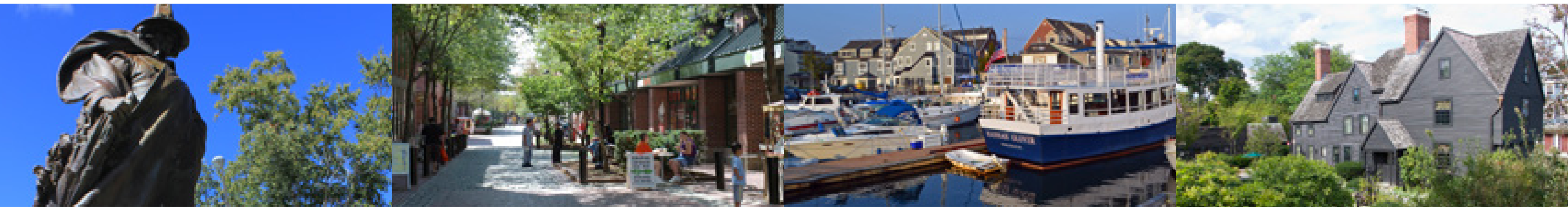
APPENDIX A



TECHNICAL MEMORANDUM ON POTENTIAL CLIMATE CHANGE IMPACTS IN SALEM, MASSACHUSETTS

CDM Smith

Salem
Still making history.

Memorandum

To: *Jeffrey Elie, City of Salem*

From: *Oliver Sellers-Garcia, AICP, LEED AP; Lauren Miller; Tim Cox, Ph.D., P.E; and Brian Caufield, P.E., CFM, CDM Smith*

Date: *October 9, 2013*

Subject: *Salem Climate Change Vulnerability Assessment, Revised Technical Memorandum on Potential Climate Change Impacts in Salem, Massachusetts*

This technical memorandum summarizes the research and analysis conducted for Task 1: Characterize Future Climate Change Scenario. As described in the Salem Climate Change Vulnerability Assessment Background & Approach document, the purpose of Task 1 is to quantify projected impacts of climate change in Salem.

This memorandum reflects CDM Smith's research and analysis, as well as the decisions that were made collectively by the CDM Smith project team, the City of Salem, and the Working Group during recent meetings.

A preliminary version of this memorandum was submitted on September 16, 2013. This memorandum reflects changes and revisions discussed with the Working Group on September 19, 2013. Comments regarding table and graph formatting will be addressed when the content is included in the final Vulnerability Assessment report and presentation materials.

Selected Climate Change Impacts

Climate change is predicted to occur in Massachusetts in various forms. These include increased annual and seasonal temperatures; changes in annual and seasonal precipitation; more frequent droughts; increases in intensity, duration, and frequency of extreme storms; sea level rise, and changes in the timing of peak stream flow.[1]

For the purposes of this study, the City of Salem and the Working Group chose the three key impacts that are considered most likely to have consequences for the City. These climate impacts are: 1) extreme heat events, 2) extreme precipitation events, and 3) sea level rise and storm surge. For the purposes of this vulnerability assessment, these impacts are defined as the following:

[1] Massachusetts Executive Office of Energy and Environmental Affairs. 2011. *Massachusetts Climate Change Adaptation Report*.

- *Extreme Heat Events:* Extreme heat events are days in which the ambient temperature high is equal to or greater than 90˚F. These conditions will place a high demand on the electric grid, risking more frequent power outages. There are also air quality implications leading to health concerns for the occupants of buildings.
- *Extreme Precipitation Events:* For this study, the 50-year and 100-year storms[2], as defined by historical climate records, have been selected to represent extreme precipitation events. Storms of this magnitude are known to cause flooding in Salem today. The frequency of such storms is expected to increase in the future as a result of climate change.
- *Sea Level Rise and Storm Surge:* Sea level rise is caused by local coastal subsidence coupled with the expansion of ocean water caused by increased temperatures and the melting of land ice in places such as Greenland and Antarctica. Storm surge is the rise of water above tide levels that occurs during storms. Higher sea levels can increase the severity of coastal inundation on a regular basis and during storms.

Planning & Research Context

This study's climate change projections analysis methodology is designed to be consistent with the leading regional and international standards, while incorporating the latest scientific research. The Massachusetts Executive Office of Energy and Environmental Affairs' *Climate Change Adaptation Report* (MA Report) is considered by policy-makers to be the current standard for planning-level climate change projections in our region. The MA report serves as a benchmark for our Salem-specific analyses. The MA Report employs the standard practice of comparing current conditions (average of the years 1961-1990) to future mid-century conditions (average of 2035-2064, often referred to as conditions in 2050) and end of century conditions (2100).

The MA Report uses the most recent information and climate predictions available at the time (2011), including data from the International Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) and other peer-reviewed scientific climate change projections.[2] Climate change impacts are presented in a range of low to high projections, reflecting the range of the six greenhouse gas (GHG) emissions scenarios from the IPCC AR4. The IPCC emission scenarios project the potential concentration of GHG emissions in the atmosphere by 2100, based on different social, economic, and technical trends. Each emission scenario represents a unique set of forcing variables and assumptions used to drive groups of global climate models (GCMs) to provide a range of climate impacts. The highest emissions scenario is "A1F1" with atmospheric GHG concentrations over 970 parts per million (ppm) and the lowest emissions scenario is "B1" with atmospheric GHG concentrations of 550 ppm. The remaining four emission scenarios fall between A1F1 and B1. The

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[2] Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Intergovernmental Panel on Climate Change, Fourth Assessment Report.

"A1B" emission scenario is considered a moderate scenario. "A1B" has an atmospheric GHG concentration of 700 ppm.[3]

IPCC is expected to issue the Fifth Assessment Report (AR5) in 2014. This forthcoming report will take a slightly different approach to the emission scenarios. IPCC will use four Representative Concentration Pathways (RCPs) which base climate impacts on radiative forcing values. Radiative forcing is the net amount of energy that the earth absorbs from the sun and is expressed in terms of watts per square meter (W/m2). Greenhouse gases increase the amount of solar radiation in the atmosphere, which increases the net radiative forcing of the earth (the greenhouse effect). The RCP "value" indicates the level of radiative forcing expected by 2100 (i.e. RCP2.6 is the rising radiative forcing that results in 2.6 watts per square meter by 2100). As in AR4, these RCPs serve as unique sets of inputs for groups of GCMs and are labeled according to the projected 2100 GHG concentration associated with them.[4,5] RCPs are analogous to the "scenarios" in AR4. Table 1 below outlines the differences in expected GHG concentrations in the atmosphere by 2100 between the AR4 scenarios and the AR5 RCPs.

Table 1. Comparison of the AR4 Climate Scenarios and AR5 Radiative Concentration Pathways

	AR4 Climate Scenarios
B1	**~550 ppm CO_2e by 2100**
A1T	**~575 ppm CO_2e by 2100**
B2	**~625 ppm CO_2e by 2100**
A1B	**~700 ppm CO_2e by 2100**
A2	**~850 ppm CO_2e by 2100**
A1F1	**~970 ppm CO_2e by 2100**

	AR5 Radiative Concentration Pathways
RCP2.6	**~490 ppm CO_2e by 2100**
RCP4.5	**~650 ppm CO_2e by 2100**
RCP6	**~850 ppm CO_2e by 2100**
RCP8.5	**~1370 ppm CO_2e by 2100**

Technical Approach

As a consequence of climate change, planning for the future using historical observations may no longer be valid. The approach presented here, therefore, focuses on quantifying the future changes in climate, as projected by the best available science, to provide for more robust planning decision support. We have employed a technical approach to calculate climate change impacts in Salem that

[3] Intergovernmental Panel on Climate Change. 2000. IPCC Special Report, Emissions Scenarios: Summary for Policymakers.
[4] Van Vuuren, et al. 2011. The Representative Concentration Pathways: An Overview. *Climatic Change*, 109:5-31.
[5] Bureau of Reclamation, et al. 2013. Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs.

incorporates elements of the MA Report, IPCC AR4 and AR5, and several other climate change reports, plans, and scientific papers (see bibliography).

The City and the Working Group chose to take a "middle of the road" approach, and the vulnerability assessment will be conducted using the intermediate range of climate change predictions. Employing the intermediate range of projections is a practical approach to identify immediately actionable vulnerabilities. As with the MA Report and other plans, we have estimated climate change impacts for emissions scenarios that fall above and below the intermediate value. For planning purposes, the moderate projections presented best match Salem's "middle of the road" approach. The high and low projections were also included to provide context for users of the Vulnerability Assessment and Adaptation Plan.

We have elected to use the most recent GCMs[6] and RCPs that will be used in the IPCC AR5 to estimate extreme precipitation and heat events. Downscaled GCM data were collected from World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5). These data correspond to a 1/8° latitude/longitude grid cell overlying the City of Salem. For the extreme heat and precipitation analyses, downscaled GCM data were ensembled from up to 21 different GCMs for each of four available RCP scenarios.

Sea level rise and storm surge are not predicted by GCMs. Sea level rise was determined by employing a methodology used by the U.S. Army Corps of Engineers to evaluate Sea-Level Change. To evaluate the potential risk to Salem under storm conditions, we utilized the return period stillwater elevations reported in the Preliminary Flood Insurance Study for Essex County.

We have calculated climate impacts for the year 2050, consistent with the MA Report, and reflecting the City of Salem's desire for this Vulnerability Assessment to identify immediate, actionable adaptation priorities. Because the RCPs are based on dynamic GCMs, the results of the vulnerability assessment use a range of years.[7] This helps to ensure the results capture both climate impacts reflective of the 2050 planning horizon and "natural" year-to-year variability in climate while not being biased by anomalous single years (e.g. a particularly cold or rainy year).

While predictions for all three climate impacts in this study are based on the same general technical approach, specific unique methods were required for each. In the sections that follow, we summarize the methodology for each of the three impacts and present our findings on the range of projected 2050 impacts compared to the baseline.

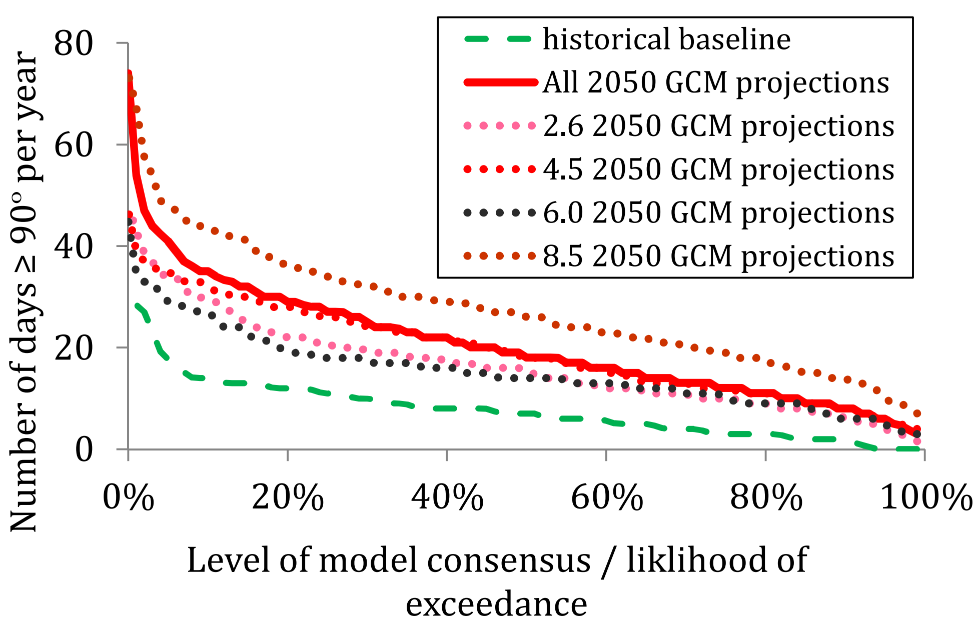
[6] World Climate Research Programme. 2011. Coupled Model Intercomparison Project Phase 5 (CMIP5). http://cmip-pcmdi.llnl.gov/cmip5/
[7] The range for extreme heat events is 2045-2055 and the range for extreme precipitation events is 2040-2060.

Extreme Heat Events

The decade of 2001-2010 was the hottest on record, warmer than the global average land and ocean-surface temperatures from 1880-2010[8]; this trend is expected to continue. Extreme heat events are defined as days in which the daily maximum temperature is equal to or above 90˚F. The projected number of days equal to or above 90˚F from the GCMs was compared to historical data to determine how much more frequently Salem may expect this type of event. Historically, on average, our analysis indicates that there have been 5.8 days per year equal to or above 90˚F, based on data from 1950-1999.

The extreme heat event analysis is summarized with percentile plots showing levels of consensus among models within each RCP category with respect to 2050 projections (Figure 1). Alternatively, the quantified levels of consensus (x axis) can be interpreted as relative *risk* levels associated with a given number of extreme heat events occurring in 2050. The historical baseline curve summarizes the observed number of extreme heat events from 1950-1999 and thus its x-axis represents a true probability of occurrence calculated with historical data. For example, the results show that 1 out of 50 years (2% probability of occurrence) in the historical period of record (1950 – 1999) had at least 27 days with maximum temperatures over 90ºF. Conversely, the worst case GCM projections (RCP8.5) predict an approximately 50% chance of the same number of extreme heat days occurring in 2050. At the high end (1% level of consensus), GCMs project 2050 extreme heat days in the range of 35 – 70 days per year.

Figure 1. Results of the Extreme Heat Analysis



[8] World Meteorological Organization. 2013. 2001-2010: A Decade of Climate Extremes.

In order to conduct the vulnerability assessment, a percentile of model consensus should be selected. This planning metric should reflect the level of risk that the City is comfortable with for planning purposes. It may also be important to consider specific event magnitude thresholds that would trigger adaptation or response activity. For example, how many expected days equal to or above 90˚F would require specific actions in the adaptation plan?

Extreme Precipitation Events

For this study, extreme precipitation events are defined as the current 50-year storm (7.35 inches of precipitation over a 24-hour period) and the current 100-year storm (8.76 inches of precipitation over a 24-hour period). The frequencies of such extreme events are continuously changing as a result of climate change.[9] As such, this vulnerability assessment focuses on the increased future frequency of precipitation events with these levels of rainfall, rather than with defining the new 100- and 50-year storms. Historical storm event statistics were obtained from the Northeast Regional Climate Center for Boston, MA[10,11] based on data from approximately 100 years of record.

As with extreme heat events, the future occurrence of extreme precipitation events in Salem was calculated based on the four GCM categories and observed baseline data for 1950-1999. GCM projections of precipitation have been found to have a dry bias for the Eastern United States[10]. In other words, predictions of both past and future precipitation are lower than they should be and require future calibration refinements (bias correction). To address this issue, we employed a "delta" method that normalized future model projections to model simulations of past projections: only the relative changes predicted by the climate models are used rather than directly using the actual magnitudes of projected precipitation. Any bias that is occurring in the model projections of the future is also occurring in model simulations of the past. Therefore, by using only the relative differences between the two, we eliminate this bias from our calculations.

Using this method, we created a table of new 24 hour precipitation values corresponding to the targeted set of recurrence intervals and reflective of future (2050) climate. Linear interpolation between data points was used to estimate future recurrence intervals for the specific historical design storm magnitudes. As an example, the magnitude of the historical 50 year 24 hour design storm (7.35 inches) lies between the 25 and 50 year design storm magnitudes reflective of future conditions. Using linear interpolation, the new recurrence interval for the 7.25 inch storm was calculated as 37 years (using the fully ensembled GCM data set).

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[9] Brekke, L. 2013. Errata for "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs", May 2013, available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf

[10] Northeast Regional Climate Center. 2009. http://www.nrcc.cornell.edu/page_services.html

[11] Boston, MA is the closest location to Salem, MA with a full, historical precipitation data set.

The results of this analysis show that recurrence intervals associated with the selected extreme events (7.35 and 8.76 inches of precipitation in 24 hours) are predicted to decrease in the future. In other words, the likelihood of such events occurring in the future is predicted to increase compared to the past 100 years. There is fairly good consensus across the five GCM groupings on the magnitude of this change, ranging from approximately 15 to 30% reduction in recurrence intervals for the two storm events, respectively (Table 2).

It should be noted that the GCM projections show even greater changes towards the end of the century. Thus we would expect that the changes quantified here would be even greater for a longer planning horizon. It should also be noted that there is generally less certainty associated with GCM precipitation projections compared to temperature projections. Therefore, we can surmise that the levels of uncertainty associated with results presented here are greater than those presented for extreme heat forecasts. We have not attempted to quantify this uncertainty in the results presented in Table 2.

Table 2. Results of the Extreme Precipitation Event Analysis

Recurrence Interval	Precipitation Event	
	7.35 inches/24 hours	**8.76 inches/24 hours**
1950-1999, Historical	• 50-year storm • 2% chance of occurring in any year	• 100-year storm • 1% chance of occurring in any year
2050, Average of All RCPs	• 37-year storm • 2.7% chance of occurring in any year	• 77-year storm • 1.3% chance of occurring in any year
2050, RCP2.6	• 44-year storm • 2.3% chance of occurring in any year	• 83-year storm • 1.2% chance of occurring in any year
2050, RCP4.5	• 35-year storm • 2.9% chance of occurring in any year	• 72-year storm • 1.4% chance of occurring in any year
2050, RCP6.0	• 36-year storm • 2.8% chance of occurring in any year	• 73-year storm • 1.4% chance of occurring in any year
2050, RCP8.5	• 34-year storm • 2.9% chance of occurring in any year	• 72-year storm • 1.4% chance of occurring in any year

Sea Level Rise and Storm Surge

The Atlantic Ocean is experiencing sea level rise due to climate change, which on its own may cause additional nuisance flooding in Salem, MA. In addition to sea level rise, the City is susceptible to storm surge, which is the additional increase in water levels caused by a storm. Storm surge has the potential to cause additional flooding.

Sea level rise was determined by employing a methodology used by the U.S. Army Corps of Engineers to evaluate Sea-Level Change.[12] The U.S. Army Corps of Engineers use three curves to establish their design bases for any planning study and engineering design. The U.S. Army Corps of Engineers Low Curve is the future projection of the historically observed sea level rise rate, which for Boston is observed from 1921 to 2012 as 2.79 mm/yr. The U.S. Army Corps of Engineers Intermediate Curve and High Curve use National Research Council curves based on the recent IPCC projections and accounting for the local rate of vertical land movement. Boston is reported as a subsidence rate of 0.84 mm/yr.

Included in these three U.S. Army Corps of Engineers curves are curves reported in NOAA Technical Report OAR CPO-1 Global Sea Level Rise Scenarios for the United States National Climate Assessment. There are 4 curves reported in the NOAA report termed High, Intermediate High, Intermediate Low, and Low corresponding to global sea level rise by 2100 of 2.0, 1.2, 0.5, and 0.2 m respectively. The NOAA High scenario uses the IPCC AR4 estimates of ocean warming and the maximum possible glacier and ice sheet loss by 2100, and is recommended for situations with little tolerance for risk. The NOAA Intermediate High is based on an average of the high-end of semi-empirical global SLR projections, several of which utilize the A1B emission scenario, and considers risk with limited ice sheet loss. The NOAA Intermediate Low is based on the upper end of the global SLR projections using the B1 emission scenarios, and can be used to assess risk primarily from ocean warming. The NOAA Low curve is the projection of the observed sea level rise rate at a tide gage.

Based on the USACE and NOAA Curves, we can evaluate a total of 5 SLR projections:

- USACE/NOAA Low (projection of observed sea level rise)
- USACE Intermediate/NOAA Intermediate Low (projections accounting for ocean warming)
- NOAA Intermediate High (projections accounting for limited ice sheet loss)
- USACE High (projections accounting for a more rapid loss of the ice sheet)
- NOAA High (projections accounting for maximum ice sheet loss by 2100)

[12] U.S. Army Corps of Engineers. 2011. Sea-Level Change Considerations for Civil Works Programs.

We consider the NOAA Intermediate High as a useful projection of SLR for the City of Salem in order to assess vulnerability using a "middle of the road" approach. (These curves are shown in Figure 2, below, for the 100-year storm.)

In order to evaluate the potential impact of nuisance flooding, or that associated with normal tidal cycles, we evaluated future projections of the tidal datums adjusted by SLR. The City of Salem lacks established tidal datums by NOAA, and the closest established tidal datums are for Boston (Station 8443970). Mean Higher High Water (MHHW) is the average of the higher high water height of each tidal day, which in a diurnal tidal cycle such as Salem is the higher of the two high tides occurring daily. NOAA currently reports MHHW for the Boston station as 4.76 feet NAVD88. Table 3 contains the projections of MHHW (in feet NAVD88) in 2100 from each of the SLR curves considered for this study. [13] This table indicates that by 2100, MHWW could be nearly 1 foot to over 11.5 feet higher than current.

Table 3. 2100 Coastal Inundation Levels with USACE and NOAA Sea Level Rise Scenarios

Tidal Datum	1998 Baseline	USACE/NOAA Low	USACE Intermediate/NOAA Intermediate Low	NOAA Intermediate High	USACE High	NOAA High
	(feet)					
MHHW	4.76	5.70	6.74	9.03	10.02	11.66
Change from 1998 Baseline	n/a	0.94	1.98	4.27	5.26	6.90

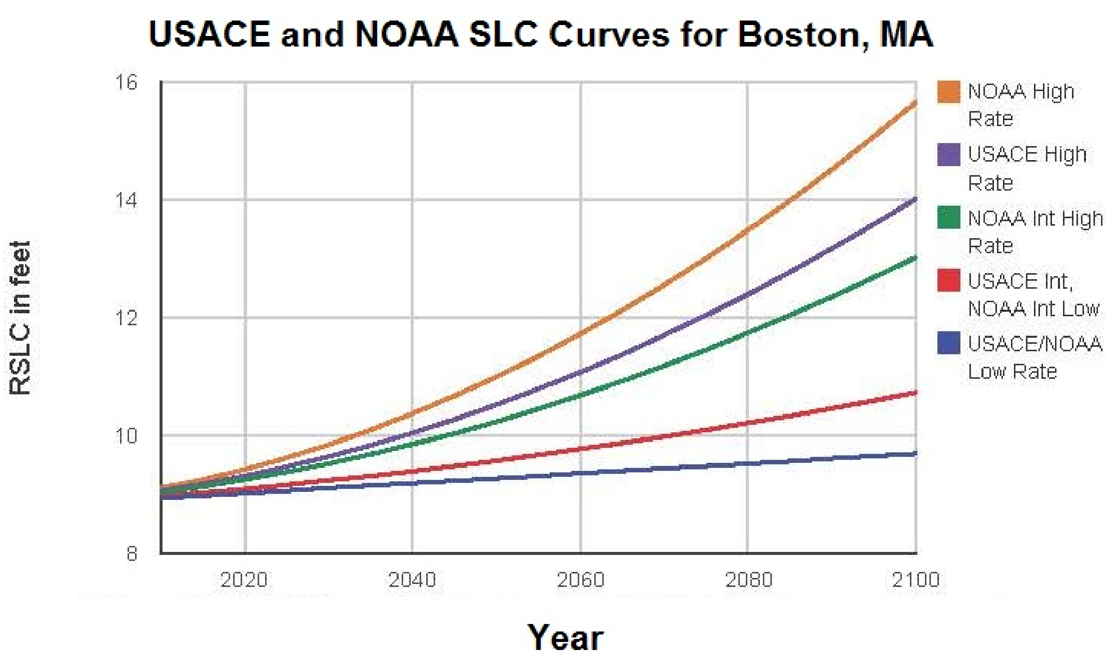
When evaluating the potential risk to Salem under storm conditions, we utilized the return period stillwater elevations reported in the Preliminary Flood Insurance Study for Essex County[14]. FEMA reports the 10-, 2-, 1-, and 0.2-percent-annual-chance stillwater elevations. In these SLR projections, we are not considering the effects of global climate change on storm intensity, but rather the shift in the stillwater elevations. Table 3 contains the projections for each of these return periods (in feet NAVD88) in 2050 for each of the SLR curves considered in this study, with our recommendation bolded. The projections from 2010-2100 for the 100-year storm are shown in Figure 2.

[13] North American Vertical Datum of 1988 (NAVD88) is the vertical control height for surveying the U.S.
[14] Federal Emergency Management Agency. 2013. Flood Insurance Study: Essex County, Massachusetts (Preliminary).

Table 4. 2100 Storm Surge with USACE and NOAA Sea Level Rise Scenarios

Return Period	**1998 Baseline**	**USACE/NOAA Low**	**USACE Intermediate/NOAA Intermediate Low**	**NOAA Intermediate High**	**USACE High**	**NOAA High**
	(feet)					
10-percent	7.7	8.60	9.64	11.93	12.92	14.56
2-percent (50-year storm)	8.5	9.4	10.44	12.73	13.72	15.36
1-percent (100-year storm)	8.8	9.9.70	10.47	13.03	14.02	15.66
0.2-percent	9.6	10.50	11.54	13.83	14.82	16.46
Change from 1998 Baseline	*n/a*	*0.9*	*1.94*	*4.23*	*5.22*	*6.86*

Figure 2. Results of the Sea Level Rise and Storm Surge Analysis, 100-year Storm



Summary

- Baseline conditions and high/medium/low 2050 projections have been calculated for
  - Extreme heat events
  - Extreme precipitation events
- Baseline conditions and high/medium/low 2100 projections have been calculated for
  - Sea level rise and storm surge
- These projections are in line with the MA Climate Change Adaptation Report.
- Newly available and more locally scaled data have been used where possible.
- At the September 19, 2013 Working Group meeting, the following projections were selected or confirmed for use in the vulnerability assessment
  - The increased frequency of the current 50-year and 100-year storm is the indicator for extreme precipitation events.
  - The likelihood of occurrence range for extreme heat events will be informed by interviews with the City staff to determine the severity of heat events that would cause major issues to the five sectors
  - The NOAA Intermediate High sea level rise curve to select as "moderate" SLR projection. The analysis year for SLR and storm surge impacts will be 2100.

cc: Julia Knisel, MA Office of Coastal Zone Management
John Hayes, Salem State University
Barbara Warren, Salem Sound Coastwatch
Lisa Gove, P.E., CDM Smith

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