Boston Coastal Flooding Analysis and Mapping

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Summary

An assessment is presented of coastal flooding hazards in Boston, MA, including future changes with sea level rise out to the 2080s. The 10-, 100-, and 500-year flood elevations were computed by fitting probability distributions to annual maximum storm tide elevations from the historical Boston tidal gauge dataset. Using three different distribution fitting procedures, we find small differences in results, ranging by 6 cm for the 100-year flood (1% chance per year flood), but we choose one with high-end results, to be conservative. We find present-day (2015) flood levels are 2.91 m NAVD88, for the 1% chance flood. Considering median and high-end sea level rise projections, increases to the likelihood of flooding were calculated under selected sea level scenarios for the 2020s, 2050s, and 2080s. Following a median sea level rise trajectory into the future, today's 1% chance per year flood will have a 2% chance of occurring per year in the 2020s and a 9% chance per year in the 2050s, nearly a factor of 10 increase.

1 Storm Tides and Return Periods

1.1 NOAA Storm Tide Data

To determine flood elevations, we first considered the water elevations listed by NOAA at the Boston gauge, Station 8443970 (NOAA, 2015). NOAA provides the 1%, 10%, 50%, and 99% exceedance probability levels, corresponding to the 100-, 10-, 2-, and 1-year return periods, respectively. In addition to providing these elevations for the established 1983-2001 epoch, NOAA provides estimates at the 2015 sea level by projecting the short-term trend to the current year. For our analysis, we considered the 2015 projections. Because we wanted to obtain a 500-year return period water level, which NOAA does not provide, and to verify the accuracy of the NOAA numbers, we then produced our own exceedance curves from the original data.

1.2 Data Selection for Return Period Calculations

To produce the exceedance curves, we first downloaded the hourly research-quality dataset for the Boston gauge from the University of Hawaii Sea Level Center (UHSLC 2014), dating back to May of 1922 and continuing through the end of 2014. Before proceeding with the analysis, we checked the quality of the data. We first calculated the annual and monthly maxima in Excel. Any dates listed in the metadata as missing, replaced, or having questionable fluctuations were incorporated into a spreadsheet. Then, we downloaded the entire dataset for Portland, ME, the nearest station with a long record. We then computed the monthly and annual maxima in Portland. In Excel, we flagged any instances where the two stations had different dates of maxima, and we flagged all of the dates that may have included missing, replaced, or questionable data. We further analyzed all of the flagged dates. We looked NOAA Tides and Currents' list of the top 12 storm tides for the Boston gauge (NOAA 2015) to check that all storms listed in the top 12 were in our annual maximum list; all storms were included in our list, and both the corresponding times and water levels were consistent. We then looked at NOAA's graphs of each year from 1922 through 2014 to visually assess any potential discrepancies in the annual maxima in Boston. Only 1974 had a potential missing maximum, but even this looks unlikely, as Portland had a continuous data set throughout 1974, and its annual maximum occurred on the same day as Boston's recorded maximum. There was one point in November 1974 when Portland recorded a level close to the annual maximum during Boston's missing period. In all other years, every measure of comparison indicated that our annual maximum series includes the true annual maximum at the Boston gauge.

1.3 Computing Flood Exceedance Statistics with Multiple Methods

With the data set's validity confirmed, we proceeded with the flood exceedance analysis. Using MATLAB, we again calculated the annual maximum water levels at the Boston gauge. We then removed the trend in mean sea level from each year's maximum water level, creating an annual maximum storm tide (AMST) dataset. The AMST data are shown in **Figure 1**.

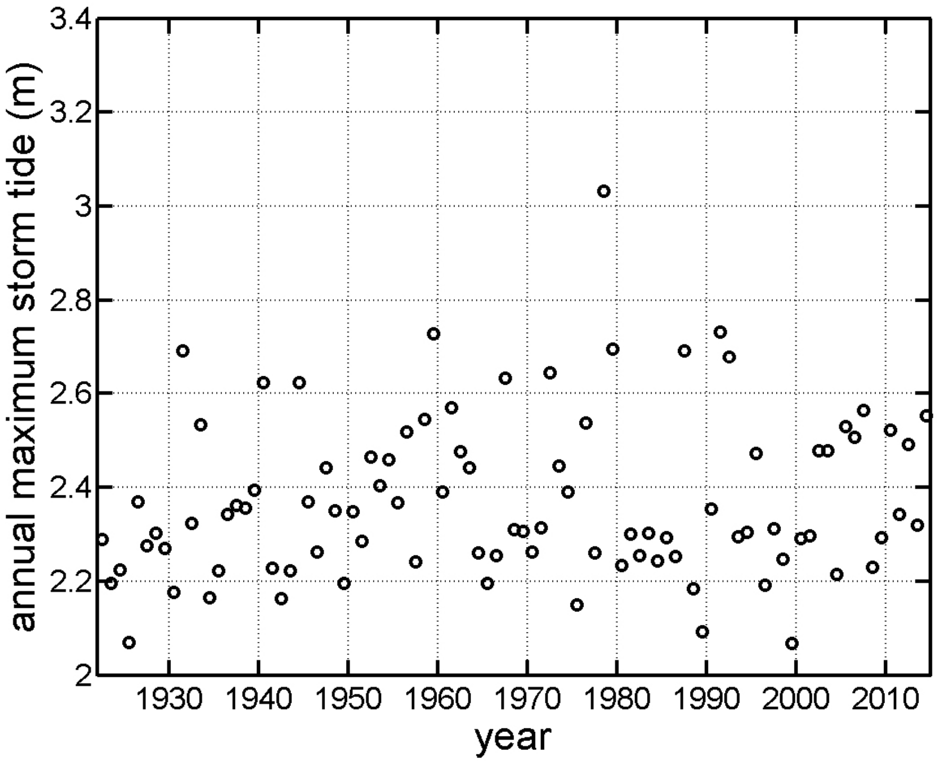

Figure 1: Annual maximum storm tides (AMST) for the Boston tide gauge, 1922-2014.

We fit the AMST data with distributions using three commonly used approaches for flood exceedance statistics, the Generalized Extreme Value (GEV) fitted with Maximum Likelihood Estimator (MLE) method (e.g. Zervas et al., 2013), the GEV fitted with the L-Moments method (e.g. FEMA, 2014), and the Generalized Pareto distribution (GP) fitted with the MLE method. The raw rate distribution and fitted GEV distribution (L-Moments method) are shown in **Figure 2**.

Using the fitted distributions, we obtained precise values for the desired return periods (**Table 1**). The fitted distributions are shown with the empirical data in **Figure 3**. Comparing the three different distribution fitting procedures, as well as the NOAA results, we find small differences, ranging by 6 cm for the 100-year flood. In subsequent analyses, we utilize the GEV fitted with L-Moments, with high-end results, to be conservative.

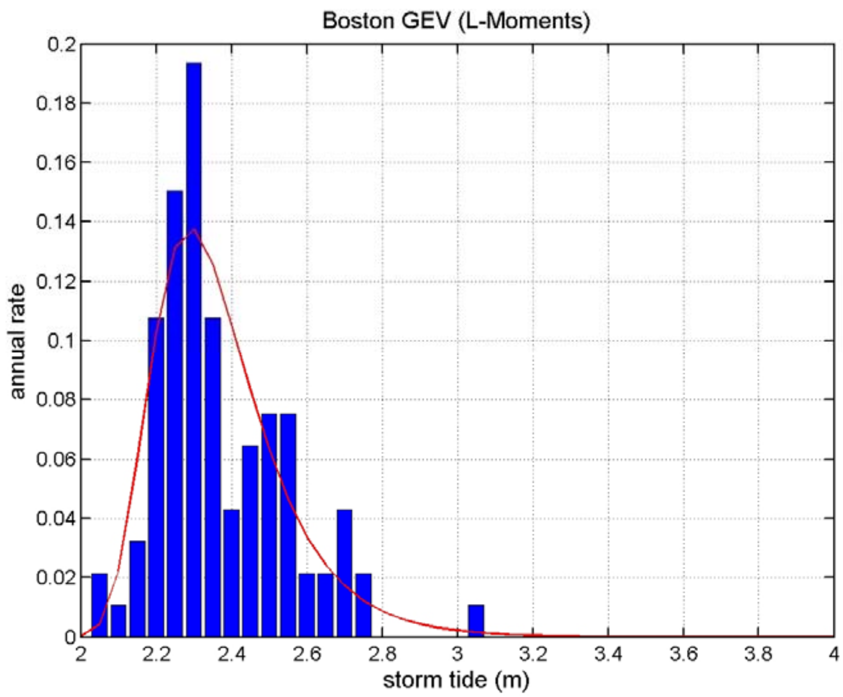

Figure 2: Rate distribution for storm tide, with GEV fit (L-moments method)

Table 1: Results – storm tides (relative to MSL) for three return periods, based on three methods plus NOAA's results. The GEV distribution (L-Moments) results are highlighted and were used in the mapping (a conservative, high-end choice).

	10-year	100-year	500-year
NOAA's GEV[1]	2.62	2.95	n/a
GEV_MLE	2.60	2.90	3.11
GEV_LMom	2.59	2.94	3.18
GP	2.63	2.89	3.01

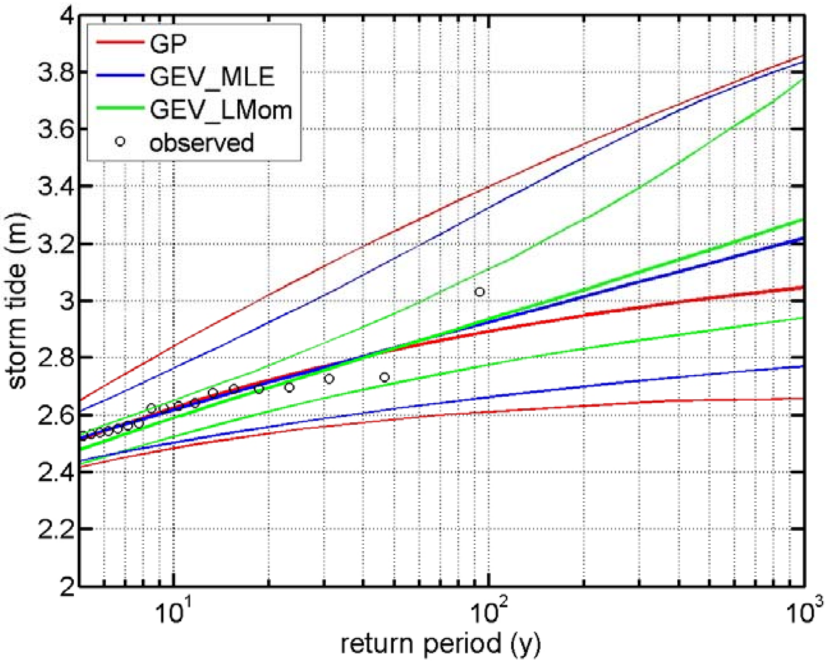

Figure 3: Storm tide exceedance curves using three different methods (thick lines), with observations (circles) and 95% confidence intervals (thin lines).

Additionally, we calculated the 95% confidence intervals surrounding the storm tide return periods (**Figure 3**). This was calculated using a bootstrap technique, wherein the existing AMST data are re-sampled with repetition, and 1000 repetitions of the historical period are synthesized and analyzed.

2 Sea Level Rise Analysis

2.1 Sea Level Rise Projections

We also performed an analysis using sea level rise (SLR) projections. In order to determine return period reductions under various SLR scenarios, we first obtained SLR estimates from the Consortium for Climate Risk in the Urban Northeast (CCRUN). Sea level rise for Boston was estimated (R. Horton, unpublished data) following methods of Horton et al. [2015], and we added these values to our current exceedance curves. That work estimated sea levels for the 2020s, 2050s, and 2080s using two representative concentration pathways (RCPs) and an ensemble of 24 global circulation models (GCMs). For each of the three decades, we were provided with a 10th percentile estimate, the range of the 25th to 75th percentile, and the 90th percentile. We wanted to show a median and high scenario for each decade. To best estimate the median with the information provided, we used the arithmetic mean of the 25th and 75th percentile. For the high estimate, we used the provided 90th percentile values as shown in **Table 2** below.

Table 2: Sea Level Rise Values Used in Analysis (meters, relative to 2000-2004 baseline sea level)

	Median (Estimated 50th Percentile)	High (90th Percentile)
2020s	0.13	0.23
2050s	0.36	0.66
2080s	0.60	1.30

2.2 Return Period Reductions under Sea Level Rise Scenarios

After superimposing the six different sea level rise values in Table 2 on our flood exceedance curve data, we determined the return period reductions under each by finding the return periods on the SLR curves that corresponded to the water elevations at the 2-, 10-, 100-, and 500-year return periods on the original curves. The results are shown in **Table 3** below. Increases in the annual percent chance of flooding are shown in **Table 4**.

Table 3: Flood Return Periods under SLR Scenarios (GEV-LMom method)

		Corresponding Return Periods (Years)					
Flood Return Period in Years	2015 Flood Height (m NAVD88)	2020s Median-SLR	2020s High-SLR	2050s Median-SLR	2050s High-SLR	2080s Median-SLR	2080s High-SLR
10	2.57	5.6	<5	<5	<5	<5	<5
100	2.91	53.6	27.4	11.5	<5	<5	<5
500	3.16	271.6	139.9	58.6	8.1	11.8	<5

Table 4: Annual chances of flooding under SLR Scenarios (GEV-LMom method)

		Corresponding Annual Percent Chance of Flooding					
Annual percent chance of flooding	2015 Flood Height (m NAVD88)	2020s Median-SLR	2020s High-SLR	2050s Median-SLR	2050s High-SLR	2080s Median-SLR	2080s High-SLR
10%	2.57	18%	>20%	>20%	>20%	>20%	>20%
1%	2.91	2%	4%	9%	>20%	>20%	>20%
0.2%	3.16	0.4%	0.7%	2%	12%	9%	>20%

3 Mapping

3.1 Flood Analysis Method

Static assumptions (superposition and "bathtubbing") methods are often used to draw coastal flood zones with and without added sea level rise (SLR), in widely-used tools such as Climate Central's Surging Seas. The superposition approach (used for sea level rise columns in **Tables 3** and **4**) assumes that sea level rise can simply be added on top of a flood elevation, and bathtubbing assumes that a flood elevation in the harbor can be extrapolated over land areas until it reaches the equivalent land elevation contour. All topographic elevations at or lower than this height are considered flooded.

For flooding during extra-tropical cyclones (e.g. Nor'easters), these static assumptions generally give an excellent approximation of flood heights, and results are usually within a few percent of dynamic modeling results (Orton et al., 2015). The New York City Panel on Climate Change official results use the static assumption, based on the finding that the differences between static and dynamic mapping methods are typically much smaller than uncertainties in sea level rise or flood return periods (Patrick et al. 2015).

It should be noted that static mapping errors will grow with increasing wind speeds (e.g. hurricanes), and for increasing floodplain widths (kilometers or more), but the floods mapped here for Boston are extratropical storms and the floodplain widths were typically shorter.

3.2 Land Elevation Data

Topographic data of Boston was available on the MassGIS web site; we used the Boston 2009 LIDAR dataset (MassGIS 2012). LIDAR data was available in small tiles, and we downloaded the tiles encompassing the neighborhoods of interest (tiles 17K through 24O, inclusive). We imported the TIFF-format LIDAR tiles into ArcMap and combined them into a single mosaic layer. The mosaic layer required some manual editing to correct some areas where the water surface in the harbor displayed at an erroneously higher elevation than the surrounding water.

The DEM does not account for closure of the Charles River dam's tide gate, yet it is typically closed during a flood event. To account for this important blockage of water flow from the harbor into Charles River and neighborhoods like Back Bay, the DEM was edited before we did our flood mapping, to raise it at this location to the height of the tide gate, 3.73 m NAVD88.

There are two low-lying pathways where flood water can flow and flood the Back Bay areas around Charles River – one around the dam, and another along a below-grade railway in Cambridge. Two options are available in the flood mapper – (1) a case where narrow flood pathways are left open (default), and (2) a case where these pathways are blocked, so that there is no back-bay flooding. Case #1 is an extreme case that allows water to flood all of the Back Bay areas up to the offshore flood elevation, and case #2 is an optimistic case that assumes the city takes precautions to block these pathways when a storm is coming. The reality if a major coastal flood occurs is likely to be either case #2 (protection), or something in between case #1 and #2.

3.3 Flood Mapping

With the land and open water elevations corrected, we could determine flood depths in ArcGIS using the static bathtub flood mapping assumption. We used the raster math function in ArcGIS to subtract the land surface elevation from each flood elevation as determined in **Section 1** and shown in the second column of **Table 3**. We used a systematic approach to remove areas without hydraulic connectivity to the open water using the NOAA Coastal Services Center methodology (NOAA 2012). This approach involved using a number of tools in ArcGIS's Spatial Analyst toolbox to group the contiguous flooded areas and extract only the largest group, the one that is connected to the open water. We mapped the extent of the 10, 100, and 500-year floods across Boston, and **Table 3** shows how return periods shrink in future decades due to sea level rise.

4 Conclusions

The results show that sea level rise could reduce the return periods (increase the annual percent chance) of extreme coastal flooding events significantly, particularly at longer time horizons and under more extreme climate scenarios. For example, following a median sea level rise trajectory into the future, a 100-year flood will become a 53.6-year flood in the 2020s and a 11.5-year flood in the 2050s. Put in terms of the annual chance of flooding, the 100-year flood currently has a 1% chance of occurring per year, and this will be increased to about 2% in the 2020s and 9% in the 2050s, ten times higher.

The results can be seen in the mapping application at following URL: ciesin.columbia.edu/fib/

Acknowledgements

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