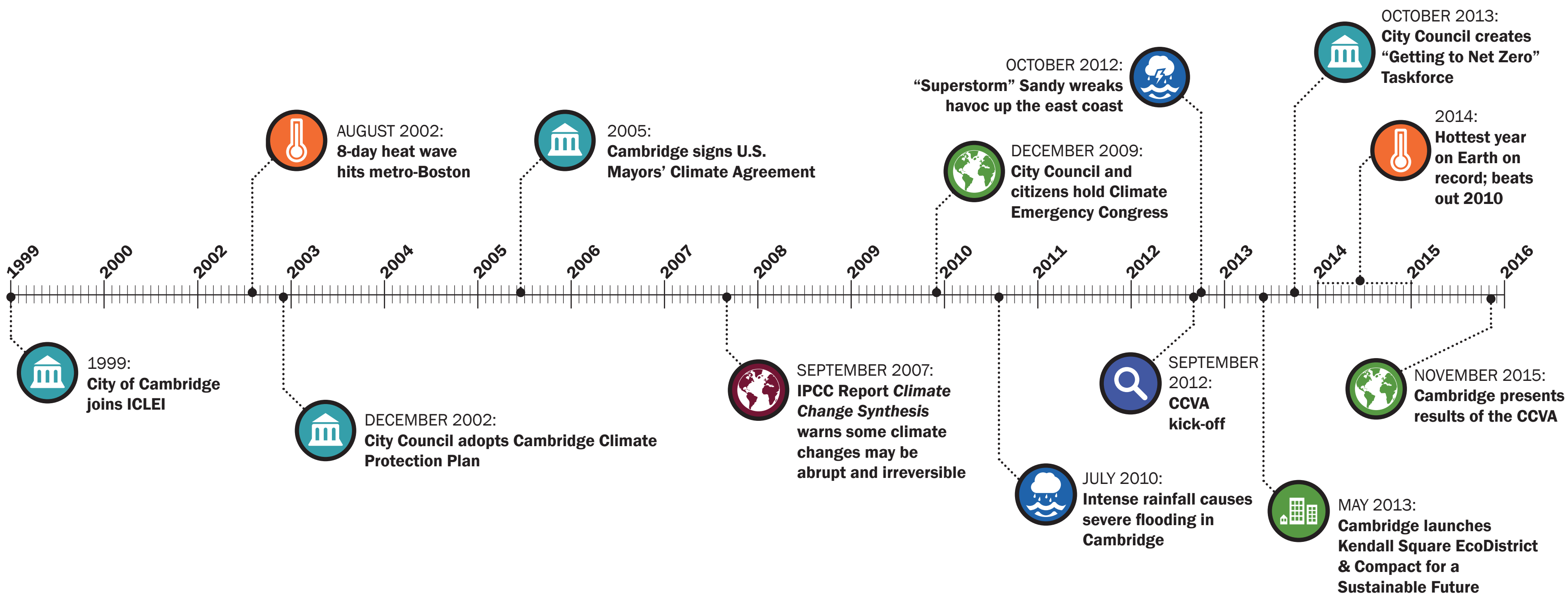

Fig. 2 **Cambridge climate change and sustainability timeline** (Source: Kleinfelder, November 2015)

KEY FINDINGS

Climate Impacts

- Coastal defenses provided by the Charles River and Amelia Earhart Dams, and the topography between the City and Boston Harbor, make it extremely improbable that a coastal storm surge will reach Cambridge, at least through 2030. However, continuing increases in sea level would eventually compromise our existing coastal defenses. The City is currently completing modeling of flood risks from storm surge and sea level rise through planning year 2070; these results will be available in Part 2 of this report.

- Precipitation-driven flooding is likely to become more frequent, expansive, and deeper. Preliminary results indicate that the area of Cambridge at risk from this type of flooding is projected to nearly double between now and 2070 for a rainstorm that has a 1% likelihood of being equaled or exceeded in a given year.

- Heat stress on human health is very likely to become much more severe. By 2030, annual days over 90 degrees Fahrenheit (90°F) may triple. By 2070, Cambridge may experience nearly three months over 90°F, compared with less than two weeks in present day. The heat index, which represents the "feels like" temperature for people, will also increase and exacerbate the likelihood of heat stress.

- Climate change is a "risk multiplier," making existing risks more likely and more severe.

Fig. 3 **Public Meeting**, March 2015

Past climate patterns can no longer be used as a guide for the future.

Vulnerability and Risk

- Cambridge is more vulnerable to increasing heat and precipitation-driven flooding in the near future than to sea level rise and coastal storm surges. Part 2 of this report will address the risks of sea level rise and coastal storm surges based on modeling for 2070.

- Vulnerability will increase for key infrastructure – public transit, energy, roads and bridges, telecommunications, critical service facilities – due to greater precipitation-driven flooding in the near term and long term.

- Heat waves and poor indoor air quality will become increasingly challenging public health concerns in the near future.

- Vulnerability is not evenly distributed among the neighborhoods or households. People who are more isolated due to infirmity, age, or language and those with lower incomes are more vulnerable.

- Economic losses from a flood event or an area-wide power loss would be significant. A citywide event shutting down Cambridge is estimated to cause at least $43 million (in current dollars) in daily economic losses. Losses from disruption of economic activity are greater than the costs of property damage.

- Climate change threatens regional systems that Cambridge depends on, such as public transit and electricity. An unprecedented level of coordination and cooperation among agencies, cities, the state, businesses, institutions, and residents will be required to prepare effectively for climate change.

Climate change threatens infrastructure, critical services, public health, and the City's economic well-being.

THE "WHOLE PICTURE"

There are financial and social costs if no action is taken against climate change.

The Priority Planning Areas Map (Figure 4) summarizes the most at-risk services and populations, with respect to climate change within the boundaries of Cambridge. It represents a risk assessment that compares seemingly unrelated resources, such as public health and the transportation system, and compares the risks within each (e.g., what is the greatest public health concern?), as well as between them (e.g., how does the risk of an overheated school rate against the risk of a flooded MBTA station?).

The Priority Planning Areas Map clearly illustrates that risk from climate change, posed by flooding and increased heat, is not evenly distributed throughout the City. Northern Cambridge and eastern Cambridge have relatively more physical and social vulnerability. Risk does exist elsewhere, but from a citywide perspective, the at-risk resources shown here would cause impacts to large segments of the population, often accompanied by significant economic, public health, and social effects.

Flooding has obvious implications in causing physical damage to buildings and infrastructure, as well as making areas inaccessible and creating an immediate public safety concern. There are also public health consequences associated with flooding events. Flooding can carry contaminants into buildings and create conditions for indoor mold growth. This has significant negative impacts on indoor air quality. This risk is exacerbated in buildings that have poorly sealed exterior windows and roofs and those that use forced hot air, which can become a conveyor of air from damp basement areas. Indoor dampness is well known to be a cause of adverse respiratory effects. Any residential or commercial structure that experiences flooding can face potential long-term challenges related to contamination and mold growth and their remediation if not prepared for this consequence.

Heat vulnerability, to both people and to infrastructure, is a major, possibly underappreciated, risk to the community. Factors that contribute to vulnerability in cities include:

- the urban heat island effect, which can amplify the impacts of rising temperatures;
- areas with minimal tree canopy;
- a relatively high proportion of older housing stock that may be poorly adapted to hot weather due to lack of adequate natural ventilation or air conditioning; and
- equipment not suited for higher temperatures.

From a public health perspective, heat has been the largest single weather-related cause of death in the U.S. since the National Oceanic and Atmospheric Administration (NOAA) began reporting data in 1988. Fortunately, heat impacts on health are the most well understood, measurable, and potentially preventable impacts of climate change.

There are also economic repercussions associated with a significant climate change event, such as substantial flooding or power failure caused by extreme heat. Such an event could impact the City's 128,000 jobs and result in a loss of $43 million per day (in current dollars) within Cambridge alone. Such interruptions fall heaviest on minimum wage workers with dependents and jobs that cannot be performed from home.

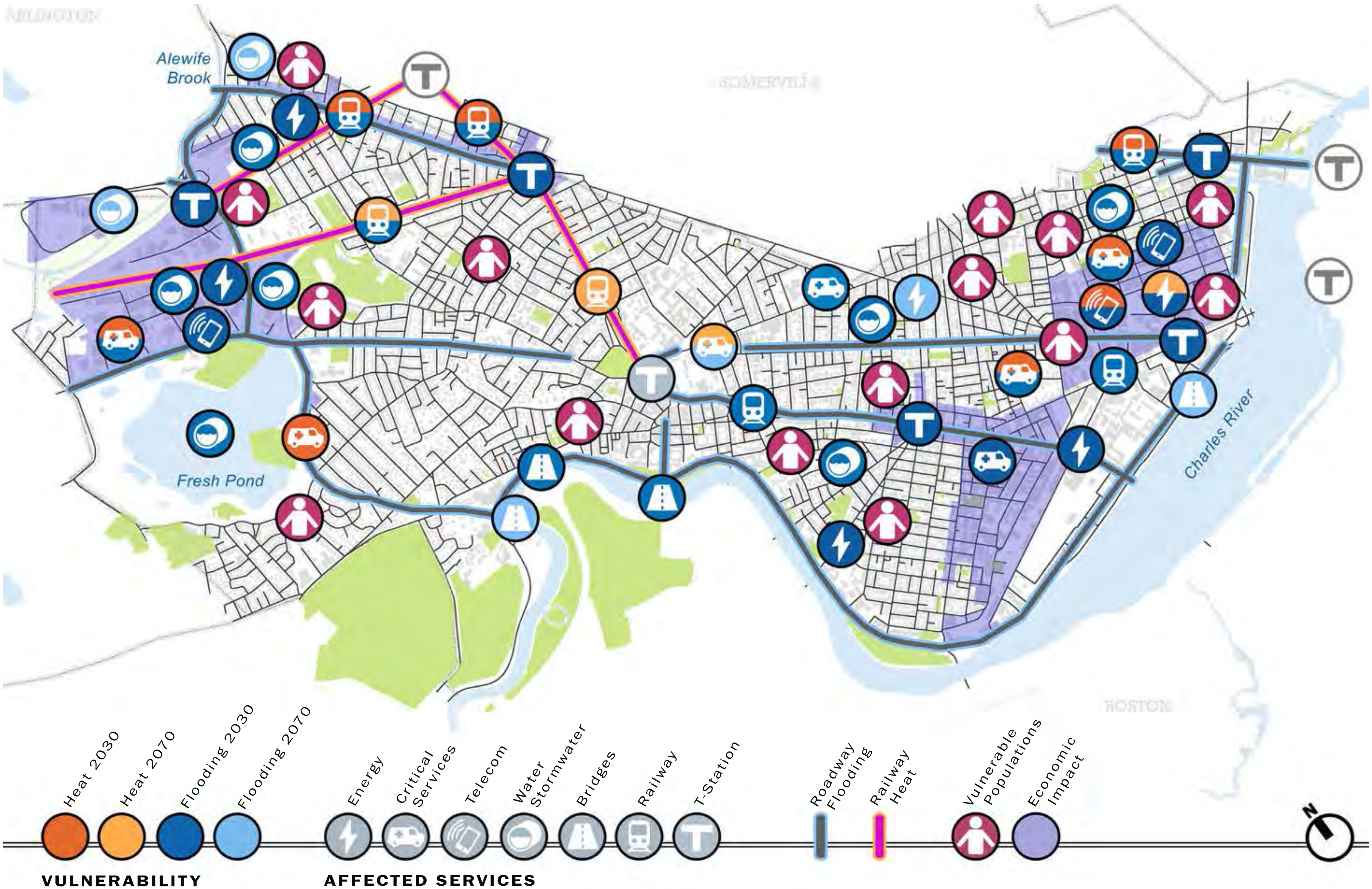

Fig. 4 **Priority Planning Areas Map** (Source: Kleinfelder, November 2015)

CLIMATE SCENARIOS

Climate change is no longer just a future threat; evidence of change can be seen today.

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

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.

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 5). 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 assumes 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.

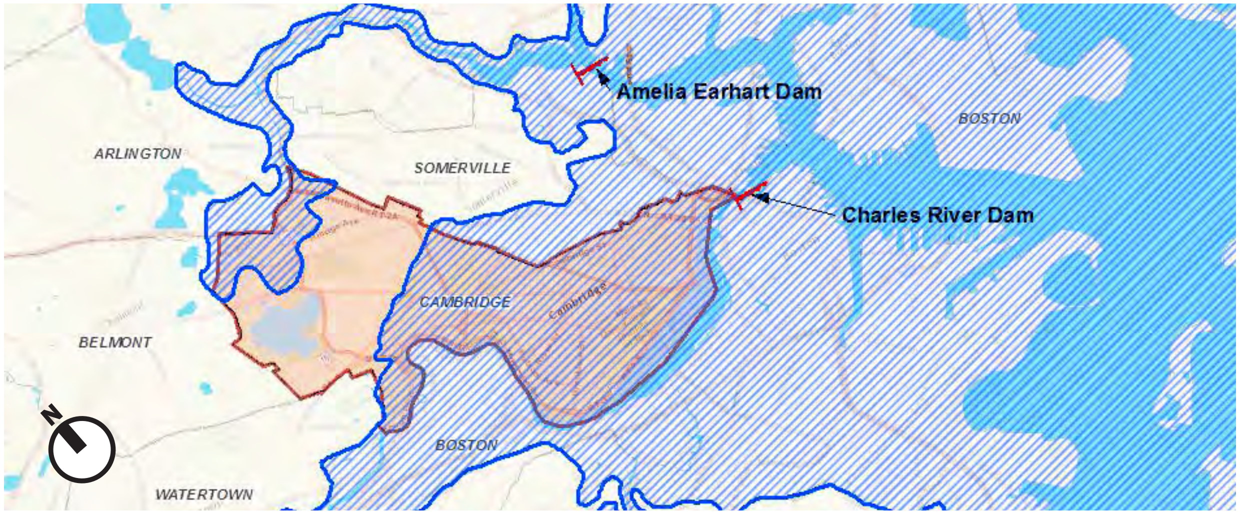

Fig. 5 **Boundaries of MassDOT study: Shaded area in blue indicates the extent and location of the project area included in this analysis** (Source: MassDOT, Woods Hole Group, UMass Boston, March 2015)

Cambridge's coastal storm surge protections will hold until at least 2030, but as sea level rises these protections could be surpassed.

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 6). 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.

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 7.

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.

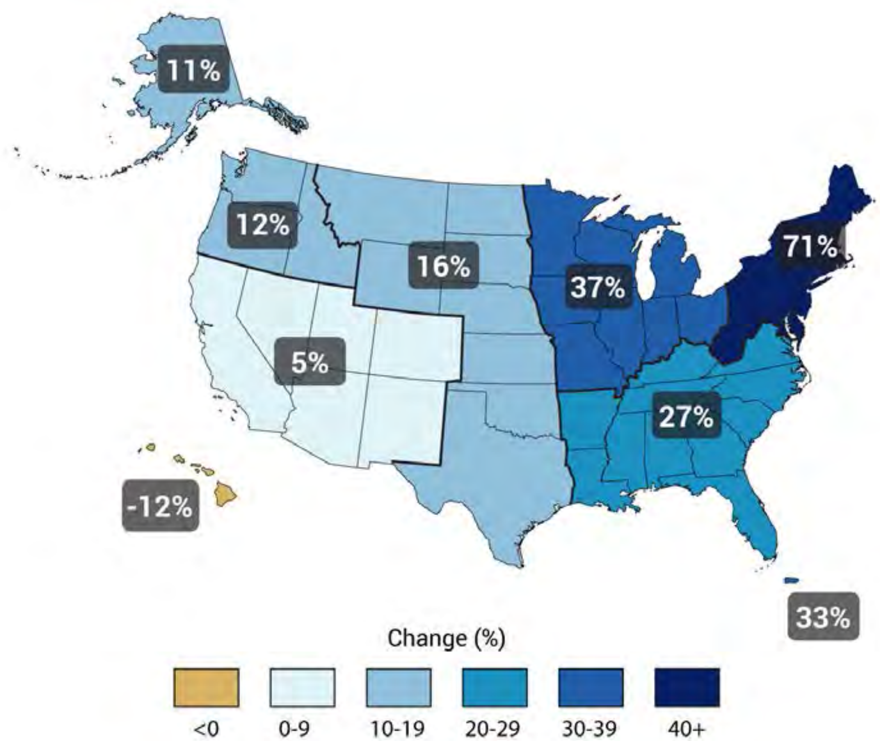

Fig. 6 **Observed change in heavy precipitation events (defined as the heaviest 1% of all daily events) from 1958 to 2012** (Source: 2014 U.S. National Climate Assessment Report)

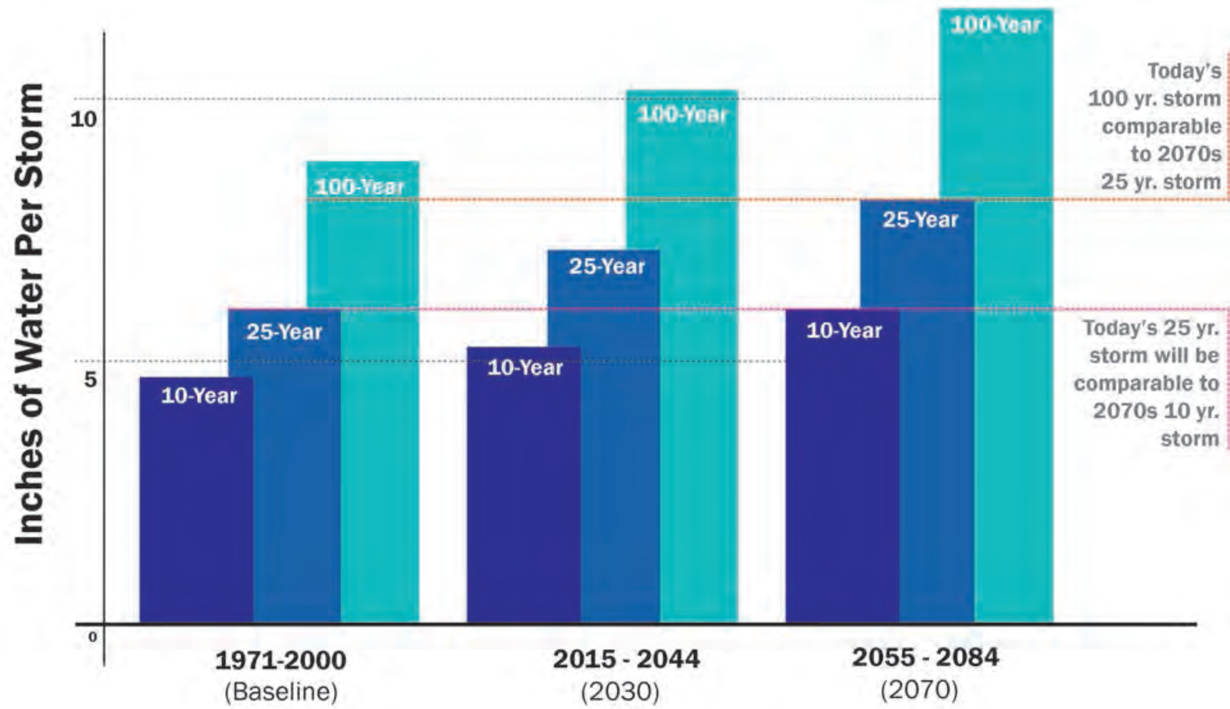

Fig. 7 **Precipitation projections** (Source: Kleinfelder based on ATMOS projections November 2015)

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. A 100-year storm 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 7, 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.

The 10-year storm has a 10% chance of happening in any year, and a 25-year storm has a 4% chance of happening in any year.

PRECIPITATION

To conduct the vulnerability assessment, it was necessary to delineate the extent and depth of flood risk for areas. The 10- and 100-year storms were used to provide low and high precipitation-driven flood scenarios.

The three maps shown in Figure 10 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 storm 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 10. 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.

Fig. 8 **Urban Flooding** (Source: City of Cambridge, July 10, 2010)

Fig. 9 **Urban Flooding** (Source: City of Cambridge, July 10, 2010)

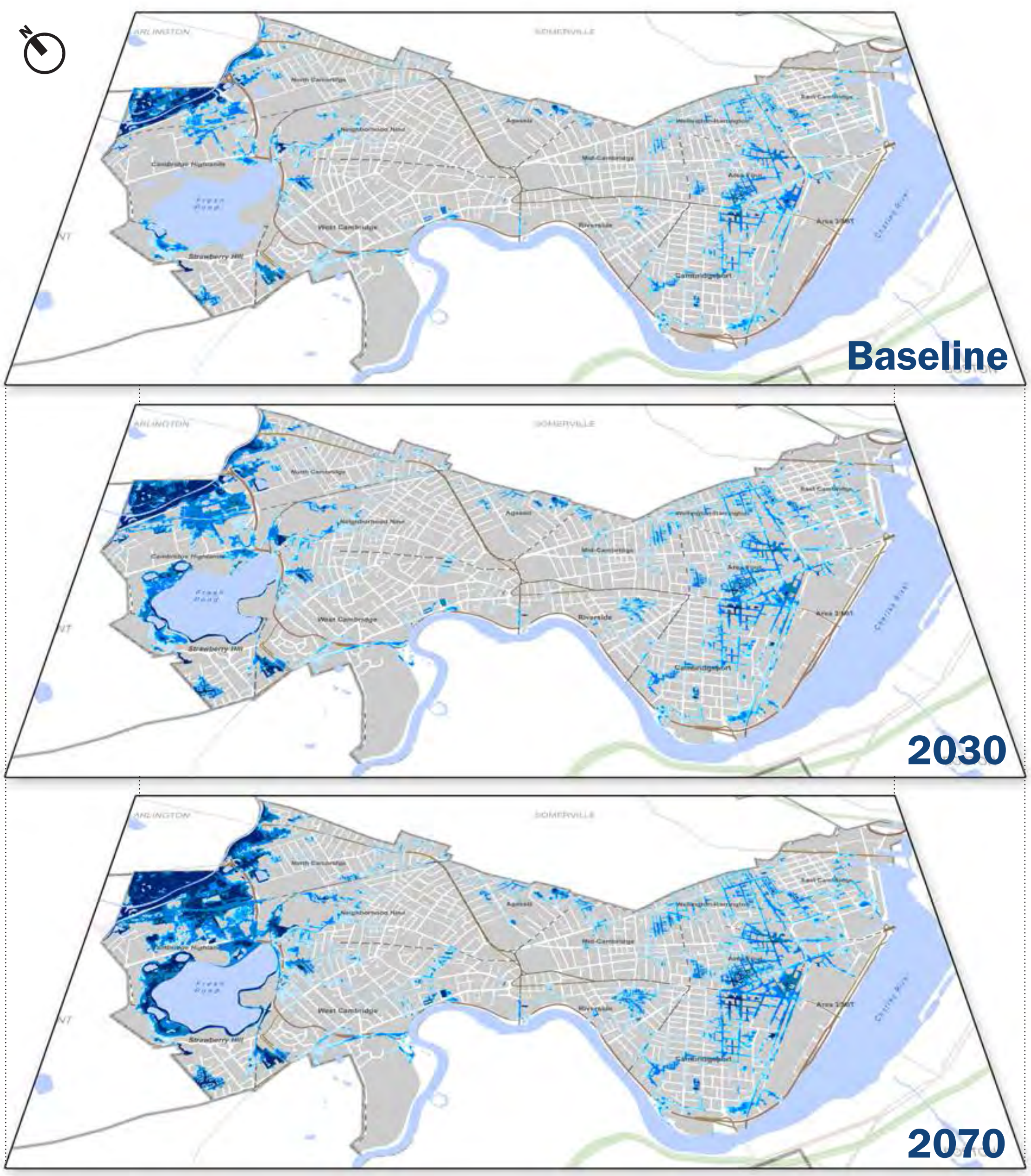

Fig. 10 **Inland Flooding – 100-year 24-hour storm** (Source: Kleinfelder with manhole flooding by MWH, riverine flooding by VHB, November 2015)

The Baseline map 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 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 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.

Depth of Flooding above Ground (feet)

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

PRECIPITATION

Flooding transcends municipal boundaries. Regional coordination will be needed to address increased stress on stormwater infrastructure.

The flooding maps help identify the neighborhoods, streets, and individual structures most at risk of flooding. The 100-year storm flood maps (Figure 10) depict a larger at-risk area compared to the 10-year storm flood maps (Figure 13). 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, that have already experienced repeated flooding (Figures 11 and 12).

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), and the City of Boston have shared data and information, and coordinated assumptions for our mutual studies.

Fig. 11 **Urban Flooding** (Source: City of Cambridge, July 10, 2010)

Fig. 12 **Urban Flooding** (Source: City of Cambridge, July 10, 2010)

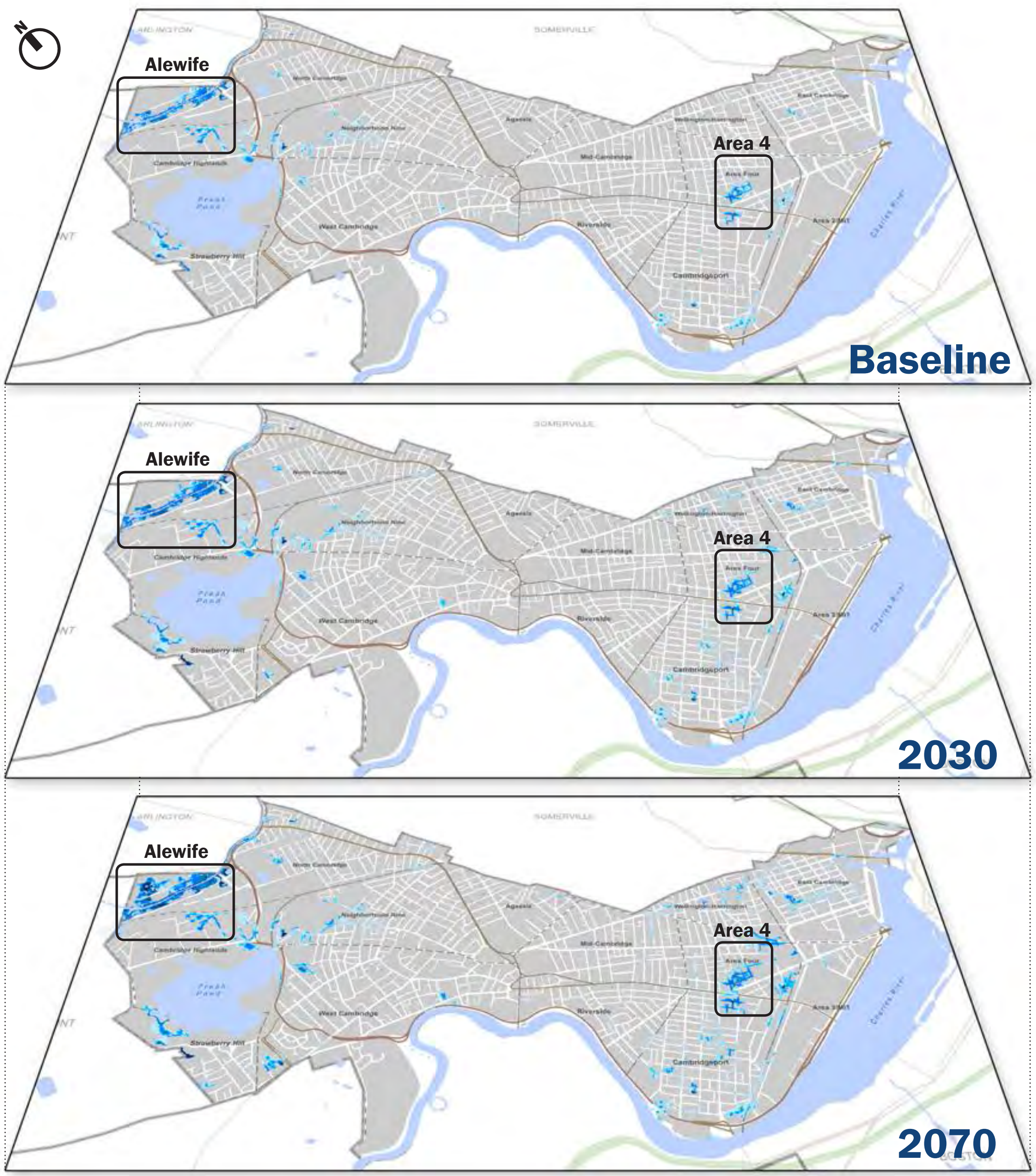

Fig. 13 **Inland Flooding – 10-year 24-hour storm** (Source: Kleinfelder with manhole flooding by MWH, riverine flooding by VHB, November 2015)

The Baseline map 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 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 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.

Depth of Flooding above Ground (feet)

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

TEMPERATURE

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. The heat changes are reported in three different ways: ambient air temperature, heat index, and heat wave.

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 NOAA, in Figure 14 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.

Both average annual temperature and heat waves are likely to be exacerbated.

NWS Heat Index — Temperature (°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										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution
Extreme Caution
Danger
Extreme Danger

Fig. 14 **Heat Index Chart** (Source: National Weather Service NWS, NOAA)

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 maximum ambient temperatures greater than 90ºF.

This assessment projects that the number of days over 90ºF 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 15).

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

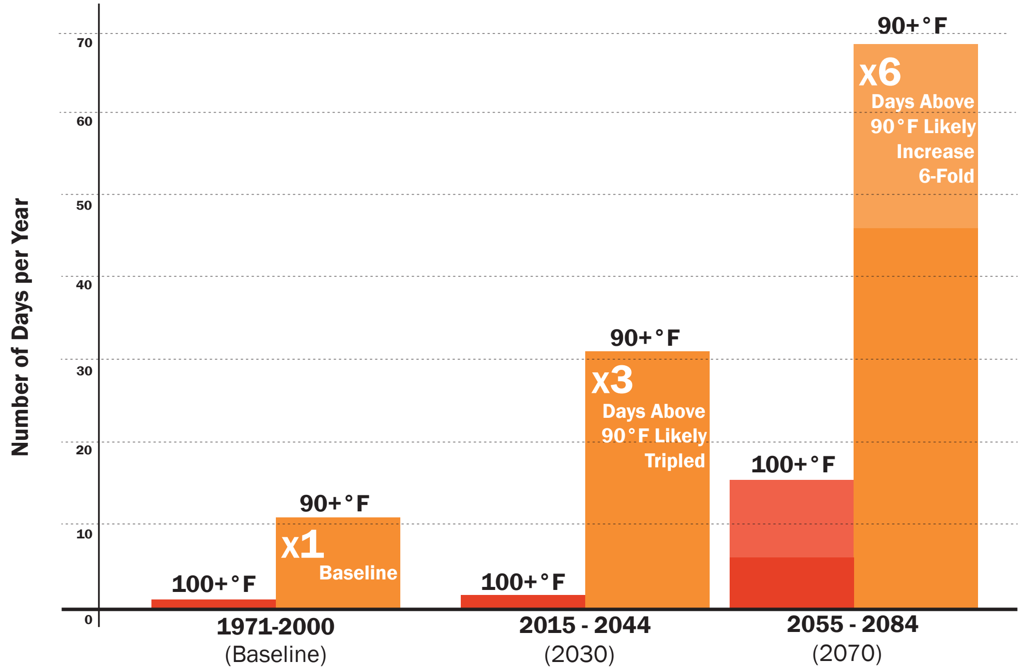

Fig. 15 **Number of days above 90ºF** (Source: Kleinfelder based on ATMOS research, November 2015)

Heat waves are expected to increase significantly. By 2030, the number of days each year above 90ºF could triple. By 2070, there could be more than 2 months in a year over 90ºF.

The City has documented impervious surfaces, mapped the tree canopy, and surveyed public shade trees to better understand heat island impacts in Cambridge.

the very young, the elderly, and those with existing health challenges like cardiovascular, circulatory, and respiratory conditions.

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 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 16) 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 90ºF, of which there could be as many as 16 days greater than 100ºF. While these days may be spread out over more than three months (as shown in Figure 16), the calendar illustrates the possibility that temperatures in Cambridge could exceed 90ºF 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 17) illustrate the current distribution of heat index throughout the City and how that might evolve by 2030 and 2070. The heat index temperature selected in the maps for 2030 and 2070 are based on probable temperature from climate change projections. According to these scenarios, the entire City could be experiencing dangerous levels of heat stress by 2070.

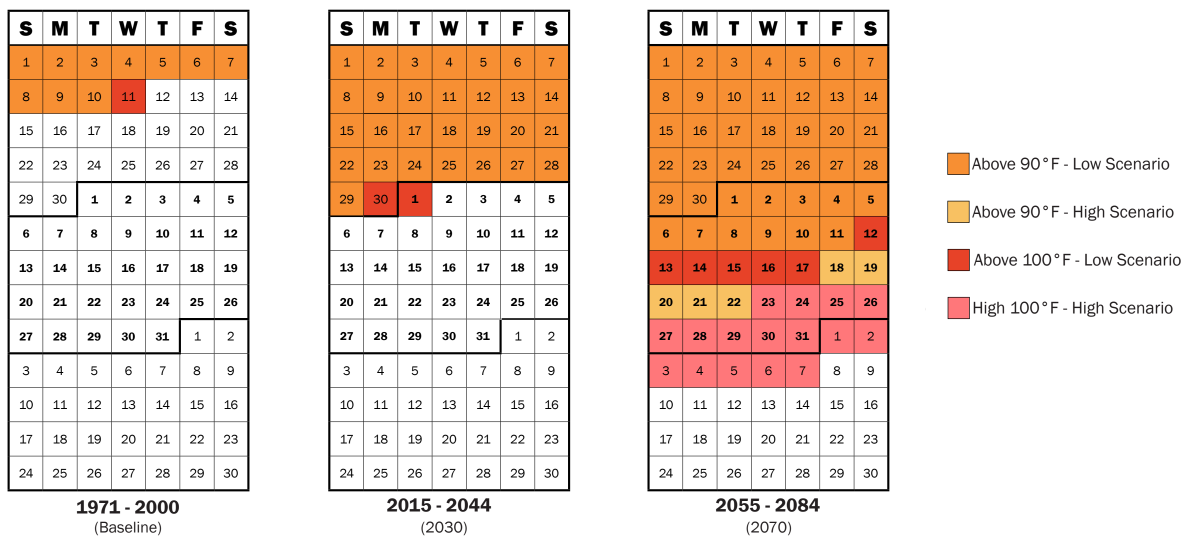

Fig. 16 **Relative increase in possible projected days above 90ºF and 100 ºF over a 3-month period** (Source: Kleinfelder based on ATMOS research, November 2015)

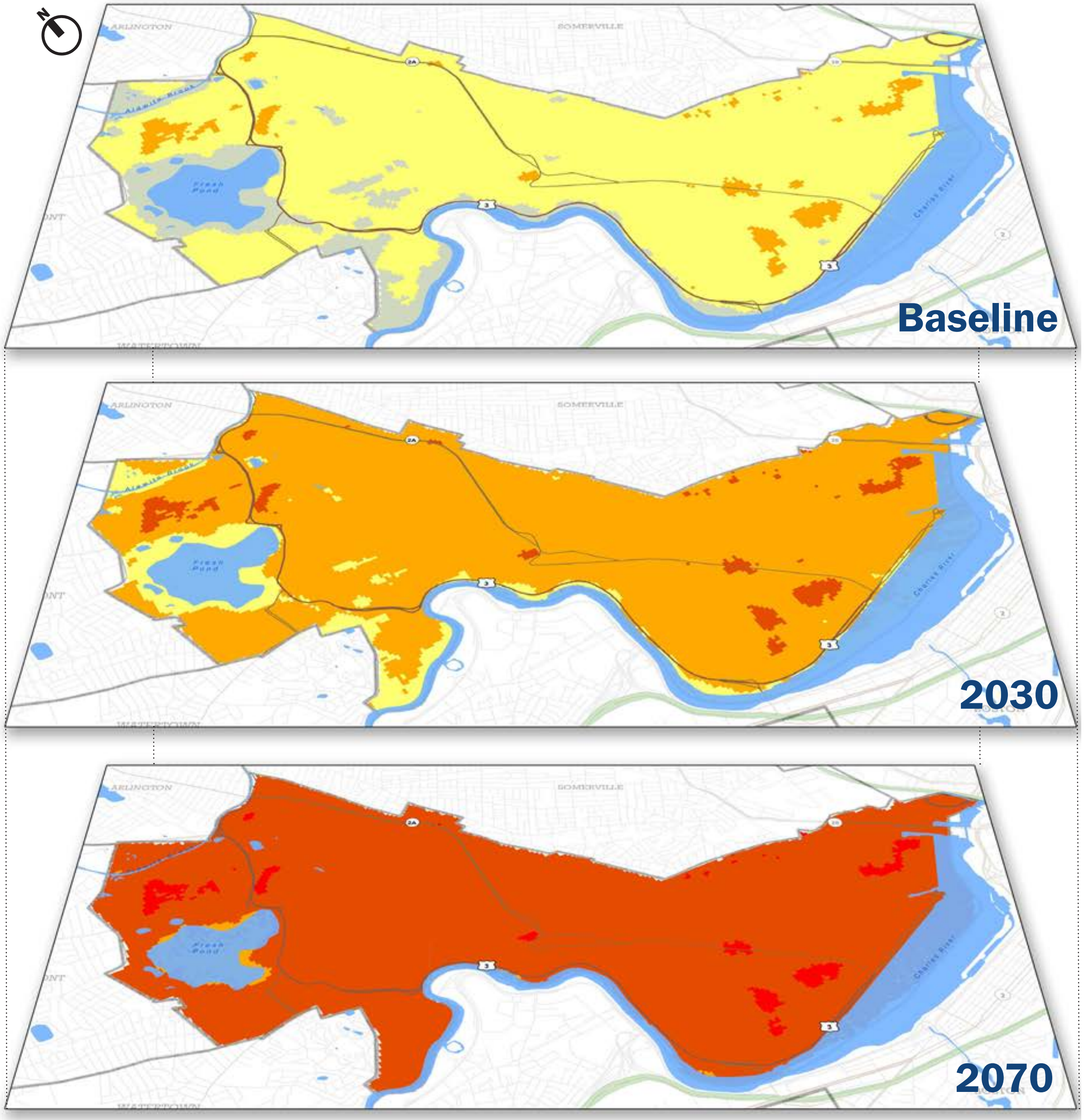

Fig. 17 **Heat Island Map (Heat Index)**
(Source: Produced by Kleinfelder based on ATMOS research, November 2015)

The baseline map illustrates the variability in "feel-like" temperature across the City under present conditions with localized heat islands above 100°F when average heat index for the City is 85°F (based on available recorded data).

The 2030 map illustrates the variability in "feel-like" temperature across the City by 2030 with localized heat islands above 100°F when average heat index for the City is 96°F (90°F ambient temperature with relative humidity of 50-55%).

The 2070 map illustrates the variability in "feel-like" temperature across the City by 2070 with localized heat islands above 120°F when average heat index for the City is 115°F (100°F ambient temperature with relative humidity of 45-50%).

Estimated Heat Index (°F)

- <= 80°
- 80° - 90°
- 90° - 103°
- 103° - 124°
- > 124°

VULNERABILITY AND RISK ASSESSMENT

Vulnerability is defined by a person's or asset's exposure, sensitivity and capacity to adapt.

Risk is defined by the extent and probability of harm occurring.

The vulnerability and risk assessment for Cambridge is the ultimate outcome of this project. With this process, the City sorts through numerous assets, systems, and vulnerable populations to compare the relative vulnerability of each and identify the most critical and urgent needs. Since resources available to address the vulnerabilities are finite, it is important to prioritize the ones on which to concentrate. The most at-risk elements will become the primary focus of the subsequent Climate Change Preparedness and Resilience Plan.

To ensure the City's resources are focused on assets, systems, and vulnerable populations most at risk of harm from climate stressors, planning-level vulnerability analyses were performed for nearly 1,000 resources, social factors, assets, and critical services. A standardized methodology was applied to each item in a system (e.g., energy infrastructure) to rate its vulnerability and compare it to other items in seemingly disparate categories (e.g., energy infrastructure and public health) to assess interdependencies. The vulnerability ranking methodology included quantitative, qualitative, and map-based criteria (see Figure 18).

Due to a variety of considerations, including cost, time, and available methodologies, the City chose to focus on assessing the vulnerability of individual assets, populations, and systems and compare them. While a large number of assets and factors were assessed, many more could also have been assessed. The additional assets and factors that should be considered in the future include food and fuel supply delivery, food storage, food safety and food establishment inspectors, health care access, medication access and delivery, and emergency medical and public safety services.

The potential for cascading effects is critical to consider, although it is a complex question to analyze. For example, the loss of electricity may be the most important factor leading to wide-ranging, cascading effects since it can affect the availability of air conditioning, drinking water, lighting, refrigeration, communications, and other systems that require power. But there can also be other types of cascading effects, such as a disruption to the postal delivery system due to flooding or other impacts, which could lead to the disruption of home delivery of medication and medical supplies.

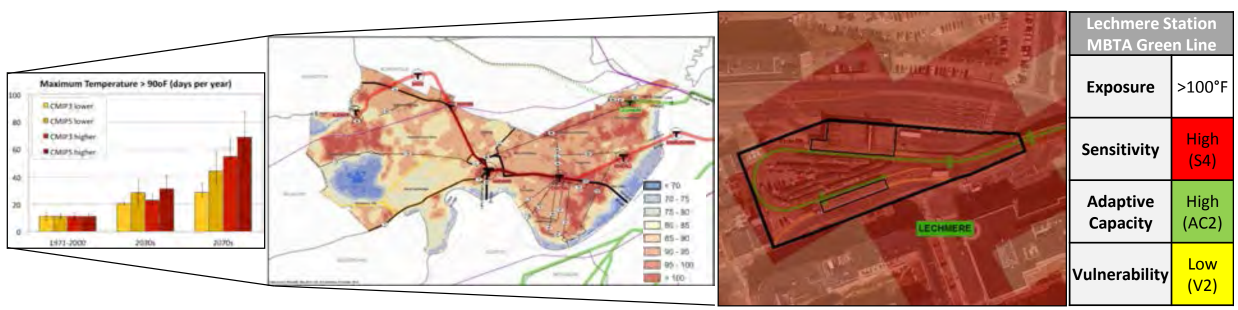

Fig. 18 **Ranking Process** (Source: Kleinfelder, November 2015)

How Vulnerability is Assessed

Vulnerability is a measure of the extent to which a demographic group, asset, or system will be impacted by climate change. It is assessed asset by asset, population by population, or system by system, and is defined by three main criteria:

Exposure – How much heat and/or flooding will affect the asset, demographic group, or system

Sensitivity – How much function will be lost due to the effects of exposure to flooding or heat

Adaptive Capacity – How well the asset, demographic group, or system can cope with or compensate for the loss of function

Exposure is assessed using the flooding and heat island maps. The vulnerability score (Figure 19) is a result of the sensitivity and adaptive capacity of exposed assets, systems, and population.

How Risk is Determined

Risk is a function of the ***probability*** of impact and the overall ***consequence*** of that impact. The City focused the risk analysis on the most vulnerable assets and resources identified earlier in the study. In the case of people, "higher consequence" meant that populations less able to adapt were affected. This type of analysis is intended to help focus resources where intervention is needed most. In the case of infrastructure, "higher consequence" meant that more people were affected by its failure. For example, if a bike path and a power station had equal vulnerability to climate stressors, the substation would rank as higher risk because the consequences of it failing would be far more severe (see Figure 20). High priority areas are highly vulnerable assets with high risk scores (R3 and R4).

The risk analysis captures the high probability and high consequence events impacting the City. It also captures low probability and high consequence events that should be considered.

		Sensitivity: Low → High				
		S0	S1	S2	S3	S4
Adaptive Capacity: Low ↓ High	AC0	V2	V3	V4	V5	V5
	AC1	V1	V1	V2	V3	V4
	AC2	V0	V0	V0	V1	V2

Fig. 19 **Vulnerability Scoring Chart** (Source: Kleinfelder adapted from ICLEI, November 2015)

		Probability	
		Low	High
Consequence	High	R3	R4
	Medium	R2	R3
	Low	R1	R2

Fig. 20 **Risk Scoring Chart** (Source: Kleinfelder adapted from ICLEI, November 2015)

CRITICAL INFRASTRUCTURE

The ability of a city to function is tied to its infrastructure, much of which is out of public view, or simply goes unnoticed until it ceases to function.

Six major systems were studied in this phase of work:

- **Energy**
- **Critical Services**
- **Telecommunication**
- **Roadways & Bridges**
- **Transit**
- **Water/Stormwater**

With the climate scenarios in hand, the team conducted the vulnerability and risk assessments for each system to determine the most at-risk assets. Figure 21 presents the results of the risk assessments and how data were analyzed and compiled. The map of most at-risk infrastructure (Figure 22) highlights the degree of interconnectivity among the various assets. Cascading impacts based on dependencies on upstream systems, such as an electricity blackout leading to the loss of public transit, was incorporated into the consequence scores, influencing the overall risk scores for infrastructure.

		Asset	Heat		Flood	
			2030	2070	2030	2070
E Energy	E.1	MIT Co-generation Plant				
	E.2	North Cambridge Substation				
	E.3	Putnam Substation				
	E.4	Prospect Substation				
	E.5	Third Street Regulator Station – natural gas				
	E.6	Brookford Street Take Station – natural gas				
C Critical Services	C.1	Police Department headquarters				
	C.2	Public Health Department office				
	C.3	Professional Ambulance Services				
	C.4	Youville Hospital				
	C.5	Fire Company 2				
	C.6	Fire Department headquarters				
	C.7	Water Department building / City's Emergency Operations Center				
	C.8	Windsor Street Health Center				
TC Telecom	TC.1	City Emergency Communications Center (Police HQ)				
	TC.2	BBN Technologies data hub				
	TC.3	AT&T telephone office/long-line switch				
	TC.4	AT&T data hub/co-location center (CO-LOC)				
R Roadways & Bridges	R.1	Alewife Brook Parkway				
	R.2	Massachusetts Ave				
	R.3	Monsignor O'Brien Highway at Charlestown Ave/ Land Boulevard				
	R.4	Monsignor O'Brien Highway / McGrath Highway / Route 28				
	R.5	Fresh Pond Parkway / Route 60				
	R.6	Cambridge St Underpass				
	R.7	Broadway				
	R.8	Alewife Brook Parkway - intersections with Rt. 2 and Mass Ave/Rt. 16				
	R.9	Concord Turnpike/Route 2				
	R.10	Land Boulevard				
	R.11	Lars Anderson Bridge				
	R12	Memorial Drive				
	R.13	Longfellow Bridge				
	R.14	Eliot Bridge				
T Transit	T.1	Alewife Station (Red)				
	T.2	Lechmere Station (Green)				
	T.3	Alewife – Davis – Porter Rail Line (Red)				
	T.4	Lechmere – Science Park Rail Line (Green)				
	T.5	Central – Kendall Rail Line (Red)				
	T.6	Porter Square Subway / Commuter Rail Station (Red)				
	T.7	Central Square Station (Red)				
	T.8	Kendall Station (Red)				
	T.9	Fitchburg Commuter Rail Line				
	T.10	Porter – Harvard Rail Line (Red)				
	T.11	Harvard - Central Rail line (Red)				
W Water/Stormwater	W.1	Western Flagg (Charles, Separated)				
	W.2	New Street Pump Station				
	W.3	Fresh Pond Reservoir				
	W.4	CAM 004 (Alewife, Separated)				
	W.5	CAM 017 (Charles, Combined)				
	W.6	CAM 400 (Alewife, Separated)				
	W.7	Lechmere (Charles, Separated)				
	W.8	CAM 001 (Alewife, Combined)				
	W.9	D46 (Alewife, Separated)				

Fig. 21 **Most At-Risk Infrastructure Legend**
(Source: Kleinfelder, November 2015)

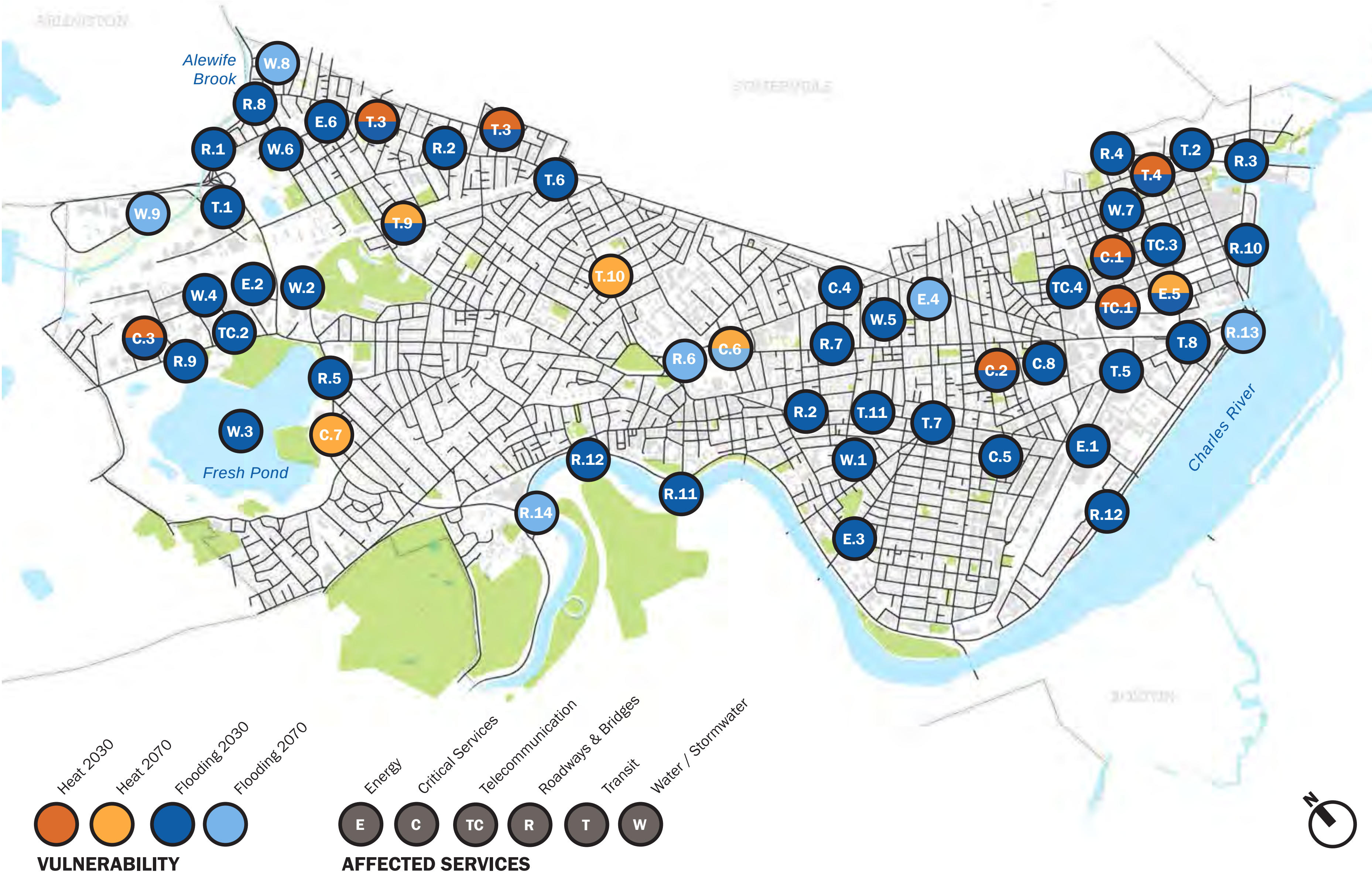

Fig. 22 **Most At-Risk Infrastructure** (Source: Kleinfelder, November 2015)

The assets and resources that are ranked as most vulnerable and presenting the greatest risk of disrupting Cambridge will be the focus of the Climate Change Preparedness and Resilience Plan.

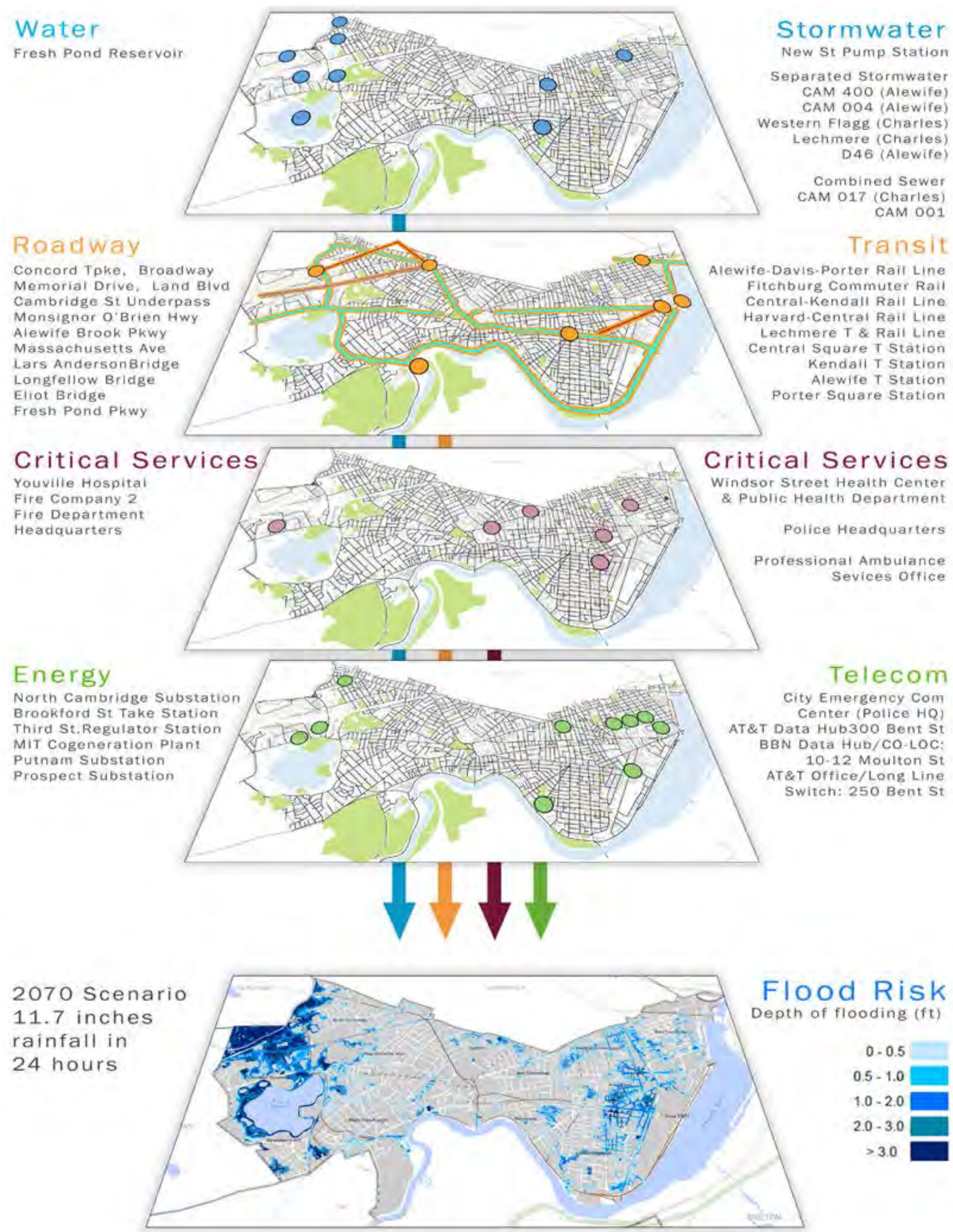

Fig. 23 **Assets Most at Risk to Flooding**
(Source: Kleinfelder, November 2015)

Cambridge Assets Most At Risk to Flooding

A flooding stress test was conducted for critical assets and systems (Figure 23). The 2030 and 2070 flooding scenarios were used to conduct the stress test. In other words, what would happen to the City's built environment if there is more flooding in the future, and what the failure of these critical assets means for the City.

W **Water/stormwater** system assets include stormwater and combined storm-sewer systems. In Cambridge, they are highly vulnerable and at high risk from inland flooding. Where there are combined sewer systems, flooding could pose a public health and environmental risk that could result in significant impacts to buildings, including sewer back-ups into homes and businesses without backflow controls.

R **Roadway** failures could occur due to direct exposure to localized flooding, whereby the road becomes impassable or inaccessible. Failure of key roadway segments will have cumulative and cascading impacts on multiple critical transportation assets including MBTA bus routes and access to bridges. Major at-risk roads include Alewife Brook Parkway, Massachusetts Avenue, Monsignor O'Brien Highway, and Broadway.

T **Transit** is highly vulnerable to inland flooding. By 2030, the following assets could be highly impacted during flood events: five of the City's six MBTA stations; four segments of MBTA rail lines; the only commuter station and rail line; and two of the four most critical bus routes and hubs.

C **Critical service facilities** in Cambridge, such as hospitals and fire stations, are vulnerable to flooding and may be at risk of failure during future extreme rainfall events. The identified facilities could be impaired from direct flooding preventing operations and/or preventing access. Flooding could also impact lifeline systems such as energy, transportation, and telecommunications without which critical services facilities may not be able to properly function. At-risk facilities include the Police Department, Youville Hospital, and Fire Company 2.

E **Energy** infrastructure is significantly more vulnerable to flooding than to heat. North Cambridge and Putnam electrical substations are the assets at greatest risk for energy system failure due to their vulnerable locations. They also have high consequences of failure, including cascading impacts on other energy infrastructure. Natural gas conveyance facilities are also at risk from flooding.

TC **Telecommunication** assets are exposed to sufficient flooding to threaten failure by 2070. Flood vulnerability and risk are more widespread in this time period since it is assumed that current assets have a low adaptive capacity to flooding. At-risk facilities include the City's Emergency Communications Center, the AT&T switch facility, and the data hub/co-location center in the Alewife area, which is a distribution and switching station.

Cascading Impacts and Interdependencies

Flooding could impact lifeline systems such as **energy** and **telecommunication**, without which some **roadway** infrastructure (e.g. traffic signals, lighting) may not be able to properly function. **Critical services**, such as police headquarters and emergency medical services, are also vulnerable to flooding, given their reliance on operational **roadways** to ensure public safety before, during, or after an event.

CRITICAL INFRASTRUCTURE

Cambridge has built a reputation as one of the best cities in the U.S. for cycling. In New York City, after Superstorm Sandy, pedestrians and cyclists represented more than half the river crossings from New Jersey to Manhattan while the subway system was shut down and roads were congested. In response, some 20,000 New Yorkers who usually used other forms of transportation commuted by bike. This highlights the role and viability of pedestrian and bicycle transport in emergencies.

Longer, more frequent heat waves are likely to test the adaptive capacity of infrastructure.

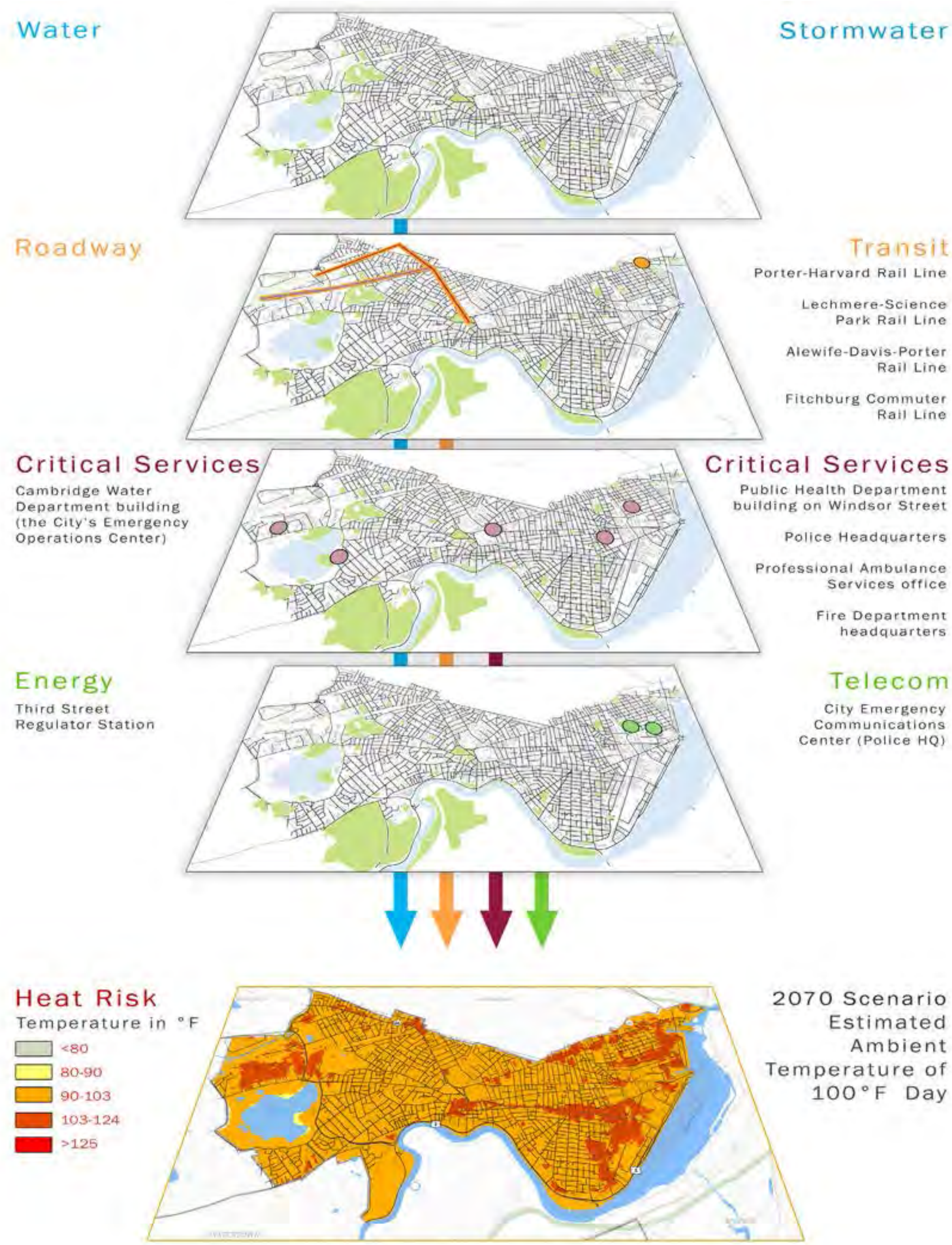

Fig. 24 **Assets Most at Risk to Heat**
(Source: Kleinfelder, November 2015)

Cambridge Assets Most At Risk from Increased Heat

(W) **Water/stormwater** system assets are not highly vulnerable to heat, and consequently no high risks from heat for the water systems have been identified.

(R) **Roadway** infrastructure is not highly vulnerable to heat primarily due to the low sensitivity of roadways to heat (high critical threshold for damage).

(T) **Transit**, particularly subway and commuter rail lines, are vulnerable to heat and may pose a risk from failure during future extreme heat events. Asset failures would likely result from rail exposure to extreme heat, which could cause damage to rails (rail buckling, sun kinks) or supporting electrical equipment. It is also important to note that while subway cars have air conditioning, the subway stations do not.

(C) **Critical services** are vulnerable to heat and may pose a risk from failure during future extreme heat events. Asset failures would likely be due to a combination of system-wide stress caused by increased demand for services and asset-level exposure to extreme heat, which could impact occupant health and safety as well as damage heat-sensitive equipment. For example, many fire stations do not have air conditioning or passive measures to keep them cool during heat waves.

(E) **Energy** infrastructure is not highly vulnerable to heat primarily due to the relatively high adaptive capacity of energy assets. Major substations are designed to have redundancy for individual equipment failures caused by heat. There are also emergency response measures to reduce the ambient heat of substation equipment, such as misting and other tactics, which would be deployed during extreme heat events to reduce the stress on equipment and decrease the risk of failure.

(TC) **Telecommunication** assets, such as the City's Emergency Communications Center located at the Cambridge Police Department Headquarters, are main high-risk assets because they serve the entire City and provide critical system-wide and cross-system functions. For example, failure of the area's telecommunication system would impact the Emergency Communications Center and the telephone office/long-line switch with significant consequences for operation of many businesses.

The City of Cambridge places high value on its **urban forest** (Figure 25) for enhanced air quality, wind and heat island reduction, aesthetics, reduced energy consumption, reduced noise pollution, wildlife habitat, decreased runoff, shading, and increased property values. The City worked with the U.S. Army Corps of Engineers to conduct a vulnerability assessment of the urban forest, focusing on nearly 60 tree species with respect to flooding and heat impacts. The study concluded that Cambridge's urban forest appears relatively resilient to both flooding and heat based on the Army Corps of Engineers projected climate parameters, looking out over the next 50 to 100 years. However, it should be noted that a warmer climate increases the probability of pest infestation such as the Asian longhorn beetle (ALB) that could have a significant impact on the City's population of trees.

Cambridge's urban forest will help mitigate expected temperature increases.

Fig. 25 **Urban Forest** (Source: City of Cambridge)

SOCIAL VULNERABILITY

Strong social networks can substantially improve the resiliency of the City's most vulnerable members.

How At-Risk Populations are Identified

The project team worked closely with public health scientists, critical service providers, and social service professionals to develop proxy indicators from 2010 census data for the City's populations vulnerable to increased heat and flooding. This approach enabled the assessment to identify areas of the City with greater concentrations of at-risk residents, understanding that people rely on social and service networks to ensure their safety and comfort. These complex, often invisible, social networks are much harder to assess than the built environment and are not completely captured by the geographic or quantitative demographic data captured in this study.

Sensitivity to harm from climate stressors was ranked based on income and age. People living below the poverty level, young children, and elderly adults living alone were assumed to be the most affected by significant heat and/or flooding events.

Ability to adapt was ranked based on income, education level, and physical and language isolation. People living in poverty, with low educational attainment, low English reading or speaking skills, and/or elderly living alone were seen as having the greatest difficulty avoiding harm during flood and high heat events.

While the social vulnerability index employed in this assessment does not capture complex social support systems and regional service networks, the use of data at the census tract level enables us to visualize important geographic aspects of social vulnerability and also serves as a useful starting point and a tool for further planning and assessment efforts.

The mapping of most vulnerable populations illustrates that social vulnerability is not evenly distributed among the neighborhoods (Figure 26). Portions of North Cambridge, Area 4, and Riverside are relatively more vulnerable to flood and heat impacts than other parts of the City. This vulnerability is driven by the greater presence of at-risk residents exposed to enhanced flood risk and the urban heat island effect.

Indeed, under both the 2030 and 2070 high flooding scenarios, the most socially or economically vulnerable neighborhoods are also the ones with greater exposure to flooding. The relative distribution of social vulnerability and exposure to climate change impacts has the potential to be a useful factor for the City in determining "vulnerability hotspots" to inform emergency planning.

The City – its government, residents, institutions, and businesses – can draw on this information to craft a more nuanced picture of the community as it engages in self-assessment and prepares for greater resiliency in the face of future climate-driven threats.

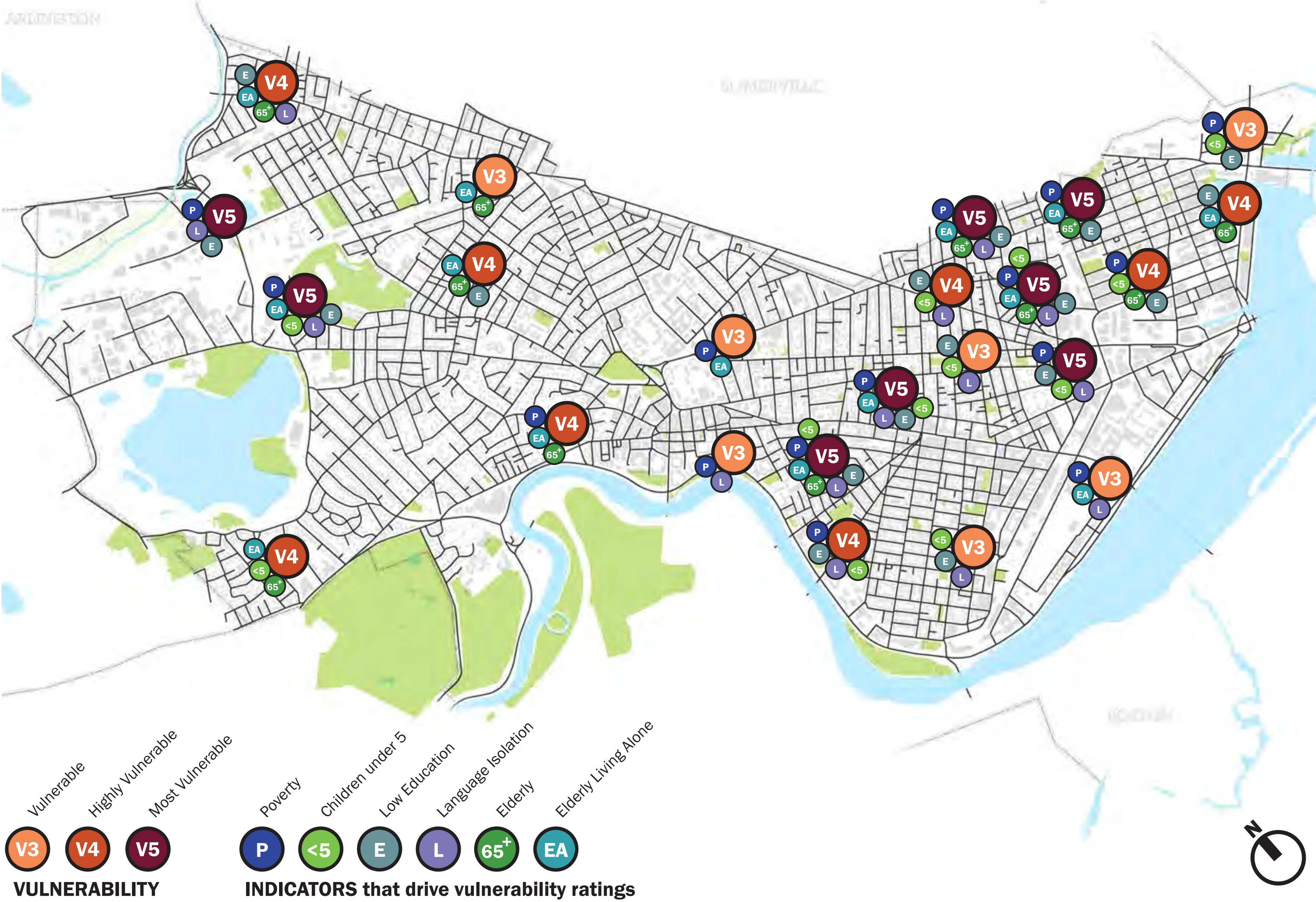

Fig. 26 **Vulnerable Populations to Climate Change Impacts** (Source: Kleinfelder, November 2015)

The City examined the extent to which **community resources** are at risk of harm from climate stressors as a proxy for measuring harm to social support systems. Figure 27 indicates that many of the City's community resources are at risk of both flooding and extreme heat.

Affordable housing, public schools, daycare and youth centers, pharmacies, food pantries, and municipal resources provide important support services that need to be operational when climate stressors impact the City.

Other priority public resources that will be included in the Climate Change Preparedness and Resilience Plan include:

- **Municipal and federal buildings** such as City Hall, and its satellites, schools, daycare and youth centers, libraries, and post offices are Cambridge's traditional places where people can gather to ask for and provide help.
- **Public pools, sprinkler parks, and other open spaces** are public places where residents can go to cool off during heat waves.

The map of the Community Resources Priority Areas (Figure 28) illustrates which resources are most at risk of failure with greatest impact to vulnerable populations.

Cambridge's places of worship, schools, daycare centers, and other community centers provide critical places for residents to connect with each other.

		Asset	Heat		Flood	
			2030	2070	2030	2070
H Affordable Housing	H.1	Roosevelt Towers (Mid-Rise)(14 Roosevelt Towers), 75 units				
	H.2	Roosevelt Towers (Low-Rise)(14 Roosevelt Towers), 124 units				
	H.3	Daniel F. Burns Apt (50 Churchill Ave), 198 units				
	H.4	Auburn Court I (80 Auburn Park), 77 units				
	H.5	Harwell Homes (1 Citizens Place), 56 units				
	H.6	Miller's River Apts (15 Lambert St)				
	H.7	Briston Arms (247 Garden St), 105 units				
	H.8	808 Memorial Dr (808-812 Memorial Dr)				
	H.9	Truman Apts (25 Eighth St), 60 units				
	H.10	Johnson Apts (150 Erie St), 180 units				
	H.11	2050 Mass Ave/ Leonard J. Russell Apts, 51 units				
	H.12	YMCA (820 Mass Ave), 128 units				
	H.13	Manning Apts (237 Franklin St), 199 units				
	H.14	Inman Sq Apts (1203-1221 Cambridge St), 116 units				
	H.15	Washington Elms (131 Washington St), 175 units				
	H.16	Auburn Court II (80 Brookline St), 60 units				
S Public Schools, Daycare, and Youth Centers	S.1	Daycare at Roosevelt Towers (14 Roosevelt Towers)				
	S.2	Moore Youth Center & Daycare				
	S.3	Tobin School & Daycare				
	S.4	King Open School & Daycare (850 Cambridge St)				
	S.5	Kennedy / Longfellow School & Daycare				
	S.6	CRLS 9th Grade Campus / Martin Luther King Jr Elementary School & Daycare (359 Broadway)				
	S.7	Baldwin School & Daycare (28 Sacramento St)				
	S.8	Daycare at YMCA (820 Mass Ave)				
	S.9	Area IV Youth Center & Daycare (243 Harvard St)				
	S.10	Morse School & Daycare (40 Granite St.)				
	S.11	Fletcher/Maynard Academy & Daycare (225 Windsor St)				
	S.12	Graham & Parks School & Daycare (44 Linnaean St)				
	S.13	Cambridgeport School & Daycare (89 Elm St)				
P Pharmacy, Food Assistance, Municipal Resources	P.1	Margaret Fuller Neighborhood House (71 Cherry St				
	P.2	Salvation Army / Daily Lunch (402 Mass Ave)				
	P.3	WIC Program Services (119 Windsor St - Public Health Dept)				
	P.4	Human Services Department (51 Inman St)				

Fig. 27 **Community Resources Priority Areas Legend** (Source: Kleinfelder, November 2015)

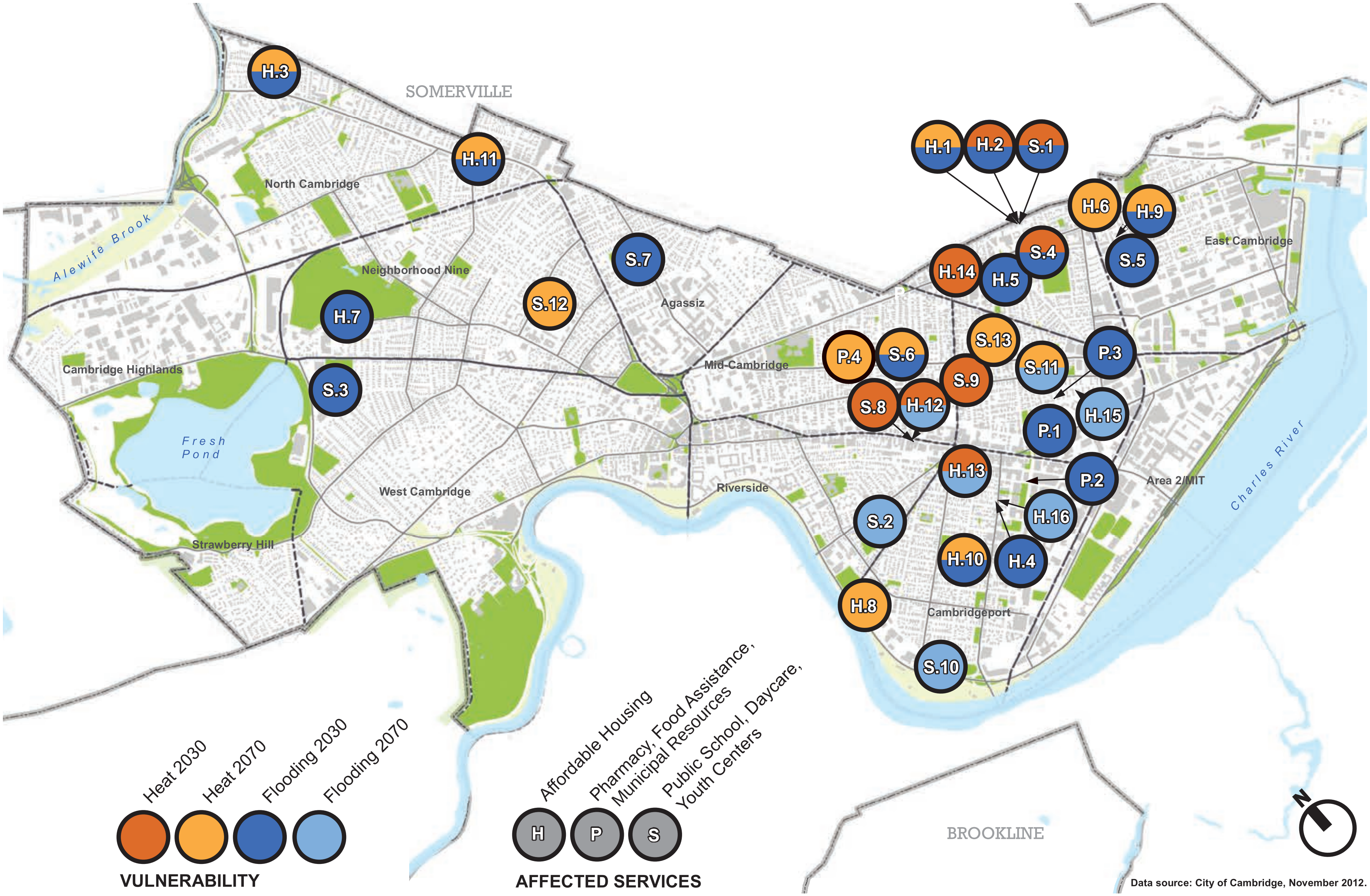

Fig. 28 **Community Resources Priority Areas** (Source: Kleinfelder, November 2015)

ECONOMIC IMPACTS

The CCVA economic analysis presents estimates of the value of:

- One-time structural damage to buildings from flooding was estimated using extent and depth of inundation from the 10- and 100-year (10% probability and 1% probability, respectively) rainfall events in 2030 and 2070 and U.S. Army Corps of Engineers Depth-Damage Function (DDF). A DDF is a mathematical relationship between the depth of floodwater and the amount of physical damage to a building that can be attributed to that water (in current dollars).
- One-time, direct and indirect losses in economic activity due to flooding from the 10% and 1% probability rainfall events in 2030 and 2070 in terms of Gross Regional Product (GRP) as estimated with an economic model (in current dollars). The GRP is a measure of how much a particular economy is worth, according to what it can produce. The annual GRP for all of Cambridge in 2012 was $15 billion.
- The cost of lost economic activity from one day for all of Cambridge, for any disaster event with a citywide extent, such as a heat-induced power failure, in terms of GRP as estimated by an economic model (in current dollars).

The estimation of potential economic effects from climate change is subject to considerable uncertainty, particularly due to the lack of precise economic data. However, using an economic activity model source, preliminary findings indicate that a citywide disaster could impact nearly all of the City's 128,000 jobs and result in a loss of nearly $43 million a day (in current dollars) based on the City's GRP.

The cost of business disruption could dwarf the cost of property damage.

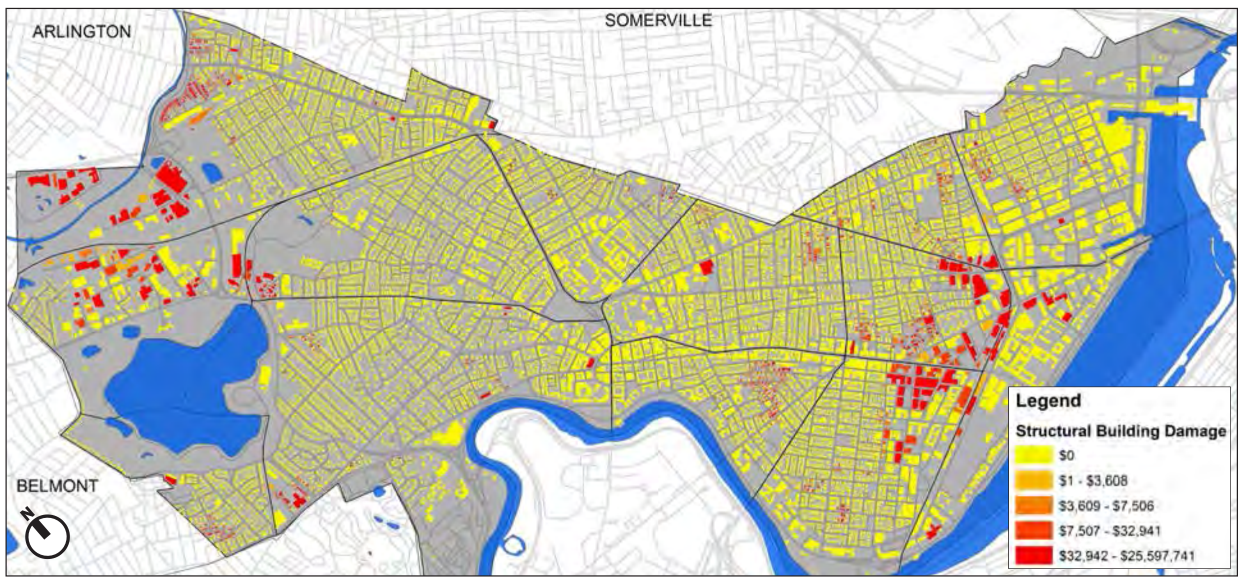

Fig. 29 **Estimate of structural damage to all buildings by 2070 from a 24-hour 100-year rainfall event** (Source: Catalysis, March 2015)

The impact of the temporary loss of employment was estimated using the IMPLAN model, which incorporates analysis of employment, wages and income, population, and output.

Furthermore, the effects of citywide interruption would likely spread well beyond Cambridge. The estimates were based on impacts to the present day level of economic activity and present day taxable assessed value of the City's building stock.

Structural Damage

- A single projected 1% probability rainfall event could cause $61 million in structural damage (in current dollars) in 2030 and over $232 million (in current dollars) in 2070 (Figure 29). These damage estimates are conservative, as they do not account for building contents.

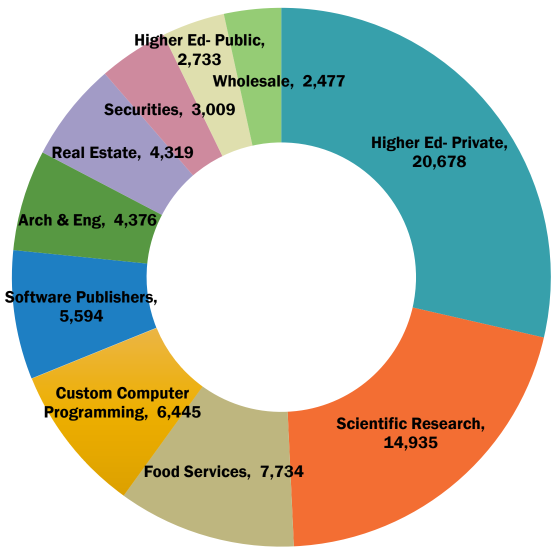

Fig. 30 **Chart of Top-Ten Industries in Cambridge by Employment (IMPLAN)**
(Source: Catalysis Economic Impact Report, March 2015)

- By 2070, Kendall Square, Central Square, and Fresh Pond would be the business districts most damaged by a precipitation driven 1% probability storm.

Disruption of Economic Activity

- A single 1% probability rainfall event would cause a drop in GRP of $3.4 to $4.6 million per day (in current dollars) in 2030, and $12 to $16 million per day (in current dollars) in 2070.
- Roughly $16.1 million per day (in current dollars) and as much as 25% of annual GRP could be affected by extreme precipitation or extended heat waves. This is based on the highest estimated impact that as many as 30,000 jobs or nearly one quarter of the 2012 employment level could be disrupted (see Figure 30 for employment by industry).
- A one-day, citywide disruption of Cambridge's 128,000 job economy would result in a loss of $43 million (in current dollars).
- The top ten industries employ 72,300 people (Figure 30) or 56% of Cambridge employment. The top ten industries make up 92% of the City's total GRP.
- The economic effects would most probably spread well beyond Cambridge. In addition, climate impacts outside of Cambridge could affect the City economically if systems such as food or fuel supply were disrupted. This reinforces the need to think more regionally and systematically about preparedness strategies.

NEXT STEPS

This report summarizes the extensive Climate Change Vulnerability Assessment completed for the City of Cambridge. The assessment will serve as the technical foundation for the next phase involving the development of Cambridge's first Climate Change Preparedness and Resilience Plan. The next phase will include the following tasks:

- Complete and issue Part 2 of this report on the vulnerability assessment based on coastal storm surge and sea level rise scenarios using the Boston Harbor Flood Risk Model (BH-FRM) developed for the Massachusetts Department of Transportation
- Perform additional technical analyses as needed
- Engage in regional coordination with key stakeholders undertaking their own preparedness efforts
- Coordinate with the upcoming Citywide Plan and the Getting to Net Zero Task Force recommendations
- Develop strategies to protect our most affected assets, systems, and population

The **Climate Change Preparedness and Resilience Plan** is expected to be a two-year effort starting in 2016. Early actions will be programmed into the process.

The City is committed to integrating the information developed to date into upcoming planning processes and the City's infrastructure projects.

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NOTES

The CCVA Report

Climate Change Vulnerability Assessment

City of Cambridge,
Massachusetts

Part 1