Prepared in cooperation with the Federal Emergency Management Agency

Documentation and Mapping of Flooding from the January and March 2018 Nor'easters in Coastal New England

Scientific Investigations Report 2021–5109

U.S. Department of the Interior
U.S. Geological Survey

Cover. [Background] Satellite image of nor'easter over the eastern seaboard of the United States on January 4, 2018; image courtesy of National Oceanic and Atmospheric Administration and the Cooperative Institute for Research in the Atmosphere. [Inset] Flooding map for Boston, Massachusetts, reflecting water-surface elevations observed during coastal flooding from the January 2018 nor'easter; from figure 5 of this report.

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By Pamela J. Lombard, Scott A. Olson, Luke P. Sturtevant, and Rena D. Kalmon

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Contents

Abstract....1
Introduction....1
Stillwater Elevations....2
  Stillwater Elevations for Selected Annual Exceedance Probabilities....2
  Stillwater Elevations for 2018 and Other Historical Floods....4
Mapping of Coastal Flooding....5
  Methods....5
  Results....6
Attenuation of Flood Water-Surface Elevations....10
  Methods....10
  Results....11
Summary....11
References Cited....12

Figures

1. Map showing the locations of National Oceanic and Atmospheric Administration tide gages used to measure stillwater elevations before, during, and after two nor'easters in January and March 2018 in coastal New England....3
2. Maps showing high water marks from the nor'easters of January and March 2018 in New England....6
3. Graph showing the coastal flood profile of the shoreline of New England from Portland, Maine, to Eastham on Cape Cod, Massachusetts....7
4. Graphs showing coastal flood profiles of the shoreline of New England from Portland, Maine, to Cape Cod, Massachusetts....8
5. Example of a flooding map for Boston, Massachusetts, reflecting water-surface elevations observed during coastal flooding from the January 2018 nor'easter....9

Tables

1. Selected coastal gages used to compute statistical stillwater elevations in New England....2
2. Stillwater elevations for 10-, 4-, 2-, 1-, and 0.2-percent annual exceedance probabilities at selected coastal water-level gages in Maine and Massachusetts....4
3. Maximum annual stillwater elevations at selected coastal gages in Maine and Massachusetts....5
4. Comparison of stillwater elevations at the 1-percent annual exceedance probability for selected coastal gages in Maine and Massachusetts....5
5. Data used to calibrate a flood water surface attenuation model for flooding related to the January 2018 nor'easter in New England....10
6. Data used to validate a flood water surface attenuation model for flooding related to the March 2018 nor'easter in New England....11

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Documentation and Mapping of Flooding From the January and March 2018 Nor'easters in Coastal New England

By Pamela J. Lombard, Scott A. Olson, Luke P. Sturtevant, and Rena D. Kalmon

Abstract

In January and March 2018, coastal Massachusetts experienced flooding from two separate nor'easters. To put the January and March floods into historical context, the USGS computed statistical stillwater elevations. Stillwater elevations recorded in January 2018 in Boston (9.66 feet relative to the North American Vertical Datum of 1988) have an annual exceedance probability of between 2 and 1 percent (between a 50- and 100-year recurrence interval). Stillwater elevations recorded in March 2018 in Boston (9.17 feet relative to the North American Vertical Datum of 1988) have an annual exceedance probability of between 4 and 2 percent (between a 25- and 50-year recurrence interval). Flood maps show that the area inundated by the January storm is slightly more extensive than that of the March storm, reflecting the respective profiles of the two storms. On the basis of a limited dataset, the attenuation of peak water levels was estimated as a function of the hydraulic distance inland and the starting stillwater elevation computed for the flood within 0.6 foot of what was measured in the field. A simple one-dimensional model was calibrated using flood elevation data collected after the January flood, and the results of the model were validated using flood elevation data collected after the March flood to model the attenuation of the flood elevations as the storms move inland.

Introduction

During winter 2017–18, coastal areas of New England were severely impacted by the January 4, 2018, and March 2–4, 2018, nor'easters. The U.S. Geological Survey (USGS), under an interagency agreement with the Federal Emergency Management Agency (FEMA), collected total water level data (the combination of astronomical tide, storm surge, wave runup and setup, and freshwater input; Bent and Taylor, 2020) from high water marks (HWMs) and continuous water-level sensors referenced to the North American Vertical Datum of 1988 (NAVD 88). These data collection efforts are part of a larger effort to better understand the areal extent, timing, and effects of coastal flooding from strong storms.

The elevations referenced in Bent and Taylor (2020) are total water level data because the HWMs and storm sensor elevations recorded in that report have the potential to include the effects of waves, depending on where they are located. Stillwater elevations (also referred to as storm tides) are water-surface elevations in coastal waters from tide and storm surge (the rise of the ocean in response to air pressure and wind) and do not include the effects of waves. National Oceanic and Atmospheric Administration (NOAA) tide gages are sited in locations that are not impacted by waves and thus are considered stillwater elevations. Although storm sensors collect total water level data, these data can be filtered to exclude the effects of waves, if stillwater elevations are desired. FEMA publishes data on stillwater of various frequencies in their effective flood insurance studies.

Following the January 2018 nor'easter, the largest event from 1921 through 2021 for the area from Cape Cod Bay north to the border with New Hampshire, 71 HWMs were collected in coastal areas of eastern Massachusetts along the shore and at varying distances inland along waterways. The HWMs had total water level elevations that ranged from 5.8 to 15.1 feet (ft) referenced to the North American Vertical Datum of 1988 (NAVD 88), with an average elevation of 9.4 ft and a median elevation of 9.6 ft. Total water level elevations at 10 tide gages and 7 coastal streamgages from Portland, Maine, to Cape Cod Bay, Mass., ranged from 4.8 to 11.2 ft, with an average of 9.1 ft and a median of 9.6 ft. Following the March 2018 nor'easter, 111 HWMs were collected along the New England coastline. Of the 111 HWMs, 100 were along the eastern coastline of New England from Portland to Cape Cod and had elevations that ranged from 5.3 to 15.1 ft, with an average of 8.9 ft and a median of 8.6 ft. The remaining 11 HWMs along the southern coastline of New England in Connecticut, Rhode Island, and Massachusetts had elevations that ranged from 3.1 to 7.5 ft and averaged 4.3 ft with a median of 4.9 ft. Total water level elevations for 21 USGS temporary water-level sensors from Portland to Cape Cod Bay, Mass., ranged from 6.1 to 11.0 ft, with an average of 8.6 ft and a median of 8.7 ft. Total water level elevations at 10 tide gages and 6 coastal streamgages from Portland to Cape Cod Bay ranged from 7.8 to 10.8 ft with an average of 9.1 ft and median of 9.2 ft.

Bent and Taylor (2020) found that the average elevations were 0.3 and 0.5 ft higher at 10 tide gages and 5 coastal streamgages, respectively, from Portland to Cape Cod Bay for the January nor’easter than for the March nor’easter. Measurements from 52 HWM locations in Massachusetts confirmed that the January nor’easter had higher average water-surface elevations than the March nor’easter (U.S. Geological Survey, 2019a, b; Lombard and others, 2021).

Although storm surge sensors record the magnitude, extent, and timing of hurricane storm surges more accurately and reliably than HWMs (Verdi and others, 2017), HWMs are often used in cases where storm surge sensors were not deployed or did not cover the extent of the flooding. They also can be used to confirm storm sensor elevations.

After Hurricane Sandy made landfall along the northeastern Atlantic coast of the United States on October 29, 2012, the USGS carried out scientific investigations to assist with protecting coastal communities and resources from future flooding. The work included development and implementation of the Surge, Wave, and Tide Hydrodynamics (SWaTH) Network, which consists of more than 900 monitoring stations. These stations enhanced data recovery and display capabilities through development of a short-term network (STN) mapper and database online application. The STN (https://wimcloud.usgs.gov/STN/) is a web-based set of tools that includes historical and newly established monitoring sites in an interactive database and map interface that aids in network creation and development, storm-response data management, capture and analysis of storm-tide data, and data and product delivery to the scientific community and the public. The STN provides a unified and consistent source of current and archived storm-tide, wave, and HWM data.

Purpose and scope.—This report includes the computation of new statistical stillwater elevations from the January and March 2018 nor’easters in coastal Massachusetts, describes the creation of outreach tools such as interactive flood maps and profiles, and tests a one-dimensional model to predict the attenuation of peak water elevations as a function of the stillwater elevations at the coast and their hydraulic distance inland. New models and outreach tools will help emergency managers and the public better understand coastal flood risk and prepare for future coastal floods.

Stillwater Elevations

NOAA coastal water-surface elevation data from Portland to Provincetown, Massachusetts, were used for the computation of new statistical stillwater elevations in coastal Massachusetts north of Provincetown. Criteria for selected stations included a long-term record (more than 30 years), continuously recorded data, and water-surface elevations that were tied to a standard datum, such as NAVD 88.

Three tide gages operated by the NOAA Center for Operational Oceanographic Products and Services (CO–OPS) were selected for use in this analysis (fig. 1; table 1). These tide gages are in locations with minimal to no exposure to ocean waves, and thus this study assumes that recorded water-surface elevations reflect tide and storm surge levels only (stillwater elevations; Zervas, 2013). The selected gages had between 55 and 108 years of continuous water-surface elevation data (table 1).

Stillwater Elevations for Selected Annual Exceedance Probabilities

For the stillwater analyses in this report, the annual maximum stillwater elevations for the period of record (table 1) were used. Annual maximum values for the selected gages were obtained from the NOAA tides and currents database monthly reports that include the instantaneous maximum monthly water-surface elevation (National Oceanic and Atmospheric Administration, 2021). The annual maximum stillwater elevation for the calendar year was computed from these monthly maximum values. When there were data missing for at least one month from the dataset during a given calendar year, the monthly maximum elevation at nearby coastal gaging stations was used for comparison to determine if the annual maximum could have happened during a missing month. If it was clear that the annual maximum could not have happened during a missing month, then the annual maximum for that calendar year was kept in the record. If it was possible that the annual maximum happened during a missing month, then the annual maximum for that year at that gage site was not used.

Table 1. Selected coastal gages used to compute statistical stillwater elevations in New England.

[Tide gages are operated and maintained by the National Oceanic and Atmospheric Administration (2021). mm/yr, millimeter per year; ° ′ ″, degree, minute, second]

Coastal gage station number	Coastal gage name	Latitude	Longitude	Sea level trend (mm/y)r	Period of discharge record
8418150	Portland, ME	43°39′22″	70°14′46″	1.88	1912–2018
8419870	Seavey Island, ME	43°04′48″	70°44′30″	1.76	1927–34, 1941–86, 2001
8443970	Boston, MA	42°21′14″	71°03′01″	2.83	1921–2018

Figure 1. Map showing the locations of National Oceanic and Atmospheric Administration tide gages used to measure stillwater elevations before, during, and after two nor'easters in January and March 2018 in coastal New England. Tide gage details are listed in table 1.

Because there are significant long-term linear trends in the data resulting from sea-level rise, all stillwater elevations were linearly detrended using the mean sea-level trend determined by NOAA from monthly-mean sea levels (National Oceanic and Atmospheric Administration, 2021). The annual maximum stillwater elevations were detrended to the baseline year 2018 using a constant sea-level trend for each gage (table 1). The analysis to compute statistical stillwater elevations with annual exceedance probabilities (AEPs) of 10-, 4-, 2-, 1-, and 0.2-percent (5-, 25-, 50-, 100-, and 500-year intervals) was done using the detrended data.

The annual maximum stillwater elevations from the gages were fitted to selected frequency distributions using L-moment statistics (Hosking, 1990). L-moments are comparable to ordinary statistical moments in that they describe the mean, dispersion or scale, and skewness of the dataset. L-moments were computed and Pearson type III and generalized extreme value (GEV) frequency distributions were fitted using the R software (R Core Team, 2017) with the lmom package (Hosking, 2017). Although the stillwater datasets fit a Pearson type III distribution well, GEV distribution provided a better fit. Although the Pearson type III distribution is the most common distribution used for riverine flood studies, the GEV distribution was selected by NOAA in its stillwater analysis of tide data (Zervas, 2013) and has found wide application for other maxima, such as floods, rainfall, wind speed, and snow depths (Martins and Stedinger, 2000). The lmom R package was also used to compute the 10-, 4-, 2-, 1-, and 0.2-percent AEP stillwater elevations (table 2).

Stillwater Elevations for 2018 and Other Historical Floods

The coastal floods of February 7, 1978, and January 4, 2018, have the highest recorded stillwater elevations during the past 100 years in Portland and Boston (table 3). AEPs were analyzed on annual peak stillwater elevations detrended to 2018 sea levels, and event AEPs were estimated using the detrended value. Although the highest recorded stillwater elevation at the Boston station was 9.66 ft in January 2018, when adjusted for average sea level change, the water level of 9.59 ft in February 7, 1978, became the highest value, at 9.96 ft (Talke and others, 2018). Overall, the February 7, 1978, detrended stillwater elevations are the highest water levels and have an AEP of less than 1 percent (greater than the 100-year interval) at the Portland and Boston gages. The stillwater elevations in January 2018 had an AEP of between 2 and 1 percent (25- and 50-year interval) in Boston, but less than 10 percent (5-year interval) in Portland. The annual stillwater analyses for this report (table 2) only considered the single highest stillwater elevation for each year; thus, the stillwater elevation in March 2018 was not included in the development of the AEPs, even though it was the third largest storm tide on record. If the elevation of the March 2018 flood in Boston (9.17 ft) were to be considered in the context of the new AEPs (table 2), it has an AEP of between 4 and 2 percent (25- and 50-year interval).

Previous stillwater analyses at these gages without the 2018 floods produced similar results to the current study that does include the 2018 floods. The 1-percent AEP (100-year interval) of the stillwater elevation at the three study gages determined for this study was compared with the stillwater elevations in the applicable flood insurance study (table 4) and with the stillwater elevations determined by the U.S. Army Corps of Engineers (1988), Zervas (2013) and FEMA (2012). The NOAA study (Zervas, 2013) included data through 2010 that had been adjusted for sea-level change, so that it represented the center of the National Tidal Datum epoch of 1983–2001, or approximately 1992. The results published in FEMA (2012) included records through 2007 and were adjusted for sea-level change to the 2007 mean sea level. The most substantial difference from the results determined in the study for this report is that the HWMs in the FEMA (2012) study included HWMs that were affected by wave action (not just stillwater elevations), which is reflected by elevations listed in table 4 for FEMA (2012) that are from 0.6 ft higher in Portland to 1.4 ft higher at Seavey Island than the flood studies. The study in this report has an elevation in Boston that is 0.4 ft higher than the effective flood insurance study because the 2018 flood was included in the analysis for this study.

Table 2. Stillwater elevations for 10-, 4-, 2-, 1-, and 0.2-percent annual exceedance probabilities at selected coastal water-level gages in Maine and Massachusetts.

[Stillwater elevations were determined from analysis of recorded annual maximum stillwater elevations, from National Oceanic and Atmospheric Administration (2021). ft, foot; NAVD 88, North American Vertical Datum of 1988; %, percent]

Coastal gage station number	Coastal gage name	Stillwater elevation for given annual exceedance probability (ft relative to NAVD 88)				
		10%	4%	2%	1%	0.2%
8418150	Portland, ME	7.97	8.31	8.56	8.81	9.39
8419870	Seavey Island, ME	7.38	7.74	8.01	8.27	8.87
8443970	Boston, MA	8.58	9.06	9.42	9.80	10.72

Table 3. Maximum annual stillwater elevations at selected coastal gages in Maine and Massachusetts.

[Adjusted maximum annual stillwater elevations are adjusted for sea-level rise to 2018 levels from National Oceanic and Atmospheric Administration (2021) data. ft, foot; NAVD 88, North American Vertical Datum of 1988; <, less than]

Coastal gage station number	Coastal gage name	Maximum annual stillwater elevation (ft NAVD 88)	Date	Adjusted maximum annual stillwater elevation (ft NAVD 88)	Estimated annual exceedance probability (percent)
8418150	Portland, ME	[a]8.87	February 7, 1978	9.12	<1
		8.26	January 4, 2018	8.26	<10
8419870	Seavey Island, ME	7.90	February 7, 1978	8.13	<2
		7.72	February 1972	7.98	<4
8443970	Boston, MA	9.59	February 7, 1978	9.96	<1
		[b]9.66	January 4, 2018	9.66	<2

[a]A stillwater elevation of 8.86 ft was recorded on January 9, 1978, and was the second highest recorded at the Portland, Maine, coastal gage.

[b]A stillwater elevation of 9.17 ft was recorded on March 2, 2018, and was the third highest recorded at the Boston, Mass., coastal gage.

Table 4. Comparison of stillwater elevations at the 1-percent annual exceedance probability for selected coastal gages in Maine and Massachusetts.

[ft, foot; NAVD 88, North American Vertical Datum of 1988; USACE, U.S. Army Corps of Engineers; FEMA, Federal Emergency Management Agency; NOAA, National Oceanic and Atmospheric Administration; <, less than]

Coastal gage		Stillwater elevation at the 1-percent annual exceedance probability from given analysis source (ft relative to NAVD 88)				
Station number	Station name	Study in this report	Flood study	USACE[a]	FEMA[b]	NOAA[c]
8418150	Portland, ME	8.81	[d]8.9	8.8	9.51	8.69
8419870	Seavey Island, ME	8.27	[e]8.1	8.8	9.48	7.98
8443970	Boston, MA	9.80	[f]9.4	9.4	10.04	9.38

[a]Data are from U.S. Army Corps of Engineers (1988).

[b]Data are from Federal Emergency Management Agency (2012).

[c]Data are from Zervas (2013).

[d]Data are from Federal Emergency Management Agency (1998).

[e]Data are from Federal Emergency Management Agency (2005).

[f]Data are from Federal Emergency Management Agency (2016).

Mapping of Coastal Flooding

Methods

Coastal flood profiles and flooding maps for the January and March 2018 winter floods were created from USGS storm sensor data and HWMs collected following the January and March nor'easters. HWMs were filtered to remove outliers that may have been collected from poor quality GPS data or that were likely the result of waves. Final HWM data used in the profiles are from Lombard and others (2021) and Sturtevant (2021). Initially, a coastal profile line covering the geographic extent of the surveyed HWM and storm sensor data was manually drawn, oriented from north to south along the New England coastline from Portland to Eastham, Mass. (fig. 2*A*). The HWM and storm sensor data points were projected onto the coastal profile line (fig. 2*B*) and assigned to a station that reflected their distance from the northernmost end of the line (in feet). Distances and elevations for each HWM or storm sensor reading for the given flood were then used to calculate a linear relationship between stationing and elevation, and a best-fit line was drawn through the points to develop coastal flood profiles. Best-fit lines were drawn through HWMs and through storm sensors separately where available, in order to compare the two methods. Storm sensor readings of peak stillwater elevations are typically considered more precise than HWMs (Verdi and others, 2017); however, HWMs can provide a more comprehensive geographical picture, especially in locations with few or no storm sensors.

Figure 2. Maps showing high water marks from the nor'easters of January and March 2018 in New England *A*, along a generalized coastline (orange line) of New England from Portland, Maine, to Cape Cod, Massachusetts, and *B*, projected onto the coastline in order to assign them a distance along the generalized coastline as measured from Portland, Maine.

We used a "bathtub model" to create flood maps, adapting techniques outlined in Maine Geological Survey (2021) for coastal sea-level rise scenario mapping. Twelve-digit hydrologic unit code (HUC12) basin boundaries were selected from the Watershed Boundary Dataset (U.S. Geological Survey, 2021) along the New England coastline (Lombard and others, 2021). Centroids were generated for each HUC12 polygon, projected to the closest location along the coastal profile line, and then assigned stations and water-surface elevations based on the applicable flood profile.

Inundation polygons were developed for each coastal basin from its assigned water-surface elevation. This was done by creating a raster surface from the assigned water-surface elevation and determining where the water-surface elevation rasters were greater than or equal to the light detection and ranging (lidar) digital elevation model (DEM). The process produced estimated inundation surface raster data that were converted to inundation polygon layers for flood mapping. Inundation polygons for each of the coastal watersheds were merged to form a single coastal inundation map for each flood. Inundation maps do not extend north of North Hampton, New Hampshire, or south of Cape Cod due to sparsely surveyed HWM and storm sensor data outside of these geographic extents and do not extend inland of the coastal HUC 12 polygons. Inundation maps were produced using ESRI Inc. ArcGIS Pro 2.6 software.

This type of bathtub model for creating flood surfaces works for stillwater areas where waves have no effect on water level (no wave setup or wave runup) and where the area is hydraulically connected to the sea (Maine Geological Survey, 2021). Bathtub models assume that land surfaces stay static in response to rises in water. The same method as outlined above was used to develop a map that reflects the 100-year stillwater elevations calculated from tidal gages as a part of this report.

Results

All descriptions, locations, and elevations for HWM and storm sensor data points used in this report for flood profiles and flood maps can be found in Bent and Taylor (2020) and Lombard and others (2021) and can be viewed on the USGS Flood Event Viewer (U.S. Geological Survey 2019a, b). A single coastal flood profile was created from HWMs for the January 2018 flood because storm sensors were not deployed in advance of the January storm (fig. 3). Two flood profiles were created for March 2018: one from the HWMs and one from the storm sensors (figs. 4*A* and *B*). The two March profiles were in good agreement (fig. 4*C*), indicating that either HWMs or storm sensors can produce accurate flood profiles, given sufficient data. However, there is less scatter around the storm sensor profile than around the HWM profile, confirming the greater precision of the storm sensor data. Thus, when available, the storm sensor profile was used to obtain flood elevations for flood mapping. A profile and a flooding map were also created for the statistical stillwater elevation with a 1-percent AEP (100-year interval) computed at the three tide gages in Portland, Seavey Island, Maine, and Boston, as described in the "Stillwater Elevations" section of this report.

An example of a flood map created from the flood profile assuming the bathtub model for the January 2018 flood is shown in figure 5. All HWM and storm sensor data, the New England coastal flood profile line, the coastal HUC12 polygons used for the flooding maps, the shapefile layers for the flooding map for both the January and the March floods, and the 100-year stillwater elevation are available in Lombard and others (2021) and can be visualized in a dashboard in Sturtevant (2021). A geonarrative tells the story of these events in plain language and puts them into historical context (Kalmon, 2021).

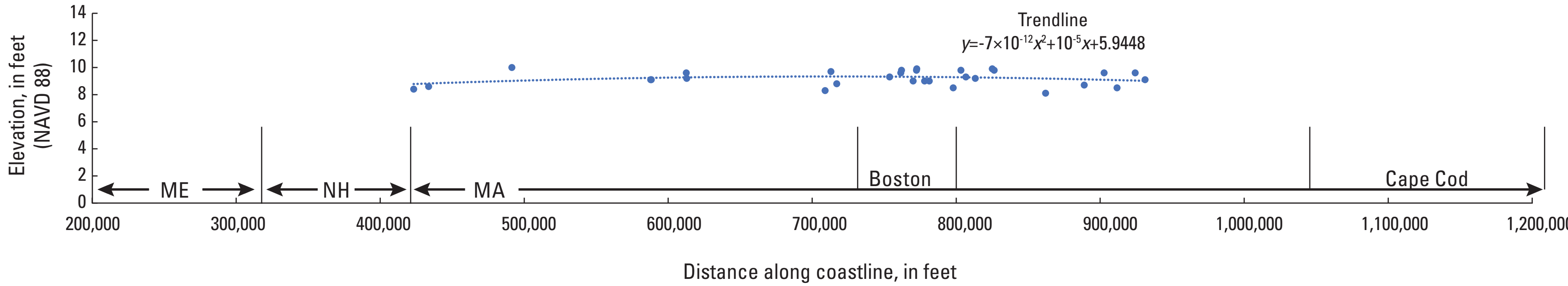

Figure 3. Graph showing the coastal flood profile of the shoreline of New England from Portland, Maine, to Eastham on Cape Cod, Massachusetts, developed from high water marks collected following flooding from the January 2018 nor'easter. ME, Maine; NH, New Hampshire; MA, Massachusetts; NAVD 88, North American Vertical Datum of 1988.

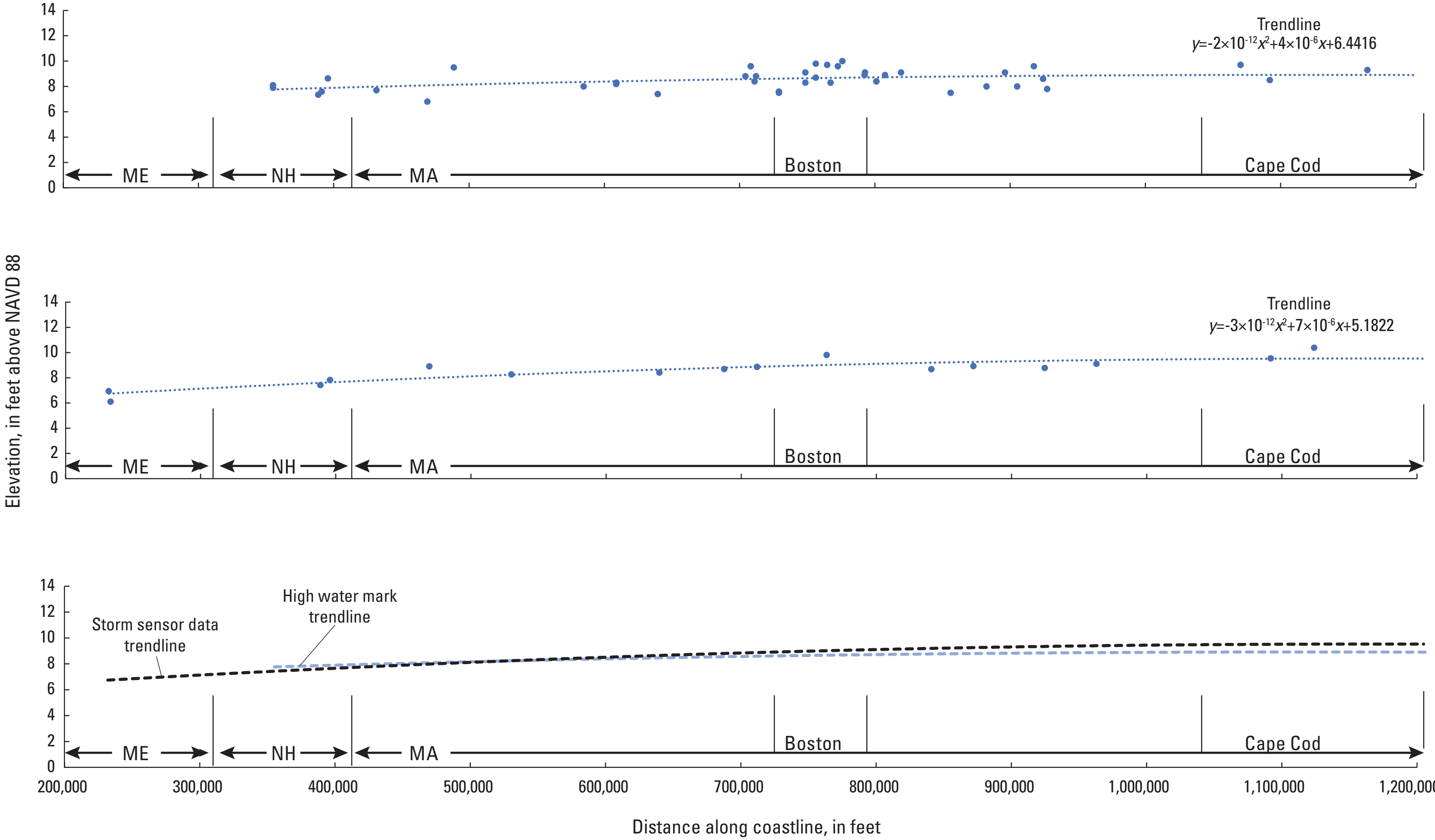

Figure 4. Graphs showing coastal flood profiles of the shoreline of New England from Portland, Maine, to Cape Cod, Massachusetts, developed using *A*, high water marks collected following flooding from the March 2018 nor’easter; *B*, storm sensor data collected during the March 2018 nor’easter; and *C*, high water marks and storm sensor data associated with flooding from the March 2018 nor’easter. ME, Maine; NH, New Hampshire; MA, Massachusetts; NAVD 88, North American Vertical Datum of 1988.

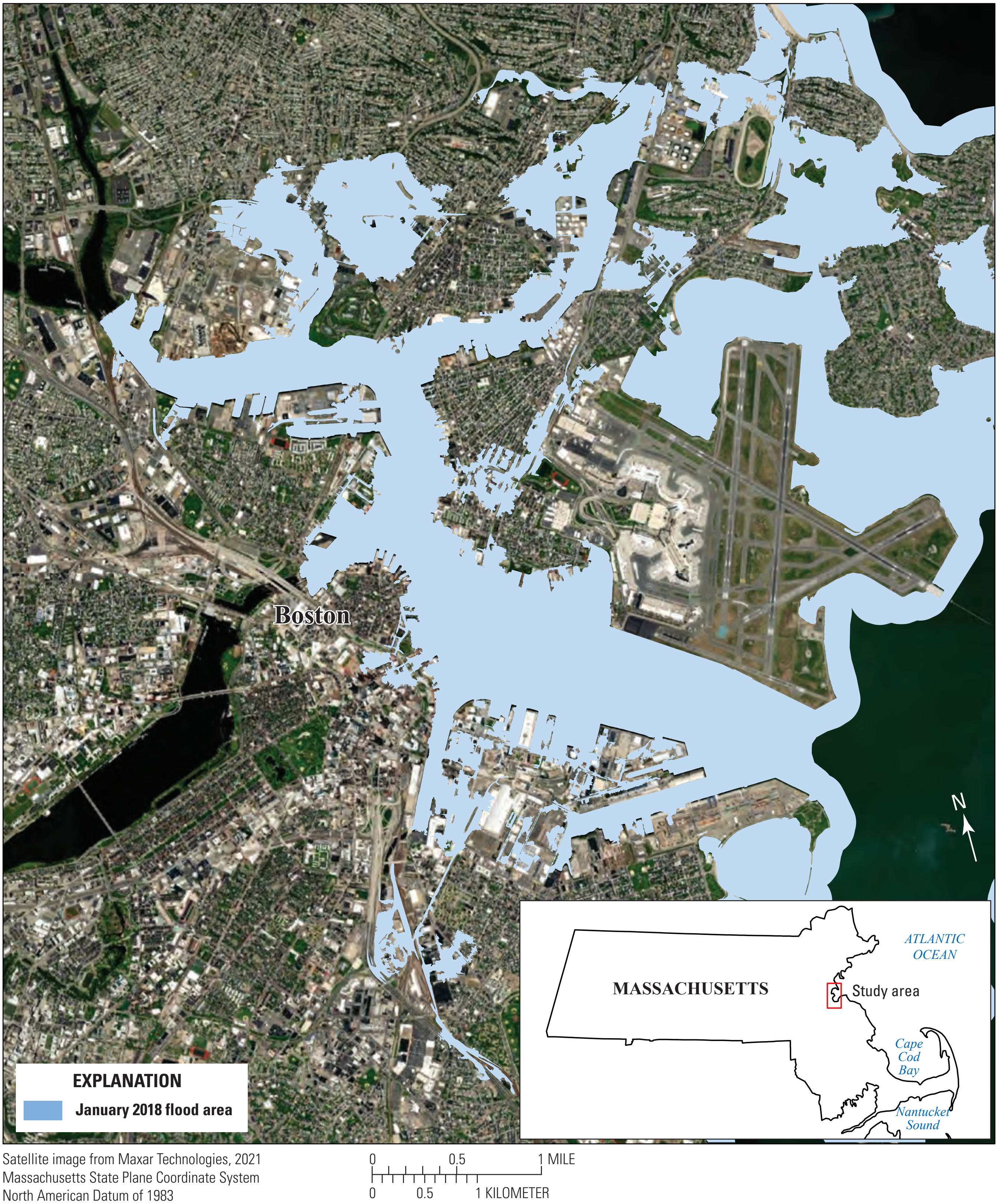

Figure 5. Example of a flooding map for Boston, Massachusetts, reflecting water-surface elevations observed during coastal flooding from the January 2018 nor'easter. Geographic information system (GIS) shapefiles for the flooding from the January and March 2018 nor'easters are available in Lombard and others (2021).

Attenuation of Flood Water-Surface Elevations

Changes in total water-surface elevations from coastal floods typically attenuate as the floods move inland, diminishing and delaying the flood surge; thus, the bathtub model of mapping is a simplification of reality. Although the simplification is useful for creating flooding maps, the ability to model that attenuation was also tested in this analysis. The elevations of the HWMs collected as a part of this work showed a wide range of variability, with the HWMs with the lowest elevations at sites farthest inland from the Atlantic Ocean (Bent and Taylor, 2020). To determine if the attenuation of the flood water surface elevation as the flood moved inland from the coast during the January and March 2018 floods was adequately predicted, a one-dimensional model developed by Bjerklie and others (2013) for estimating tide heights in coastal marshes was tested. Validation of the one-dimensional model indicated that the method has an accuracy of 0.3 ft.

Although the goal of the study was to collect HWMs that reflected peak stillwater elevations associated with the floods close to the coast that did not reflect an attenuation of the water-surface elevations, there were three locations (tables 5 and 6) where tidally influenced riverine HWMs were collected that might apply to this type of attenuation model. These locations included the North and South Rivers in Marshfield, Mass., and the Gulf River in Scituate, Mass.

Methods

The equation from Bjerklie and others (2013) was calibrated for computing the maximum tidal elevation (h_x) at distance from the coast (x) to each site of interest by adjusting the diffusivity constant to get the best agreement between the computed maximum tidal elevation and the HWM, as follows:

$$h_x = h_0 e^{-x\sqrt{\frac{\pi D_f}{t_0}}}, \tag{1}$$

where

h_x is the estimated peak water surface elevation at distance x from the coast, in feet;
h_0 is the estimated peak water surface elevation at the coast, in feet;
x is the distance from the coast, in feet;
t_0 is the tidal period, in number of days; and
D_f is the diffusivity, in number of days per square foot.

The flood stillwater elevation in the channel at the coast was used in the calculation for the h_0 variable. Stillwater elevation profiles for the January and March floods are presented in the "Mapping of Coastal Flooding" section of this report. The distance from the coast (x) was measured from the coast to the observed water surface elevation (HWM) along the river line. The tidal period (t_0) was set to 0.5 day for all sites. The diffusivity (D_f) was calibrated for each location using the observed data from the January flood (table 5). Individual point diffusivities were averaged together to compute a reach diffusivity for each of the three reaches. Diffusivities would be expected to vary within a reach because they are a function of

Table 5. Data used to calibrate a flood water surface attenuation model for flooding related to the January 2018 nor'easter in New England.

[The model is based on the model in Bjerklie and others (2013). Elevations are in feet (ft) above the National American Vertical Datum of 1988 (NAVD 88). Variables in column headings correspond to variables in equation 1 in this report. High water mark (HWM) ratings are defined in Bent and Taylor (2020). h_0, stillwater elevation at the coast for the modeled flood; x, distance from the coast for HWM; D_f, diffusivity; d/ft^2, day per square foot; t_0, tidal period; d, number of days; h_x, computed flood elevation at x; ID, identifier]

h_0 (ft NAVD 88)	x (ft)	Average computed D_f (d/ft^2)	t_0 (d)	h_x (ft NAVD 88)	HWM elevation (ft NAVD 88)	HWM ID	HWM rating	Calculated minus observed (ft)
North River								
9.3	18,000	2.1848×10^{12}	0.5	8.7	8.7	509	Unknown	0.0
South River								
9.3	20,000	5.6852×10^{12}	0.5	8.2	8.5	501	Fair	−0.3
9.3	25,837	5.6852×10^{12}	0.5	8.0	8.4	504	Poor	−0.4
9.3	29,590	5.6852×10^{12}	0.5	7.8	7.9	502	Poor	−0.1
9.3	32,432	5.6852×10^{12}	0.5	7.7	7.0	503	Poor	0.7
Gulf River								
9.3	7,921	0.7431×10^{12}	0.5	7.8	8.1	412	Fair	−0.3
9.3	10,757	0.7431×10^{12}	0.5	7.4	7.1	413	Excellent	0.3

Table 6. Data used to validate a flood water surface attenuation model for flooding related to the March 2018 nor'easter in New England.

[The model is based on the model in Bjerklie and others (2013). Elevations are in feet (ft) above the National American Vertical Datum of 1988 (NAVD 88). Variables in column headings correspond to variables in equation 1 of in this report. High water mark (HWM) ratings are defined in Bent and Taylor (2020). h_0, stillwater elevation at the coast for the modeled flood; x, distance from the coast for HWM; D_f, diffusivity; d/ft², day per square foot; t_0, tidal period; h_x, computed flood elevation at x; ID, identifier]

h_0 (ft NAVD 88)	x (ft)	Average computed D_f (day/ft²)	t_0 (day)	h_x (ft NAVD 88)	HWM elevation (ft NAVD 88)	HWM ID	HWM rating	Calculated minus observed (ft)
North River								
9.2	18,000	2.1848×10^{12}	0.5	8.6	8.0	509	Fair	0.6
South River								
9.2	20,000	5.6852×10^{12}	0.5	8.2	8.0	501	Fair	0.2
9.2	25,837	5.6852×10^{12}	0.5	7.9	7.8	504	Poor	0.1
9.2	29,590	5.6852×10^{12}	0.5	7.7	7.3	502	Poor	0.4
9.2	32,432	5.6852×10^{12}	0.5	7.6	7.4	503	Fair	0.2
Gulf River								
9.1	7,921	0.7431×10^{12}	0.5	7.7	7.5	412	Fair	0.2
9.1	10,757	0.7431×10^{12}	0.5	7.2	6.9	413	Excellent	0.3

the distance from the mouth and of the distance inland from the main channel. For example, if the HWM is close to the river channel, diffusivity would vary from that of an HWM that is offset from the channel but is still connected hydraulically across a marsh. For this project, however, diffusivities for a reach were averaged together because the HWMs were all relatively close to the main channel. Diffusivity constants were tested using HWMs from the March flood. Average reach diffusivities were entered into the equation to compute h_x using the stillwater (h_0) from the March flood. The calculated h_x was then compared with the observed HWM; h_x values for the January flood were also recomputed using the average D_f values.

Results

Average diffusivity constants were computed for each reach. The North River had a computed diffusivity of 2.1848×10^{-12} day per square foot (d/ft²) based on a single HWM, the South River had a computed diffusivity of 5.6852×10^{-12} d/ft² based on four HWMs, and the Gulf River had a diffusivity of 0.743112×10^{-12} d/ft² based on two HWMs (table 5). When these diffusivities were used in equation 1 to compute observed water-surface elevations based on the March flood, the difference between the observed water surfaces and the computed water surfaces ranged from 0.1 to 0.6 ft (table 6). When these diffusivity values were used in equation 1 to compute observed water-surface elevations based on the January flood, the difference between the observed water surfaces and the computed water surfaces ranged from 0.0 to 0.7 ft (table 6). These results bracket an expected accuracy on the order of 0.3 ft (Bjerklie and others, 2013) and indicate that the method could be used to estimate inland tidal height for management applications that do not require elevation estimates at greater accuracy than ±0.5 to 1 ft.

Differences in water surface elevations measured in the field in January versus March could be the result of ice influence during January. It is also important to note that this is a very small dataset, and the results may vary more as this type of analysis is expanded to larger datasets.

Summary

Two nor'easters on January 4, 2018, and March 2–4, 2018, severely impacted coastal areas of New England. The U.S. Geological Survey (USGS), under an interagency agreement with the Federal Emergency Management Agency (FEMA), collected total water level data (the combination of astronomical tide, storm surge, wave runup and setup, and freshwater input) from high water marks (HWMs) and continuous water-level sensors. Products resulting from this work include this report, an associated data release (Lombard and others, 2021), an interactive storm event viewer webpage (Sturtevant, 2021), and an interactive geonarrative that tells the story of these events in plain language and puts them into historical context (Kalmon, 2021).

New statistical stillwater coastal flood analyses for Massachusetts from Cape Cod Bay north to the New Hampshire border document the January 2018 event as the largest recorded event for this area from 1921 to 2021. Although the third largest storm tide on record was

documented in March 2018, only a single peak event for each year is included in the stillwater analyses and development of stillwater elevations for given annual exceedance probabilities (AEPs). Stillwater elevations developed from this analysis for given AEPs are in line with those calculated from previous analyses.

New stillwater analyses allow us to evaluate water-surface elevations for the January and March 2018 floods centered around Boston, Massachusetts, in the context of other historic floods. Stillwater elevations recorded in January 2018 in Boston (9.66 ft NAVD 88) had an AEP of between 2 and 1 percent (between a 50- and 100-year recurrence interval). Stillwater elevations recorded in March 2018 in Boston (9.17 ft NAVD 88) had an AEP of between 4 and 2 percent (between a 25- and 50-year recurrence interval). Although the flooding from the January 2018 nor’easter has the highest stillwater elevation ever recorded in Boston, when the February 1978 stillwater elevation of 9.59 ft NAVD 88 is adjusted for sea level rise to 2018 levels, it exceeds stillwater elevation from the January 2018 flood and has an AEP of less than 1 percent (greater than 100-year recurrence interval).

Flood profiles and flooding maps computed as a part of this work show the flood elevations and extents for the January and March 2018 coastal floods. The method developed for this analysis to compute flood profiles and build flooding maps for coastal floods provides a template that can easily be adapted for future coastal flood documentation. The method highlights the usefulness of storm sensor data and the need for collecting HWMs following large events in cases where sufficient storm sensors were not deployed.

An additional component of this project tested a one-dimensional model for its accuracy in predicting flood water surface elevation attenuation as a flood moves inland. This model was calibrated through the development of diffusivity constants for three coastal rivers during the January 2018 flood, which were then tested using data from the March 2018 flood. The calibrated model predicted seven inland flood surface water elevations within 0.6 ft of observed coastal flood elevations for the March storm.

The calibrated model was able to predict individual water-surface elevations from the March flood with slightly more accuracy than it was able to predict individual water-surface elevations from the January flood even though the model was calibrated to the January flood. This could reflect possible ice influence during the January flood, leading to more variability in the flood elevations inland. The accuracy of the model is also a consequence of the uncertainty inherent in the very small dataset available for the analysis. Diffusivities would be expected to vary within a reach because they are a function of the distance from the mouth and of the distance inland from the main channel. For example, if the HWM is close to the river channel, diffusivity would vary from that of an HWM that is offset from the channel but is still connected hydraulically across a marsh. For this project, however, diffusivities for a reach were averaged together because the HWMs were all relatively close to the main channel.

This flood attenuation model can provide emergency workers and town planners a method for predicting approximate inland water-surface elevations given known or predicted stillwaters or storm tides. Flooding maps and flood profiles developed in this report may be of help to emergency managers and the public in better understanding the impacts and historical context of the 2018 nor’easter floods and preparing for future floods.

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