M E M O R A N D U M

TO: Abby Piersall, Town of Hingham

FROM: Indrani Ghosh, Kleinfelder

DATE: October 24, 2014

SUBJECT: Sea Level Rise and Storm Surge Model Input Parameters

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The purpose of this memorandum is to explain the choice of input parameters for the sea level rise and storm surge model, as well as the proposed planning horizons that will be used for the model simulations in Hingham. This memo is part of the deliverables of Phase I for Hingham's Climate Change Vulnerability, Risk Assessment and Adaptation Study. This memo presents the Kleinfelder team's recommendations to the Town's Steering Committee for the following parameters, each of which will be explained in subsequent sections:

- Choice of sea level rise and storm surge model
- Types of storms and storm climatology
- Selection of sea level rise scenarios
- Planning horizons
- Display of model results

Choice of Sea Level Rise and Storm Surge Model

We propose to use the Massachusetts Department of Transportation (MassDOT) Boston Harbor Flood Risk Model (BH-FRM) that is currently being developed by the Woods Hole Group for the greater Boston area, which includes other surrounding communities in Massachusetts, including Hingham. The BH-FRM model is being developed as part of the MassDOT and the Federal Highway Administration (FHWA) project for assessing potential vulnerabilities in the Central Artery tunnel system. The BH-FRM modeling system is comprised of the ADvanced CIRCulation model (ADCIRC), a two-dimensional, depth-integrated, long wave, hydrodynamic model for coastal areas, inlets, rivers, and floodplains that, in this application, is used to predict storm surge flooding, and the Simulating WAves Nearshore model (SWAN), a wave generation and transformation model. Since the BH-FRM model domain includes the entire greater Boston area, the Town of Hingham and other surrounding communities, we will be able to use this model to assess the vulnerability and risk of coastal flooding to Hingham's infrastructure and natural resources. Using this existing model will be beneficial to the Town of Hingham since much of the upfront work in developing the model has already been conducted as part of the MassDOT/ FHWA project, and the Town will be able to use the results.

The ADCIRC model is tightly coupled with SWAN, dynamically exchanging physical processes information during each time step, to provide an accurate representation of water surface elevations, winds, waves, and flooding along the Hingham coastline and surrounding upland areas. The spatial resolution of the model is 10 meters or less, sometimes as low as 1 meter to capture important changes in topography and physical processes related to storm dynamics. This high-resolution model offers more accuracy than other storm surge models, such as SLOSH. This modeling approach is also far superior compared to a more rudimentary "bathtub" approach, since the latter does not account for critical physical processes that occur during a storm event, including waves and winds, nor can it determine the volumetric flux of water that may be able to access certain areas.

The proposed modeling approach is risk-based, which will be beneficial to the Town to assess the vulnerability and risk of infrastructure, evaluate its resiliency, and plan for adaptation options to mitigate future flooding damage for the Town of Hingham. It will also produce information that can be used to inform engineering design criteria since it provides the probability of an event occurring in this changing regime, such as the "new" 100-year flood or 1% event flood levels. This risk-based approach uses a fully optimized Monte Carlo approach, simulating a statistically robust set of storms (both tropical and extra-tropical) for each sea level rise (SLR) scenario. Results of the Monte Carlo simulations are used to generate Cumulative probability Distribution Functions (CDFs) of the storm surge water levels at a high degree of spatial precision. In particular, an accurate and precise assessment of the exceedence probability of combined SLR and storm surge, provided at high spatial resolution, will be provided that can help decision makers to identify areas of existing vulnerability requiring immediate action in Hingham, as well as areas that benefit from present planning for future preparedness.

Some of the unique aspects of the BH-FRM model include the following:

- An extensive understanding of the physical system as a whole
- Inclusion of significant physical processes affecting water levels (e.g., tides, waves, winds, storm surge, sea level rise, wave set-up, etc.)
- Full consideration of the interaction between physical processes
- Characterization of forcing functions that correspond with real world observations
- Resolution that will be able to resolve physical and energetic processes, while also being able to identify site-specific locations that may require adaptation alternatives

Types of Storm Events and Storm Climatology

The types of storms that will be included in the Monte Carlo simulations will include both tropical storms (hurricanes) and extra-tropical storm (nor'easters). The storm climatology parameters that are included in the BH-FRM model include wind directions and speeds, radius of maximum winds, pressure fields, and forward track of the storms in the Boston Harbor area. While hurricanes are typically shorter duration events that often last over only one tidal cycle, nor'easters are longer duration events that typically last over multiple tidal cycles spanning multiple days. So the probability of a nor'easter occurring or lasting through a high tide is more likely than a hurricane. Also, the diameter of a nor'easter (also commonly called the "fetch") is usually 3-4 times that of hurricanes, and therefore they impact much larger areas of inland as well. Finally, the frequency of nor'easters in Hingham is also higher than hurricanes. While the Northeast may experience one hurricane landfall every five years, nor'easters occur annually with at least 20-40 in a given year, of which generally at least two are severe. Therefore, the inclusion of nor'easters is one of the unique aspects of the BH-FRM model that is not available in other storm surge models, such as SLOSH.

The storm climatology for the hundreds of different types of storms are all factored in the Monte Carlo simulations of these storm events. The storm climatology is based on present climate for planning horizons until 2050, but for storm simulations beyond the 2050, the 21st century climatology is used to simulate the storms. The latter half of 21st century climatology projections factored into the BH-FRM model are based on climatology projections by the notable MIT professor Dr. Kerry Emmanuel.

Selection of Sea Level Rise Scenarios

Sea level rise (SLR) scenarios recommended by Parris et al. (2012) for the U.S. National Climate Assessment (Global Sea Level Rise Scenarios for the United States National Climate Assessment, NOAA Technical Report OAR CPO-1, December 12, 2012) will be utilized in this study (Figure 1). These scenarios are the same scenarios recommended by Massachusetts Coastal Zone Management for assessing SLR, as well as those being used by MassDOT and other state agencies and communities for vulnerability assessments.

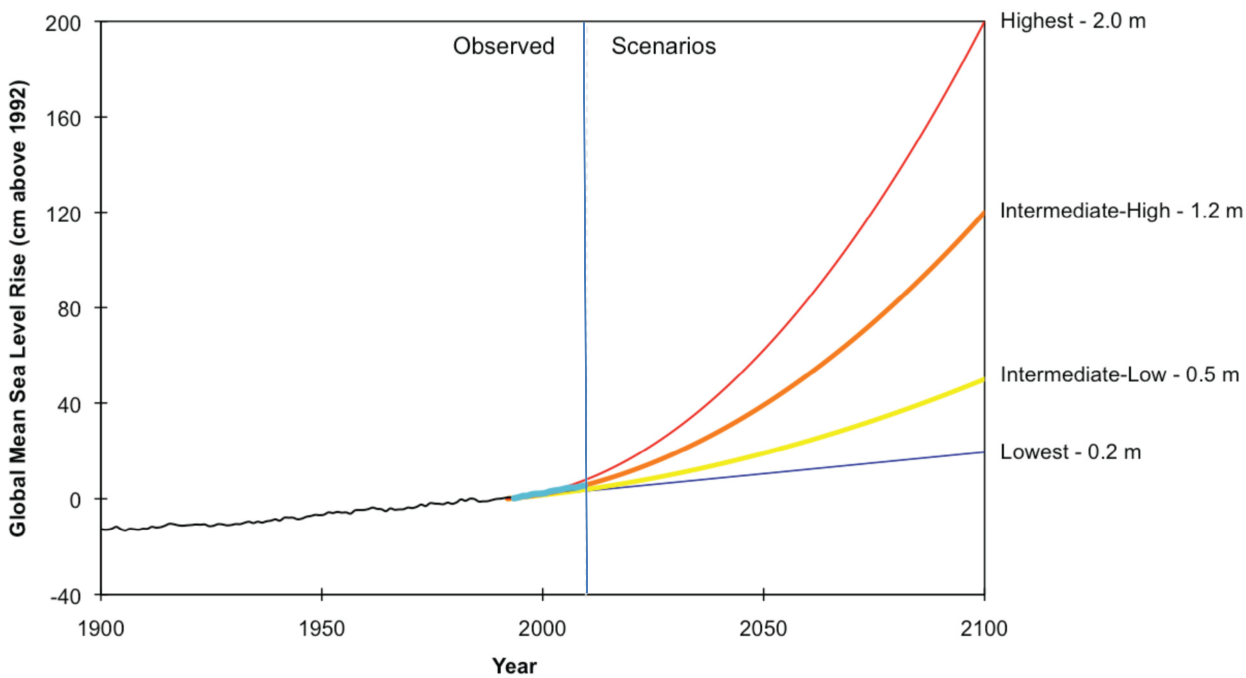

Figure 1: Global mean sea level rise scenarios as published in the NOAA Technical Report *Global Sea Level Rise Scenarios for the United States National Climate Assessment*, December 2012

According to the NOAA "Highest" scenario for global SLR from Parris et al., which combines thermal expansion estimates from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and the maximum possible glacier and ice sheet loss by the end of the century, this scenario "should be considered in situations where there is little tolerance for risk". As discussed with the Steering Committee at our kick-off meeting on September 15, 2014, we recommend using the "Highest" SLR scenario for Hingham. This scenario is also being used by MassDOT and other state agencies and communities for vulnerability assessments.

In addition to global SLR, local mean sea level changes should also be factored in. Local mean sea level changes can be estimated by considering local tide gage records in combination with models or actual measurements of Earth's local tectonic movements. The NOAA tidal gage at Boston Harbor (station ID 8443970) has recorded an increase in relative mean sea level of 2.63 mm (+/- 0.18 mm) annually based on monthly mean sea level data from 1921 to 2006. Over that same time period, the global rate of sea level rise was about 1.7 mm annually. This difference implies that there is about 1 mm (0.04 in./yr) per year local land subsidence in the relative sea level record for the Boston area (MA Adaptation report 2011). This rate of subsidence will be factored in with the global SLR scenarios to determine the relative SLR projections for Hingham.

Table 1 below presents the total relative SLR values (global SLR and local land subsidence rate of 0.04 in./yr) for years 2020 through 2100 in 10 year increments for the Town of Hingham, considering a start year of 2013 (since 2013 was used as the start year for the SLR calculations in the BH-FRM model). We also conducted the calculations using 2015 as the start year, considering 2015 will be the completion year of this project, and found that the difference in SLR projections between using 2013 and 2015 as the start years is less than one-tenth of a foot. Hence we propose to use the same SLR values that have been used in the BH-FRM model. Table 1 also presents the SLR projections for Hingham using the NOAA "Intermediate High" and NOAA "Intermediate Low" scenarios for the purposes of comparison.

While selection of the highest scenario may be interpreted as conservative, this selection also allows for representing a range of scenarios that allows decision makers to consider multiple future conditions and to develop multiple response options. For example the value for the "Highest" scenario at 2030, is also similar to the "Intermediate-High" value at that same time period, and approximately the "Intermediate-Low" value for 2070.

The SLR scenarios that will be utilized in the Hingham vulnerability assessment are:

- Existing conditions for the current time period (considered to be 2013).
- The value for the Highest scenario at 2030 (0.66 ft of SLR), which is also close to the Intermediate High value at that same time period, and approximately the Intermediate Low value for 2050.
- The value for the Highest scenario at 2070 (3.4 ft of SLR), which is also approximately the Intermediate Highest scenario value for 2090.

Table 1. Sea level rise estimates for Hingham using the 2012 NOAA NCA SLR scenarios

Scenarios	2020	2030	2040	2050	2060	2070	2080	2090	2100
Global SLR (from 2013-year of interest) "Highest" (feet)	0.21	0.61	1.10	1.70	2.40	3.21	4.11	5.12	6.23
Global SLR (from 2013-year of interest) "Intermediate-High" (feet)	0.14	0.38	0.68	1.04	1.46	1.93	2.46	3.05	3.69
Global SLR (from 2013-year of interest) "Intermediate-Low" (feet)	0.07	0.18	0.32	0.47	0.63	0.82	1.02	1.24	1.48
Land subsidence (feet) @ 0.04 in./yr	0.02	0.06	0.09	0.12	0.15	0.19	0.22	0.25	0.29
Total Relative SLR - "Highest" (feet)	0.24	**0.66**	1.19	1.82	2.56	**3.39**	4.33	5.37	6.52
Total Relative SLR – "Intermediate-High" (feet)	0.16	**0.44**	0.77	1.16	1.61	**2.12**	2.68	3.30	3.98
Total Relative SLR – "Intermediate-Low" (feet)	0.09	**0.24**	0.40	0.59	0.79	**1.01**	1.24	1.50	1.77

Planning Horizons

As discussed with the Steering Committee at our kick-off meeting on September 15, 2014, we propose to use 2030 and 2070 as appropriate planning horizons for Hingham's vulnerability analysis to provide an estimate of short-term and mid-term vulnerabilities. As discussed above, we propose to use the risk-based scenarios to assess potential vulnerabilities in the Town of Hingham.

The BH-FRM model that we are proposing to use has been developed for the years 2030, 2070, and 2100. Since the Steering Committee has requested for two planning horizons, we propose to use 2030 and 2070 planning horizons with corresponding sea level rise projections for the following reasons:

- The BH-FRM model developed for the greater Boston area includes the Town of Hingham. This is a high-spatial resolution model that provides detailed flooding results of combined SLR and storm surge in terms of exceedence probability. This makes it a useful tool for risk-based decision making. We believe the Town of Hingham can benefit from using best-available model results at a lower cost than it would take to run any other modeling scenario. In addition, the model's performance and accuracy has already been peer-reviewed by MassDOT's scientific advisory team.

- We recommend using the 2030 (15 years from 2015) planning horizon for near-term inundation modeling results since the results are readily available and consistent with planning horizons used in the majority of studies in Eastern Massachusetts, therefore allowing for easy comparisons.
- We recommend using the 2070 (55 years from 2015) as a more useful long-term planning horizon for the following reasons:
  (a) The level of uncertainty associated with sea rise projections for the end-of-century (2100 and beyond) are quite high.
  (b) The expected service life of most infrastructure that will be evaluated for risk is well below 100 years, and 2070 is closer to the expected life of typical infrastructure.
  (c) Finally, the 2070 timeframe is more consistent with other regional climate change vulnerability studies (e.g. Cities of Cambridge and Boston, MassDOT/FHWA).

Display of Model Results

One of the primary purposes of developing the sea level rise and storm surge model is to map the extent and magnitude of flooding caused by tides, sea level rise, associated storm surge, and other key physical processes (e.g., wave set-up, winds, etc.). We will develop GIS maps for the Hingham coastline for the following scenarios:

- Depth of flooding above ground elevation at Mean Higher High Water (MHHW) only (no storm surge) for present, 2030 and 2070.
- Depth of flooding above ground elevation at 1% risk of flooding with storm surge (approximately equivalent to a 100 year flood) for present, 2030 and 2070.
- Depth of flooding above ground elevation at 0.2% risk of flooding with storm surge (approximately equivalent to a 500 year flood) for present, 2030 and 2070.
- Percent risk of flooding one foot above ground elevation for present, 2030 and 2070 (see example in Figure 2)

We also propose to develop up to five (5) Probability of Exceedance curves for 2030 for critical infrastructure as identified by the Steering Committee (see examples in Figures 3 and 4). A Probability of Exceedance curve can be used to understand the risks of flooding at any given water elevation for an asset which will be very useful information in the later development of adaptation strategies.

The maps will be developed in ESRI’s ArcGIS software using the results from the BH-FRM model for sea level rise combined with storm surge.

Figure 2 shows an example of a risk map generated for Galveston, Texas using the Monte Carlo approach using results from a model similar to the BH-FRM model. The figure shows the level of risk for inundation in 2100 corresponding to a projected SLR of 125 cm. As such, stakeholders can look at any location on the map and determine the percent chance of being flooded in that year (2100). Similar maps will be generated for Hingham where the color contours will correspond to the annual percent risk of inundation for a given year.

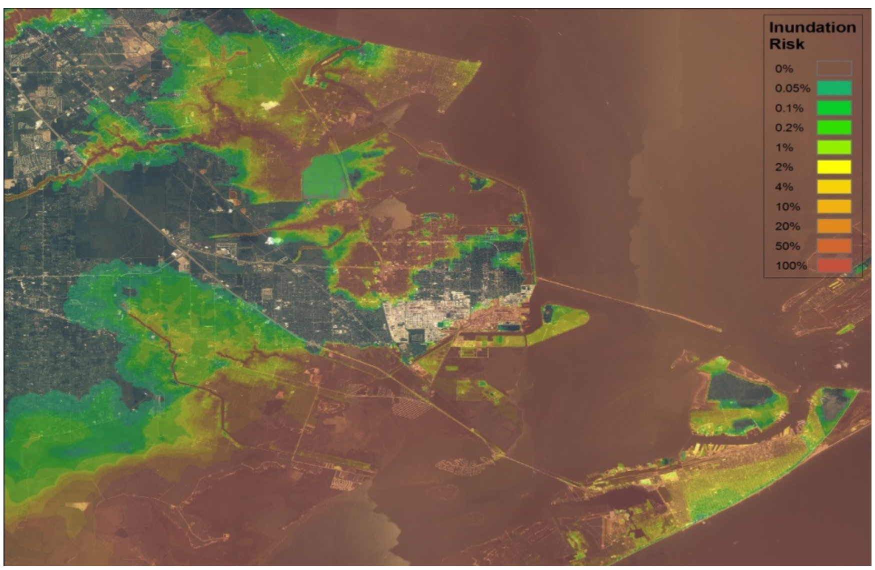

Figure 2: Inundation risk map for Galveston, Texas under a projected SLR of 125cm (approximately corresponding to year 2100). The risk percentages show the risk to be inundated any given year under this SLR scenario.

Figures 3 and 4 show examples of Probability of Exceedence (PE) tables and curves. A PE curve can be generated at any point in the GIS map. Locations of curve will be agreed to by the Steering Committee.

Surge EL (ft)	Depth (ft)	Exceedance Probability	Exceedance Percent
19.93	13.89	0.0005	0.05%
17.02	10.98	0.001	0.1%
15.90	9.86	0.002	0.2%
13.18	7.14	0.01	1%
11.37	5.33	0.02	2%
9.71	3.67	0.04	4%
7.80	1.76	0.1	10%
Dry	0.00	0.2	20%
Dry	0.00	0.5	50%
Dry	0.00	0.999	99.9%

Figure 3: Sample Probability of Exceedence Table for a Given Year

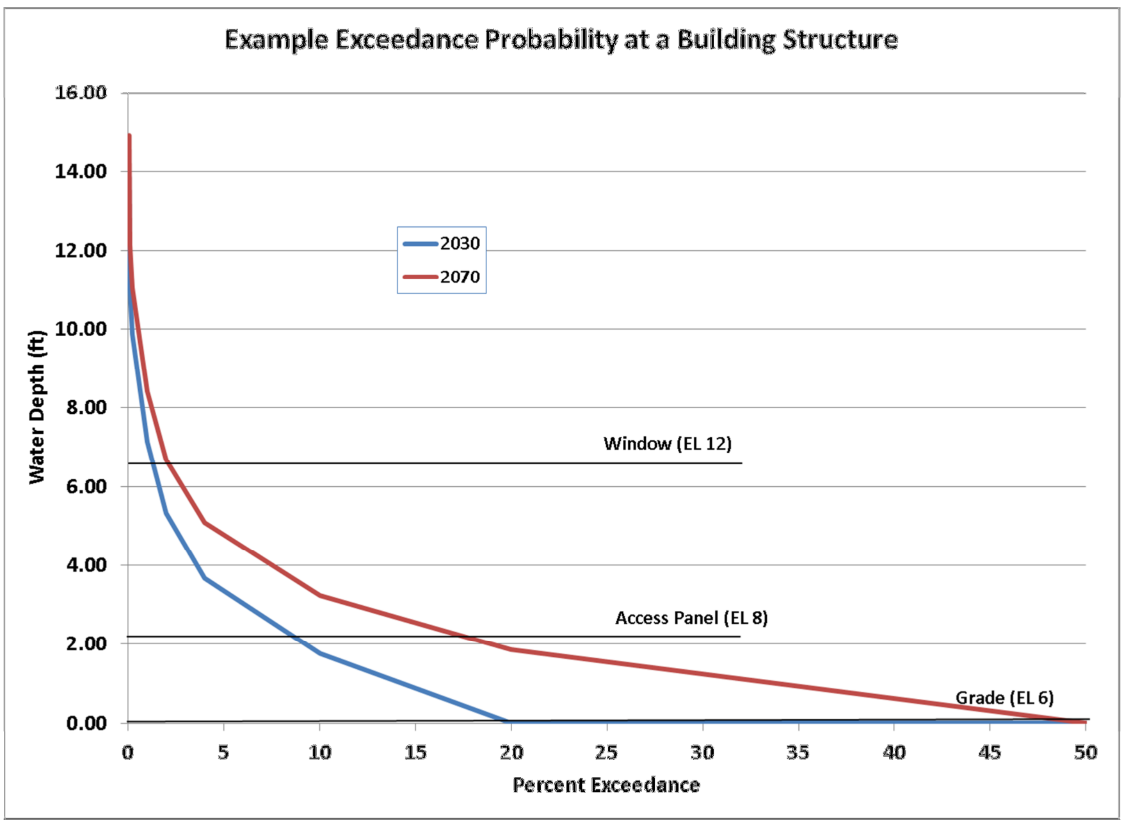

Figure 4: Sample Probability of Exceedence Curve for a Building