Updated Tidal Profiles for the New England Coastline

March 2012

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Revision History:

This report represents an update to a report titled "Updating Tidal Profiles for the New England Coastline," dated September 30, 2008, prepared by Map MOD team. All relevant data, station information, analyses, and figures from the original report are included herein. This update was performed by Strategic Alliance for Risk Reduction (STARR) to incorporate the following information: 1. Highwater mark data for significant events along the New England coastline which was not included in the original report; and 2. Tidal profiles which were omitted in the original report. The intent of this report is to provide an inclusive source for coastal stillwater elevations for all of New England to be used in analysis supporting FEMA Flood Insurance Studies.

1. Background

In 1988, the U.S. Army Corps of Engineers (USACE) developed coastal flood frequency curves for the New England coastline from Long Island Sound to the Maine-Canada border. This information, which is published in the report entitled *Tidal Flood Profiles, New England Coastline*, has been adopted by FEMA Regional Offices in New England and New York as the source of stillwater elevations (SWELs) for Flood Insurance Studies (FISs). The flood frequencies in the USACE publication were developed by fitting Pearson Type III distributions to long-term tide station data collected and archived by the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), and other organizations. Approximately 20 additional years of flood data have been captured at some of these gages since publication of the 1988 USACE study. Therefore, the need exists to update these flood frequency curves and to reassess the accuracy of the current stock of SWELs.

2. Scope of Current Analysis

The New England Tidal Flood Profiles, from Bergen Point, New York, to the Maine border with Canada, were updated by conducting new flood frequency analyses of long-term tide gage records supplemented by highwater mark data from significant events in the record. Tide gage records were available from NOS and USACE, while highwater mark data was retrieved from the USACE 1988 report. Parametric probability distributions were fit to the tide gage data using the method of L moments. The suite of probability distributions included the original Pearson Type III distribution to enable comparisons between the old tidal flood profiles and the results from the new analyses. The tidal flood profiles were updated using the best fitting probability distribution, as determined by goodness-of-fit criteria.

3. Sources of Data

Data for 16 tide stations were obtained from the NOAA/NOS Center for Operational Oceanographic Products and Services (CO-OPS) data base (http://co-ops.nos.noaa.gov/). Data for two tide stations were obtained from the USACE, New England District. Only those stations with more than 20 years of record were used for the frequency analysis. The 18 long-term stations used in the frequency analysis are listed in Table 1. Where available, data through 2007 were used in the analysis.

Monthly maximums for the 14 NOAA/NOS stations shown in Table 1 with 26 or more years of record were provided by Chris Zervas, NOS Headquarters (HQ), in Silver Spring, Maryland. Mr. Zervas, who also performs frequency analyses at long-term NOS stations (Zervas, 2005), provided data up to 2006, and data for 2007 were obtained from the CO-OPS database. Data for the two NOAA/NOS stations with less than 26 years of record were obtained from the CO-OPS database. The annual maximum elevations used in the analyses, in feet above the North American Vertical Datum of 1988 (NAVD), were determined from monthly maximums. The data for the two USACE stations were provided by Townsend Barker with the New England District. Stephen Lyles, with NOS HQ, provided data on some of the missing datum conversions.

All gage record data used in the frequency analysis were obtained from verified data bases of NOS and USACE with additional quality assurance provided by Chris Zervas, NOS.

In addition to the gage record data, highwater mark data was incorporated into the frequency analysis to provide data for those events during which gages were not operational. Specifically, the gage records for Providence, New London, Bridgeport and Stamford did not include the 1938 Hurricane, which is considered the event of record for the southern New England coastline. It is suspected that this missing data may have contributed to the underestimation of the 1-percent annual chance event in the original report. Therefore, highwater mark elevations, which were available in the USACE 1988 report, were incorporated into an extended data set for the identified locations as indicated in Table 2. Statistical analysis was then performed on the updated data set, using the L-Moments approach, to determine the 1-percent-annual-chance stillwater elevations.

Table 1. Long-term tide stations used in the frequency analysis.

Station Name	State	Owner	Station ID	Latitude	Longitude	Record Length (years)
Eastport	Maine	NOAA-NOS	8410140	44.9033	-66.9850	1929-2007
Cutler*	Maine	NOAA-NOS	8411250	44.6417	-67.2967	1983-2007
Bar Harbor	Maine	NOAA-NOS	8413320	44.3917	-68.2050	1947-2007
Portland	Maine	NOAA-NOS	8418150	43.6567	-70.2467	1912-2007
Seavey Island	Maine	NOAA-NOS	8419870	43.0800	-70.7417	1926-2001
Boston	Massachusetts	NOAA-NOS	8443970	42.3550	-71.0517	1921-2007
New Bedford	Rhode Island	USACE-NED	NA	41.6400	-70.9183	1922-2007
Newport	Rhode Island	NOAA-NOS	8452660	41.5050	-71.3267	1930-2007
Providence	Rhode Island	NOAA-NOS	8454000	41.8067	-71.4017	1938-2007
New London	Connecticut	NOAA-NOS	8461490	41.3550	-72.0867	1938-2007
Bridgeport	Connecticut	NOAA-NOS	8467150	41.1733	-73.1817	1964-2007
Stamford	Connecticut	USACE-NED	NA	41.0369	-73.5345	1938-2007
Montauk	New York	NOAA-NOS	8510560	41.0483	-71.9600	1947-2007
Port Jefferson	New York	NOAA-NOS	8514560	40.9500	-73.0767	1957-1992
Willets Point	New York	NOAA-NOS	8516990	40.7933	-73.7817	1931-2006
New Rochelle	New York	NOAA-NOS	8518490	40.8933	-73.7817	1957-1990
The Battery	New York	NOAA-NOS	8518750	40.7000	-74.0150	1920-2007
Bergen Point	New Jersey	NOAA-NOS	8519483	40.6400	-74.1500	1982-2007

*The station to NAVD vertical datum conversion was calculated using only one benchmark tied into the geodetic network. Therefore, the stability of the benchmark could not be verified, resulting in a slight uncertainty in the conversion value.

Table 2. Highwater mark elevations (feet NAVD) included in this update.

Station	1938	1944	1954	1978
Portland	-	-	-	9.9
Seavey Island	-	-	-	9.6
Boston	-	-	-	14.3
New Bedford	13.2	-	14.6	-
Newport	11.3	-	10.1	-
Providence	16.1	-	14.6	-
Bridgeport	9.3	-	8.1	-
Stamford	11.1	-	10.5	-
Willets Point	12.6	-	10.6	-

The following procedures or assumptions were made in the frequency analysis:

- Water elevations were not decomposed into astronomical (tide) and meteorological (storm surge) components. Several authors (e.g., Prandle and Wolf, 1978; Bernier and Thompson, 2007; Horsburgh and Wilson, 2007) have reported nonlinear interactions between tides and storm surges, as well as clustering of peak surges around certain tide stages. The assumption here is that the long-term records inherently capture any tide-surge interactions and correlation structure.
- A mixed population approach was not adopted for the treatment of hurricanes and nor'easters. The assumption here is that a univariate approach produces acceptable estimates if a good fit is achieved in the upper tail of the chosen frequency distribution.
- All data were updated to the current mean sea level using sea level trends computed by NOAA/NOS. Sea level trends in feet per 100 years (ft/100yr) were obtained from the NOAA/NOS website (Zervas, 2005), and the annual maximum data were corrected for this trend. The sea level trends ranged from 0.62 to 0.91 ft/100yr for the 18 stations in Table 1. Sea level trends were not available for 5 of the 18 stations. In these cases, the trend was interpolated using data for adjacent stations.

The location of the 18 stations used in the frequency analysis is shown in Figure 1. The study area is from Bergen Point, New York, up to the Maine border with Canada. The symbols in Figure 1 identify those stations that are a part of a homogeneous region, as described later.

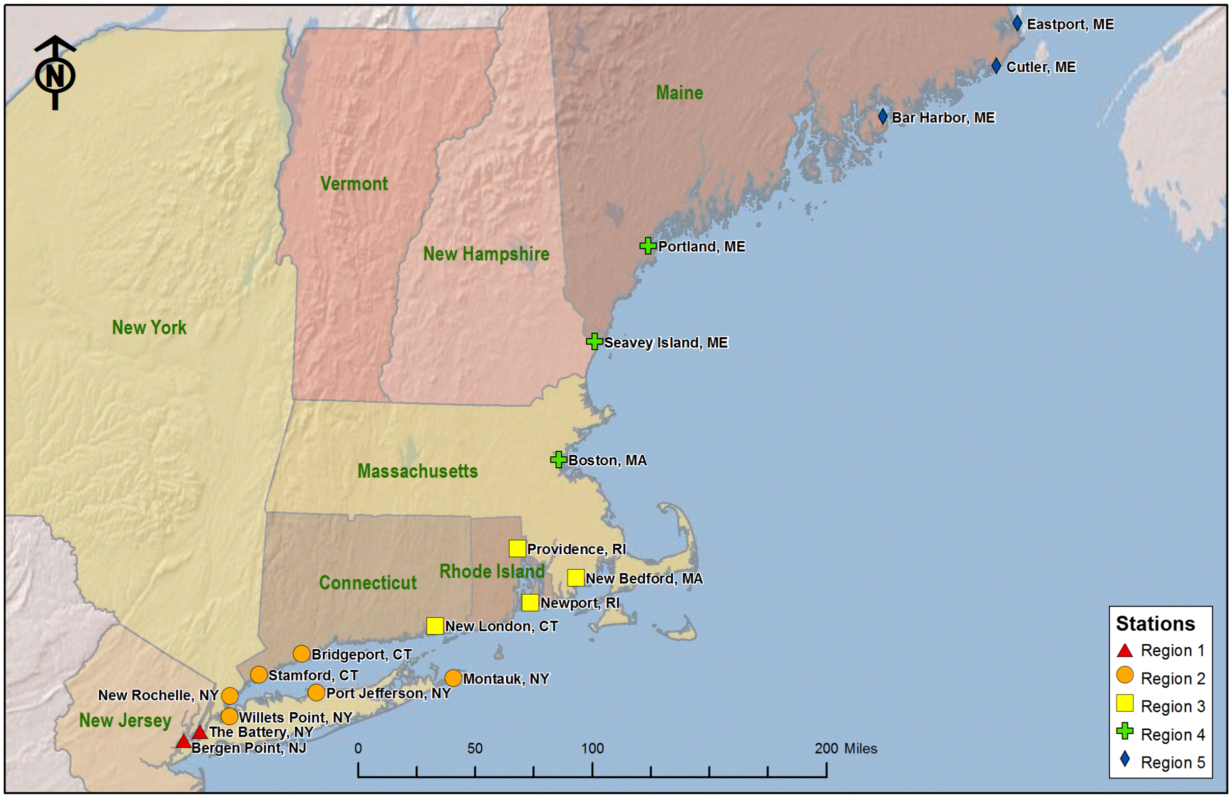

Figure 1. Location of the 18 long-term stations used in the frequency analysis.

4. Analysis Approach

4.1. L-Moment Method

Regional flood frequency analysis involves augmenting at-site data with data from other sites having similar probability distributions. The assumption is that in a homogeneous region, the environmental response variable of interest (e.g., peak storm surge elevation) is produced by one or more common climatological or hydrological forcing functions, each having the same regional probability distribution.

The procedure for regional flood frequency analysis involves: (1) screening of data, (2) partitioning of data into homogeneous subregions, and (3) fitting probability distributions to data within each subregion. These involve subjective and objective decisions regarding outliers, heterogeneity, and goodness-of-fit. The LMOMENTS package (Hosking, 1996; Hosking and Wallis, 1997) provides convenient routines for screening, clustering, and frequency analysis of regional data sets based on the L-moment method. L moments have been shown in various Monte Carlo studies (e.g., Delicado and Goria, 2008) to outperform other estimation methods, such as the method of moments and method of maximum likelihood, in terms of bias and robustness. The LMOMENTS package (Hosking, 1996) was used to perform the frequency analysis of long-term tide data in this study.

The annual maximum elevations at the tide stations were fit to selected frequency distributions using L moments to estimate the distribution parameters. In the L-moment method, a regional frequency curve is obtained by averaging the slopes of the station frequency curves in a given homogeneous region. L moments are analogous to ordinary moments in that the purpose is to summarize theoretical probability distributions and observed samples. Because L moments are computed as linear combinations of the ranked observations (instead of squaring and cubing the observations), they are subject to less variability in small samples than ordinary moments (Hosking, 1990).

A more rigorous description of the L-moment method is provided in Appendix A. The sample L moments or sample L-moment ratios needed to describe the frequency distributions and apply various statistical tests are as follows:

- l_1 = first L moment, measure of location (mean),
- l_2 = second L moment, measure of scale (dispersion),
- l_2/l_1 = L coefficient of variation (L-CV),
- l_3 = third L moment,
- l_4 = fourth L moment,
- l_3/l_2 = measure of skewness (L skewness), and
- l_4/l_2 = measure of kurtosis (L kurtosis).

The sample L moments defined above (l_i) are sample estimates of the population L moments (λ_i) defined in Appendix A.

4.2. Defining Homogeneous Regions

Regionalization involves forming clusters of subregions from the entire data set based on site characteristics. The primary goal is to choose site characteristics that best capture the relevant indicators upon which hydrological or climatological homogeneity can be predicated. Site characteristics for grouping tide gage stations could be attributes such as geographical location (longitude, latitude); storm frequency (hurricane frequency, nor'easter frequency); coastal processes; and landforms.

After the initial formation of subregions, the next goal is to ascertain that the sites within the tentative subregions can reasonably be assumed to be homogeneous. The LMOMENTS package incorporates three tests for heterogeneity:

- H1 – the weighted standard deviation of the sample L-CVs,
- H2 – the average distance from the site to the regional average on a graph of L-CV vs. L skewness, and
- H3 – the average distance from the site to the regional average on a graph of L skewness vs. L kurtosis.

These compare the between-site variations in sample L moments for sites in a subregion. The use of only one of the three options is usually adequate. A subregion is acceptably homogeneous if $H < 1$, likely heterogeneous if $H > 1$, and most likely heterogeneous if $H > 2$. These thresholds are based on expert judgment but are not definitive. Several adjustments are required when a given subregion is not homogenous. The options include: moving sites between subregions, deleting sites from the data set, subdividing subregions, merging subregions, etc. The three tests noted above were used in defining homogeneous regions for this analysis.

4.3. Fitting Frequency Distributions

Given homogeneous regions, the objective is to find the regional frequency distributions that, on average, describe the observations at each site. The LMOMENTS package fits sample data to the following three-parameter (location, scale, and skewness) frequency distributions:

- Generalized Logistic
- Generalized Extreme Value
- Generalized Normal
- Pearson Type III
- Generalized Pareto
- Wakeby

The goodness-of-fit is quantified using test statistics internal to the LMOMENTS package at a 90-percent confidence level (implying only a 10-percent chance of choosing an erroneous distribution). More details on the good-of-fit test are provided by Hosking (1990), Hosking (1996) and Hosking and Wallis (1997).

5. Analysis Results

5.1. Analyses at the Tide Stations

The LMOMENTS package was used to analyze annual maximum elevations for the 18 long-term tide stations. Five homogeneous regions, as shown in Figure 1, were defined by using the heterogeneity tests described above. The Wakeby distribution was determined to be most applicable distribution across all five regions.

In the L-moment method, the slope of the frequency curve is assumed to be same for all stations in a homogeneous region and, the x-percent chance elevations (such as the 1-percent-annual-chance elevation) are determined by multiplying the index flood by a ratio. For this analysis, the index flood was the mean annual elevation (mean of all annual maximums at a given station) or the first L moment (l_1).

The mean annual elevation and the 10-, 2-, 1-, and 0.2-percent-annual-chance elevations based on the Generalized Logistic distribution are shown in Table 3 for the 18 long-term stations. The region for each station is also shown. The 10-, 2-, 1-, and 0.2-percent-annual-chance elevations are estimated as a ratio to the mean annual elevation. The ratios of the x-percent chance elevation to the mean annual elevation are shown in Table 4.

Table 3. The mean annual and x-percent-annual-chance flood elevations in feet (NAVD), as estimated from the Wakeby distribution.

Station (Region)	Mean annual elevation in feet (NAVD)	10-percent elevation in feet (NAVD)	2-percent elevation in feet (NAVD)	1-percent elevation in feet (NAVD)	0.2-percent elevation in feet (NAVD)
Eastport (5)	13.04	13.70	14.42	14.72	15.39
Cutler (5)	9.76	10.25	10.79	11.02	11.52
Bar Harbor (5)	8.12	8.53	8.98	9.17	9.58
Portland (4)	7.32	8.01	9.01	9.51	10.85
Seavey Island (4)	7.30	7.99	8.98	9.48	10.83
Boston (4)	7.72	8.45	9.51	10.04	11.46
New Bedford (3)	4.83	6.01	9.36	11.86	22.39
Newport (3)	4.28	5.33	8.30	10.52	19.85
Providence (3)	5.61	6.98	10.88	13.79	26.02
New London (3)	3.83	4.76	7.42	9.40	17.74
Bridgeport (2)	6.30	7.79	9.33	9.95	11.30
Stamford (2)	6.86	8.49	10.17	10.85	12.32
Montauk (2)	3.70	4.57	5.48	5.84	6.63
Port Jefferson (2)	6.20	7.67	9.18	9.80	11.12
Willets Point (2)	7.22	8.93	10.70	11.41	12.96
New Rochelle (2)	6.60	8.17	9.79	10.44	11.85
The Battery (1)	4.97	5.87	6.92	7.36	8.38
Bergen Point (1)	5.11	6.04	7.11	7.57	8.62

Table 4. Ratios of the x-percent chance flood to the mean annual elevation for the five homogeneous regions.

Region	10-percent	2-percent	1-percent	0.2-percent
1	1.18	1.39	1.48	1.69
2	1.24	1.48	1.58	1.80
3	1.24	1.94	2.46	4.64
4	1.09	1.23	1.30	1.48
5	1.05	1.11	1.13	1.18

For example, the 1-percent-annual-chance elevation for New London in Region 3 is obtained by multiplying the mean annual elevation of 3.827 feet by 2.46 to obtain a 1-percent-annual-chance elevation of 9.41 feet (NAVD), as shown in Table 3. Estimates for other x-percent elevations were made through the same process.

The data for the 18 long-term stations were supplemented by adding five short-term stations to the analysis. The short-term stations were added to have more locations to compare to the 1988 USACE flood profiles. A listing of the short-term stations is shown in Table 5, and their locations relative to the long-term stations are shown in Figure 2.

Table 5. Summary of short-term tide stations used in the analysis.

STATION ID	NAME	LATITUDE	LONGITUDE	DATE ESTABLISHED	RECORD LENGTH (years)
8415490	Rockland, ME	44.1050	-69.1017	May 14, 1945	6
8447270	Buzzards Bay, MA	41.7417	-70.6167	Jul 29, 1955	7
8447386	Fall River, MA	41.7050	-71.1633	Oct 28, 1955	8
8454049	Quonset Point, RI	41.5850	-71.4083	Sep 24, 1999	8
8465705	New Haven, CT	41.2833	-72.9083	Aug 11, 1999	8

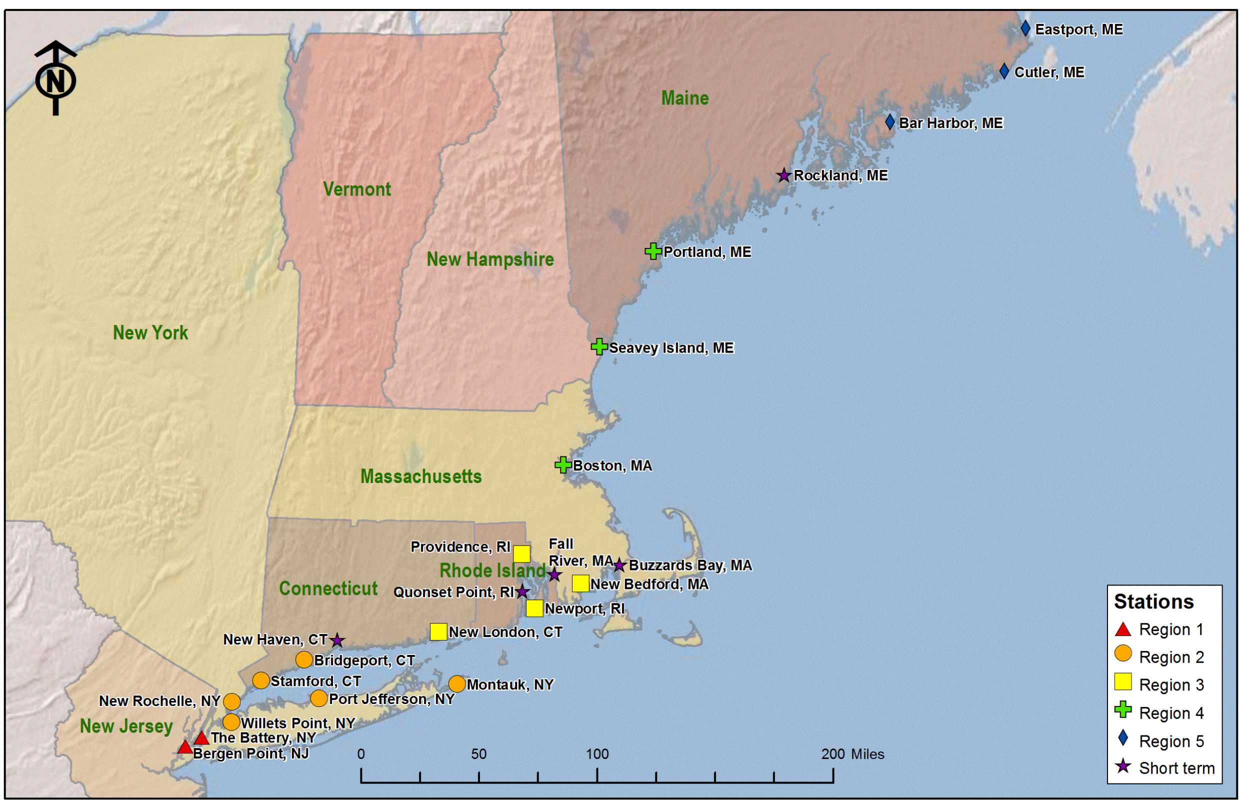

Figure 2. Location of long-term and short-term tide stations used in the analysis.

The mean annual elevations were estimated for the five short-term stations based on limited observed record. The x-percent chance flood elevations can be estimated at the short-term stations simply by multiplying the mean annual elevations by the ratios in Table 4. Engineering judgment was used to determine the appropriate homogeneous region for each station. The short-term stations do not have sufficient record length (6 to 8 years, as shown in Table 5) for frequency analyses but do have sufficient record length to estimate the mean annual elevations. Estimates can be made at any location along the coastline from New York to Maine if the mean annual elevation can be estimated and the site can be characterized as being in one of the five homogeneous regions. The mean annual and x-percent-annual-chance elevations for the short-term stations are shown in Table 6.

Table 6. The mean annual and x-percent-annual-chance flood elevations in feet (NAVD) for the five short-term tide stations.

	Mean annual elevation, feet (NAVD)	10-percent elevation, feet (NAVD)	2-percent elevation, feet (NAVD)	1-percent elevation, feet (NAVD)	0.2-percent elevation, feet (NAVD)
New Haven (2)	5.61	6.94	8.32	8.87	10.07
Quonset Point (3)	4.57	5.69	8.86	11.23	21.18
Fall River (3)	4.92	6.12	9.54	12.09	22.81
Buzzards Bay (3)	5.64	7.02	10.93	13.85	26.14
Rockland (4)	7.64	8.36	9.41	9.93	11.34

5.2. Updating the Flood Profiles

Base maps showing the locations of the long-term, short-term stations, locations of high water marks, and the distance along the New England coastline were developed and are shown in Appendix B. These base maps are similar to the base maps in the 1988 USACE report entitled *Tidal Flood Profiles, New England Coastline*. The 1988 USACE base maps were extended south from Willets Point, NY, to Bergen Point, NY. The USACE profile data do not include Bergen Point, NY, and The Battery, NY.

The 1-percent flood elevations for the updated L-moment analyses (Wakeby) are compared in Table 7 to the:

- 1988 USACE profile elevation based on Pearson Type III method of moments,
- SWELs from the effective FIS reports,
- Updated Pearson Type III at-site analyses based on L moments, and
- Observed maximum elevation for period of record.

The 1-percent chance elevation shown in the second column of Table 7 is based on the five homogeneous regions and the Generalized Logistic distribution (the best fit distribution). The Pearson Type III 1-percent chance elevations are based on at-site estimates and were provided for additional comparisons to the 1988 USACE elevations. The 1988 USACE elevations also are based on at-site estimates using the Pearson Type III distribution, but the method of moments was used to fit the distribution, rather than L moments as in our current study.

Table 7. Comparison of 1-percent-annual-chance elevations based on the regional L-moment analyses (Wakeby), effective SWELs from FIS reports, 1988 USACE profiles, Pearson Type III at-site analyses, and the maximum observed elevations (in feet NAVD).

Station	1-percent elevation, feet (NAVD)	Effective SWELs, feet (NAVD)	1988 USACE 1-percent elevation, feet (NAVD	Pearson Type III elevation, feet (NAVD)	Maximum observed elevation, feet* (NAVD	Record Length (years)
Eastport	14.72	13.99	14.80	14.31	14.38	78
Cutler	11.02	12.01	12.50	10.51	10.43	24
Bar Harbor	9.17	10.00	9.30	9.34	9.29	60
Rockland	9.93	9.51	8.70	---	---	---
Portland	9.51	8.88	8.70	9.02	9.88	95
Seavey Island	9.48	7.93	8.80	9.22	9.64	75
Boston	10.04	9.40	9.50	11.45	14.30	86
Buzzards Bay	13.85	12.96	13.60	---	---	---
New Bedford	11.86	11.97	11.40	12.07	14.58	85
Newport	10.52	10.72	10.70	9.55	11.84	77
Quonset Point	11.23	11.32	11.20	---	---	---
Fall River	12.09	13.85	13.00	---	---	---
Providence	13.79	15.18	14.80	14.20	16.18	69
New London	9.40	9.04	8.90	8.05	9.22	69
New Haven	8.87	9.66	9.60	---	---	---
Bridgeport	9.95	9.61	9.10	9.15	9.31	43
Stamford	10.85	10.49	10.50	10.74	11.11	69
Montauk	5.84	6.86	9.80	6.83	7.59	60
Port Jefferson	9.80	9.77	9.10	8.84	8.38	35
Willets Point	11.41	12.71	12.30	13.61	13.23	75
New Rochelle	10.44	10.90	11.90	9.23	8.27	33
The Battery	7.36	8.59	---	7.46	7.66	87
Bergen Point	7.57	7.20	---	6.51	6.20	25

* Reported maximum observed elevation also includes high water mark values.

The major differences (on the order of 4 feet or more) between the updated 1-percent chance elevations from the regional L-moment analyses and the 1988 USACE 1-percent chance elevations occurs at Montauk. For this station, the mean annual elevation is relatively low as compared to the 1-percent-elevations reflected in the 1988 USACE report for this site. Additionally, the difference between the mean annual elevations and the 1988 USACE 1-percent-elevations is much greater than the similar comparisons at other sites along the New England coastline. This implies that the 1988 USACE 1-percent-elevation at Montauk was driven by a singular, extremal event which far exceeded the typical high water levels for the area. With the exception of Hurricane Bob in 1991, the past 20 years have been relatively quiet with respect to high water levels for Montauk. As a result, the longer records have reduced the statistical impacts of the outlier events at Montauk, thereby reducing the 1-percent-event values at this site. This change is greater at Montauk than the other sites because the excursion between mean annual elevations and the 1988 USACE 1-percent-elevations was greater than at other sites.

With the exception of Montauk, the updated 1-percent chance flood elevations are within 1.5 feet of the 1988 USACE profile. Using data for the remaining 20 stations, the average difference is -0.02 feet. At 9 stations, the 1-percent chance elevation decreased, and at 11 stations, the 1-percent chance elevation increased. Supplementing the existing station gage data with highwater mark data has increased the x-percent chance elevation in comparison to the values from the 2008 report. The values in this report are more representative of the coastal flood hazard associated with the 1-percent annual chance event.

6. Development of Profiles

For the portions of the New England shoreline between Bergen Point, NY and Buzzards Bay, MA and between Boston Harbor, MA and Eastport, ME tidal flood profiles for the mean annual and x-percent chance elevations were developed. The profiles, located in Appendix C, were prepared using the elevations for the long-term and short-term stations in Tables 3 and 6 respectively, and the profile baseline shown on the base maps in Appendix B. For areas between gage sites, linear interpolation of the elevation information was used to extend the profiles. The profiles were created for graphical purposes only. Tables 3 and 6 are the most accurate sources of x-percent annual chance elevations at the gage sites.

For the areas between Buzzards Bay, MA and Boston Harbor, MA, the profiles from the USACE 1988 report have been recreated in Appendix C. The profiles in this area (Profile 7 through 10 in Appendix C) were not updated due to insufficient long-term gage record data between Woods Hole, MA and Boston, MA to perform the L-Moment analysis as described above. As a result, it was determined that the USACE 1988 tidal profiles remain the most applicable source of stillwater elevations for use in FEMA Flood Insurance Studies in this area.

7. Summary

Annual maximum data were obtained for 18 long-term stations with record lengths in excess of 20 years using data through 2007. These data were supplemented with data for five short-term stations where record lengths ranged from 6 to 8 years. Additionally, highwater mark data resulting from significant storms at select station sites was incorporated. The LMOMENTS package documented by Hosking (1996) was used to analyze the annual maximum data and define five homogeneous regions. The Wakeby distribution was determined to be the best fit frequency distribution for the tide data.

Updated flood elevation profiles were generated for the mean annual and x-percent chance elevations for tidal flood profiles within New England. For the areas between Buzzards Bay, MA and Boston Harbor, MA the USACE 1988 profiles were used due to insufficient gage data to interpolate results along Cape Cod.

8. References

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Appendix A: The L-Moment Method

The following summary on L moments is taken from Delicado and Goria (2008). L moments and ordinary moments are special cases of probability weighted moments introduced by Greenwood, et al. (1979) as

$$M_{p,r,s} = E\left[X^p F(X)^r (1-F(X))^s\right] = \beta(r+1,s+1)E\left[X^p_{(r+1,r+s+1)}\right],$$

which exist for all $r,s \geq 0$ if and only if $E\left|X^p\right|$ is finite, where $X_{(r+1,r+s+1)}$ is the $(r+1)$ st order statistic connected with a random sample of size $r+s+1$. For $r=s=0$ we obtain the ordinary moments. In the last expression, $\beta(a,b)$ is the usual beta function, that is, $\beta(r,s)=(r-1)!(s-1)!/(r+s-1)!$ for natural arguments. Of special interest in the present context are $M_{1,r,0}$ (denoted by β_r), which uniquely characterize the distribution requiring only the existence of the mean (see Hosking 2006 for more details on the characterization of distributions by their L moments).

$$\lambda_{r+1} = (r+1)^{-1}\sum_{k=0}^{r}(-1)^k \binom{r}{k} EX_{(r+1-k,r+1)} = \sum_{k=0}^{r} p_{r,k}\beta_k, \quad p_{r,k} = (-1)^{r-k}\binom{r}{k}\binom{r+k}{k}, \text{ r=0,1,...,}$$

Explicitly,

$$\lambda_1 = \beta_0, \quad \lambda_2 = 2\beta_1 - \beta_0, \quad \lambda_3 = 6\beta_2 - 6\beta_2 + \beta_0, \quad \lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0.$$

These first four L moments admit more easily understandable expressions:

$$\lambda_1 = \beta_0, \quad \lambda_2 = \tfrac{1}{2}E(X_{(2,2)} - X_{(1,2)}), \quad \lambda_3 = \tfrac{1}{3}E(X_{(3,3)} - 2X_{(2,3)} + X_{(1,3)}),$$
$$\lambda_4 = \tfrac{1}{4}E(X_{(4,4)} - 3X_{(3,4)} + 3X_{(2,4)} - X_{(1,4)}).$$

It follows that $\lambda_1,\ \lambda_2,\ \lambda_3/\lambda_2,\ \lambda_4/\lambda_3$ may be regarded as measures of location, scale, skewness, and kurtosis, respectively (see Hosking 1990 for more details). The sample L moments are defined as $l_{r+1} = \sum_{k=0}^{r} p_{r,k} b_k,\ \ r = 0,1,...,$ where

$$b_r = n^{-1}\sum_{k=r+1}^{n}\binom{k-1}{r}\binom{n-1}{r}^{-1} X_{(k,n)}, \quad r = 0,1,...,n-1,$$

and $X_{(k,n)}$ is the k th order statistic. One can equally represent the l_r in terms of U statistics, i.e., the average overall sub-samples of size $r<n$. The L-moment method consists of equating the sample L moments to the theoretical ones and solving for the parameters. The resulting estimators are consistent and asymptotically normal (see Hosking 1990 for more details)

Appendix B: Base Maps

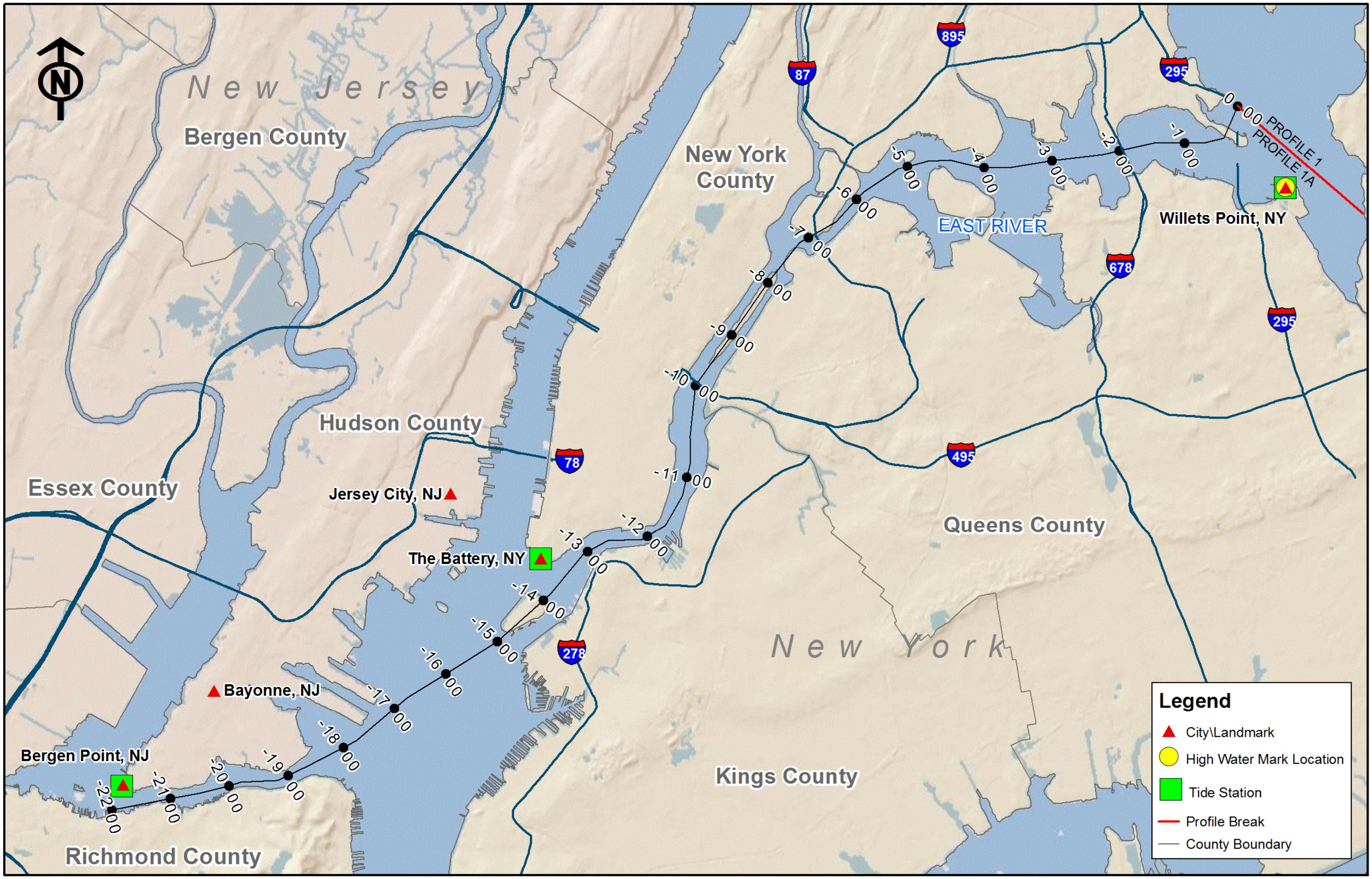


Figure B1. Base Map for Profile 1A from Bergen Point, NY to Willets Point, NY

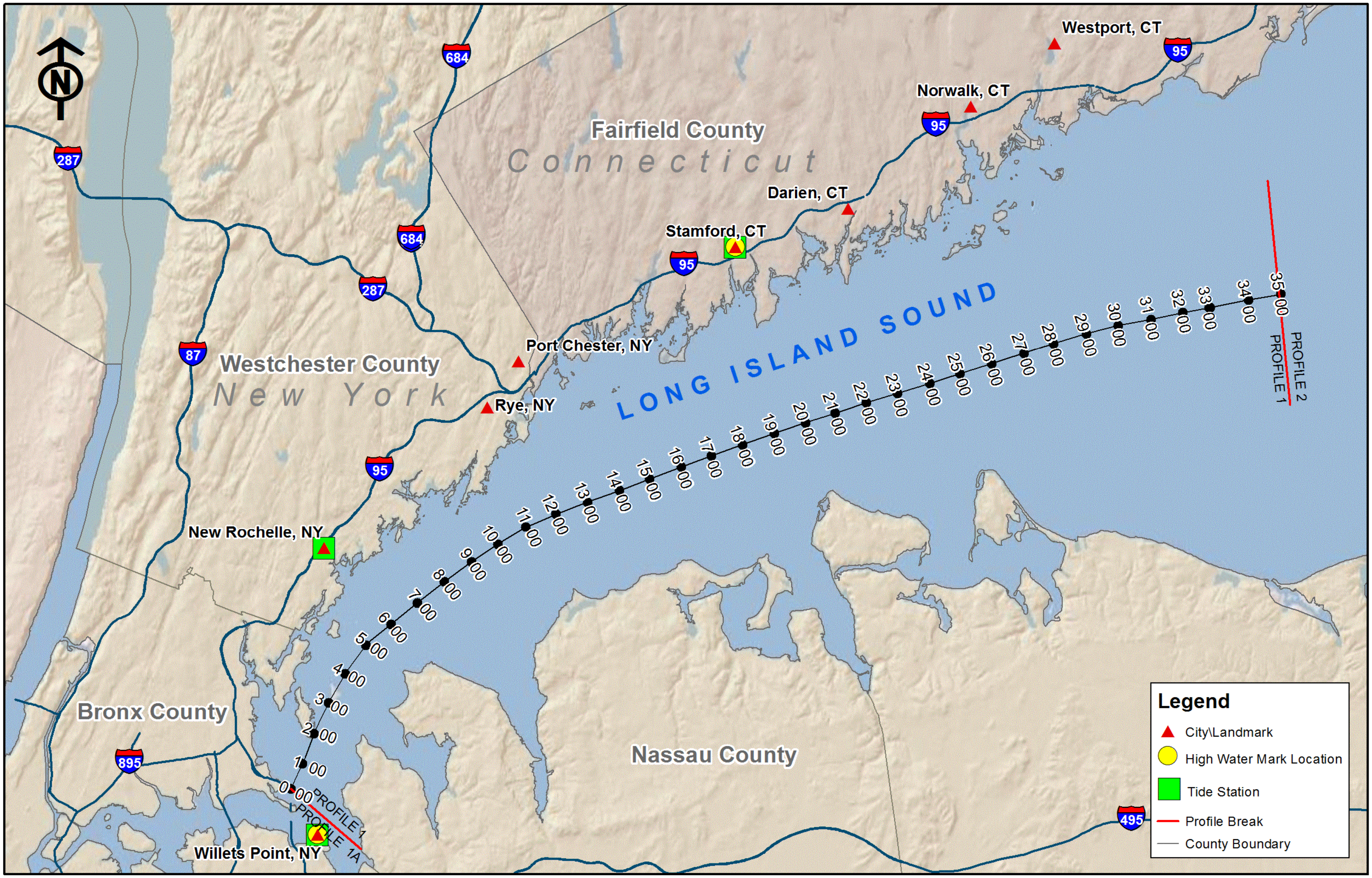


Figure B2. Base Map for Profile 1 from Willets Point, NY to mile 35

Figure B3. Base Map for Profile 2 from mile 35 to mile 60

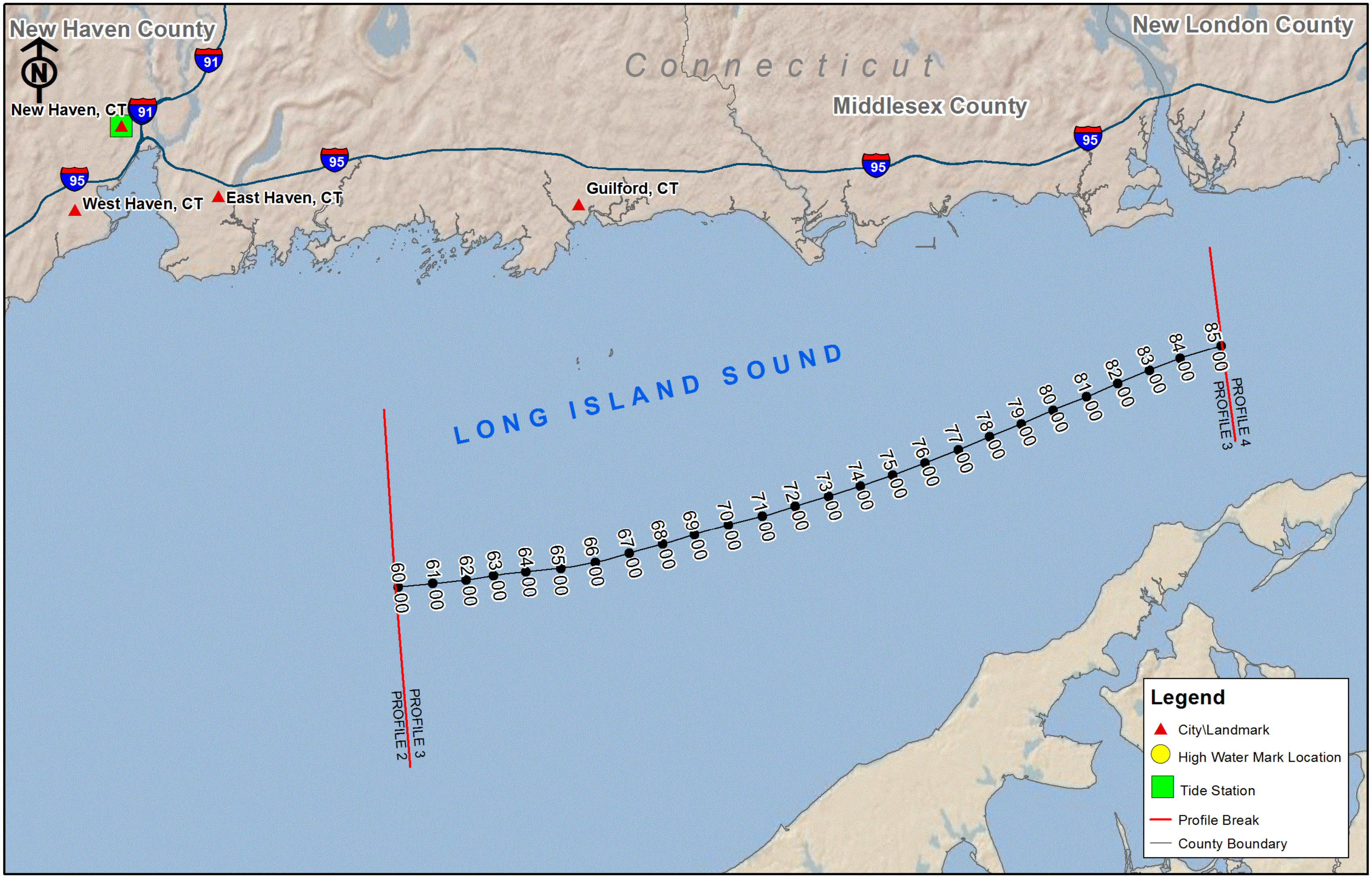


Figure B4. Base Map Profile 3 from mile 60 to mile 85

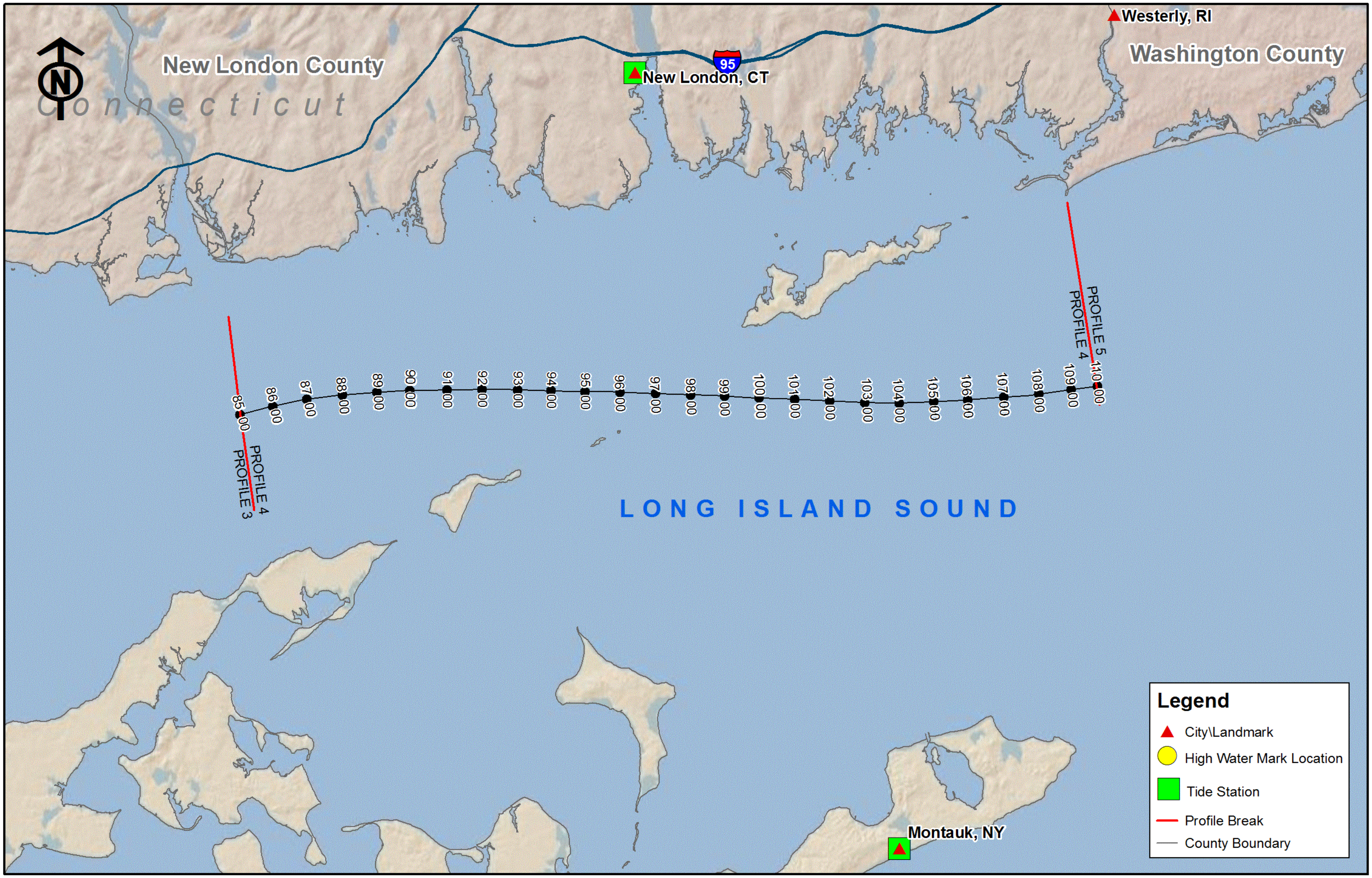


Figure B5. Base Map for Profile 4 from mile 85 to mile 110

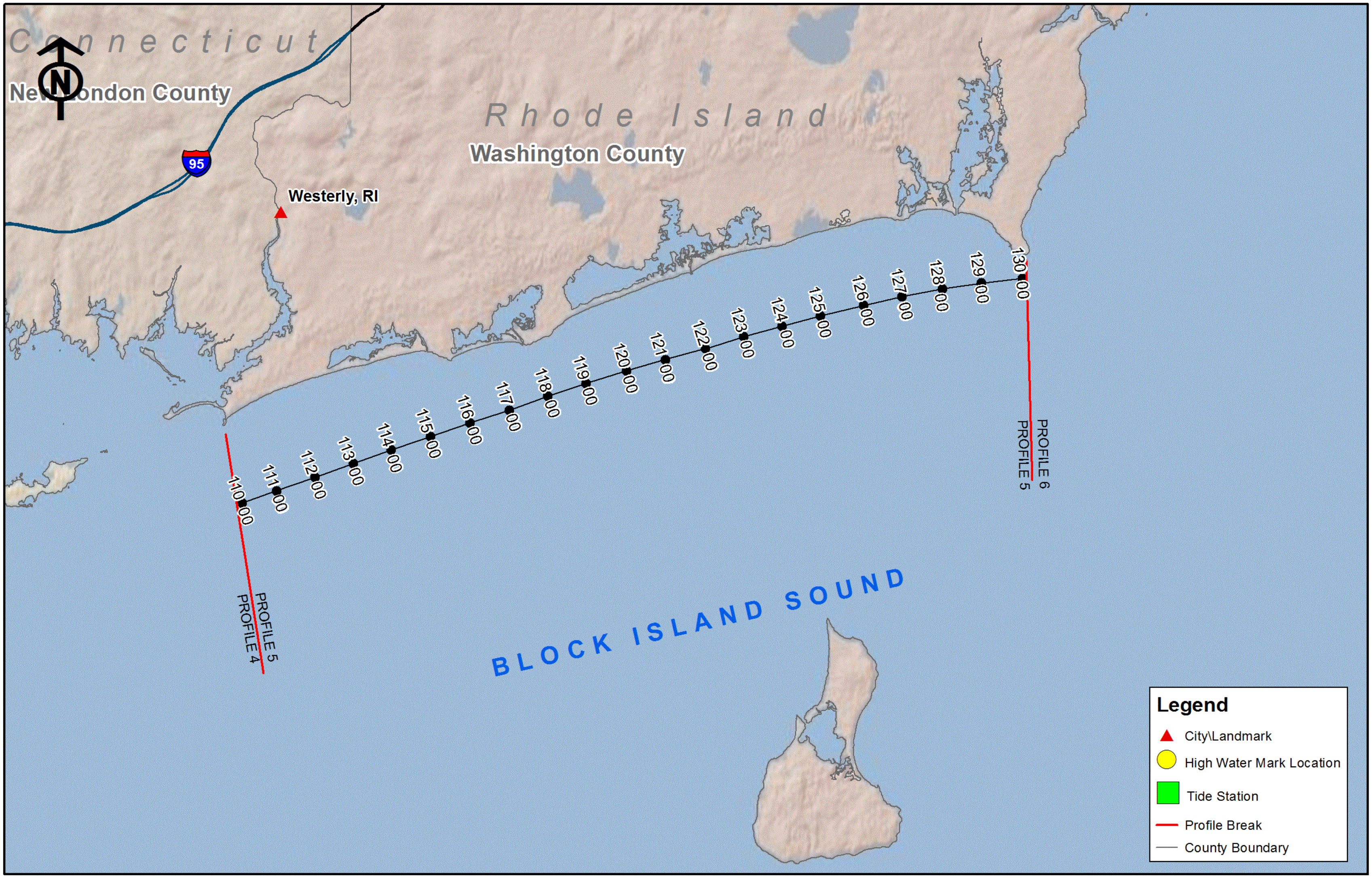


Figure B6. Base Map for Profile 5 from mile 110 to mile 130

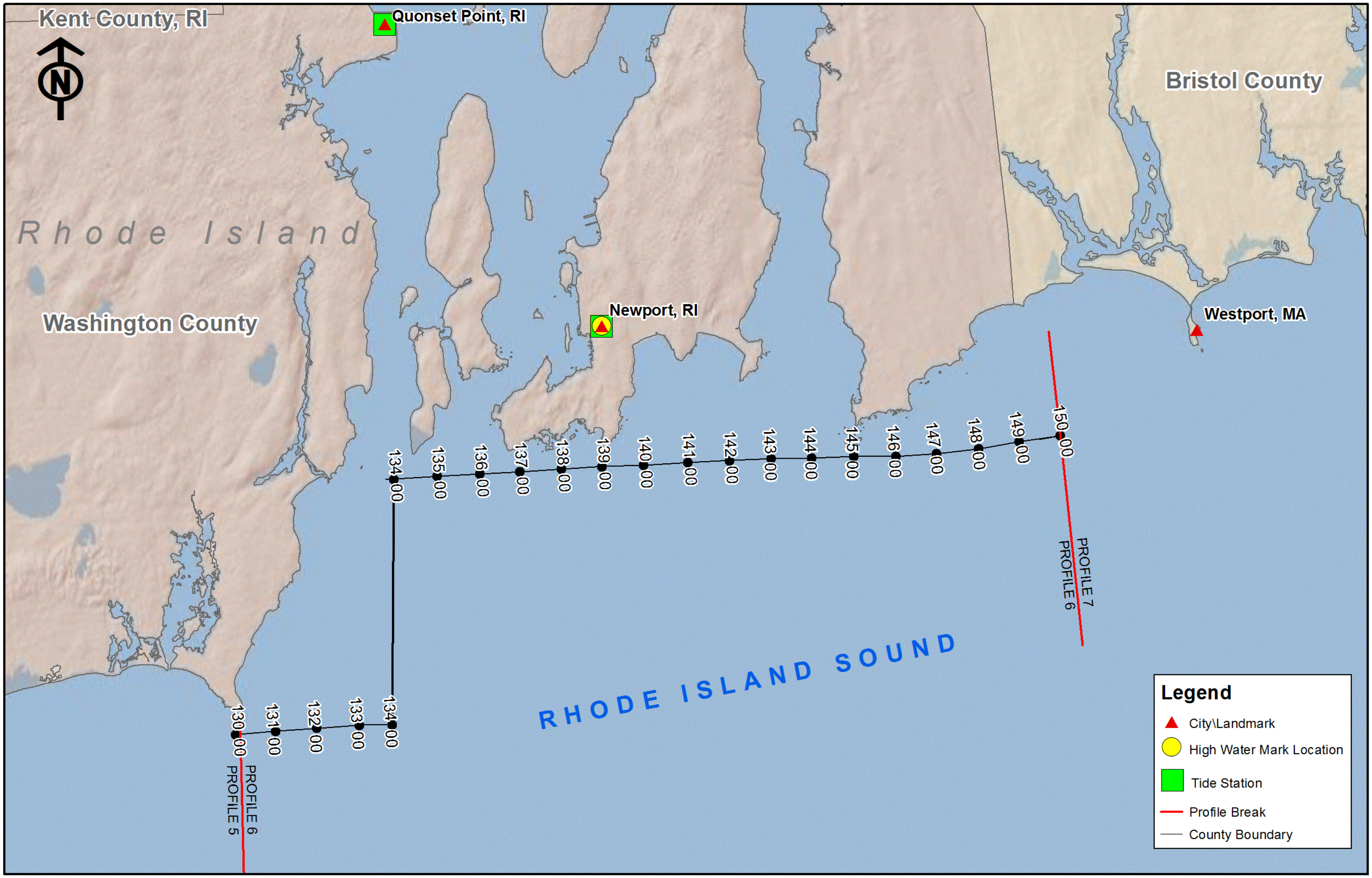


Figure B7. Base Map for Profile 6 from mile 130 to mile 150

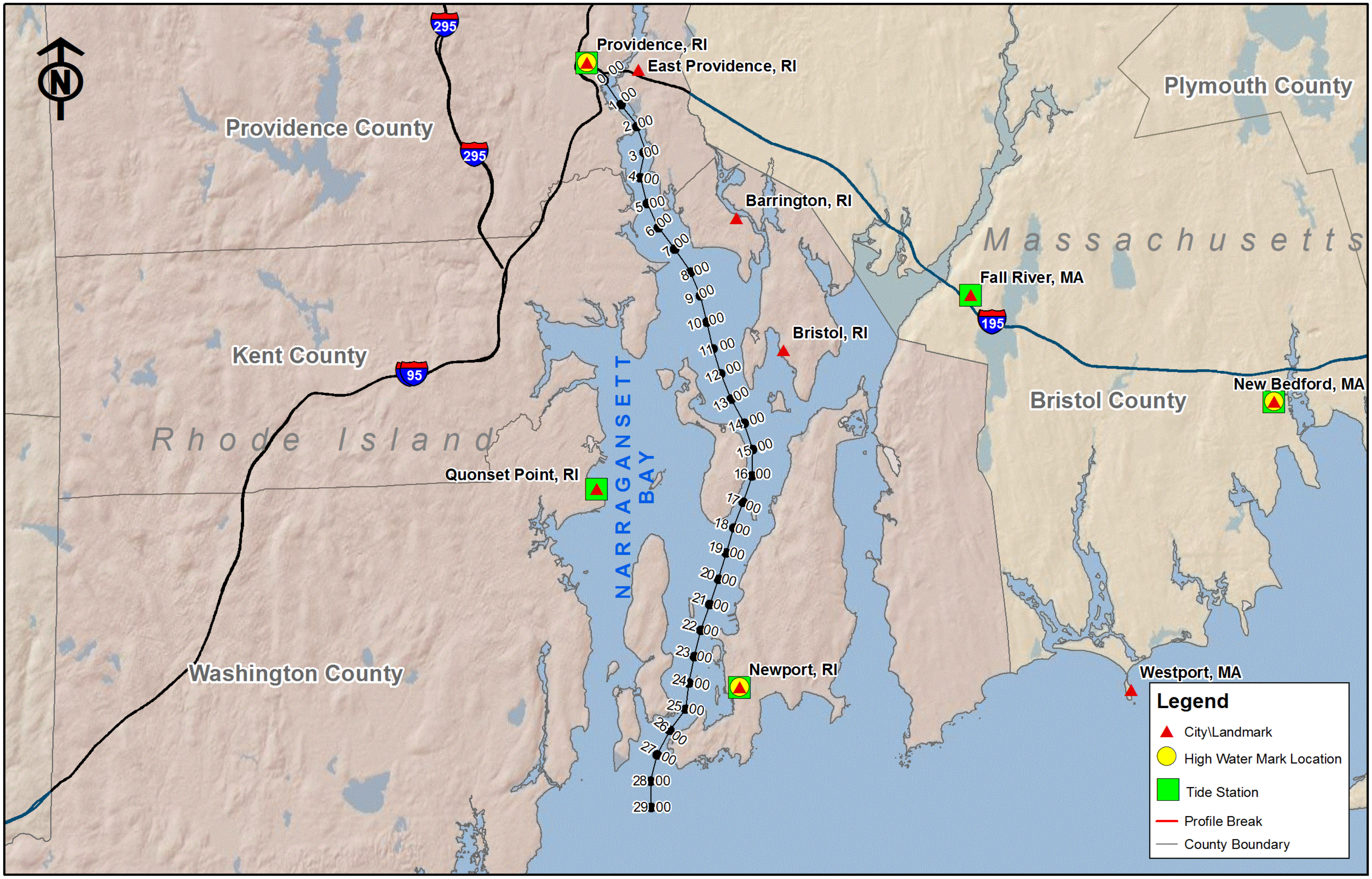


Figure B8. Base Map for Profile 6A from Providence, RI to Newport, RI

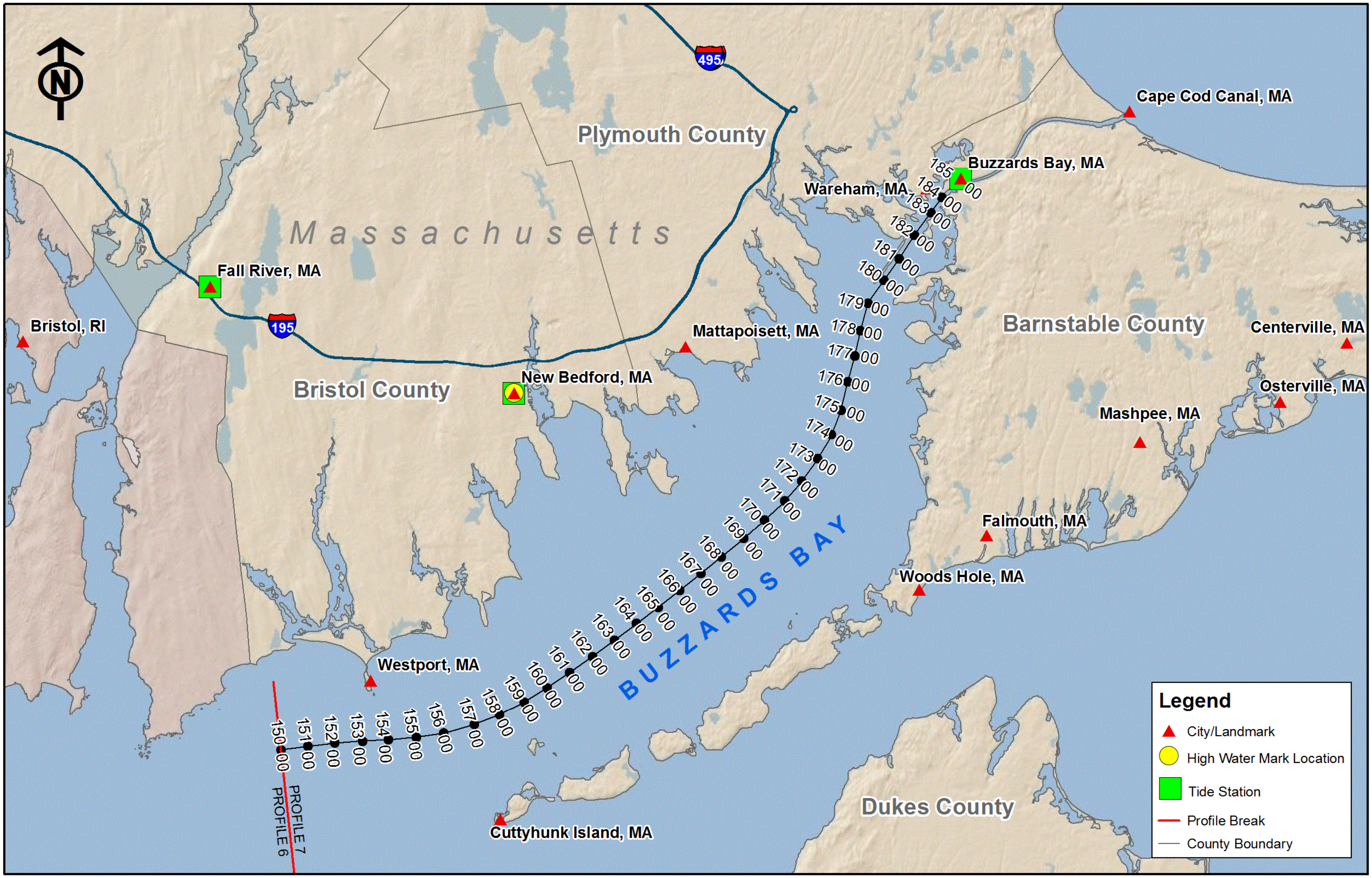


Figure B9. Base Map for Profile 7 from mile 150 to Buzzards Bay, MA

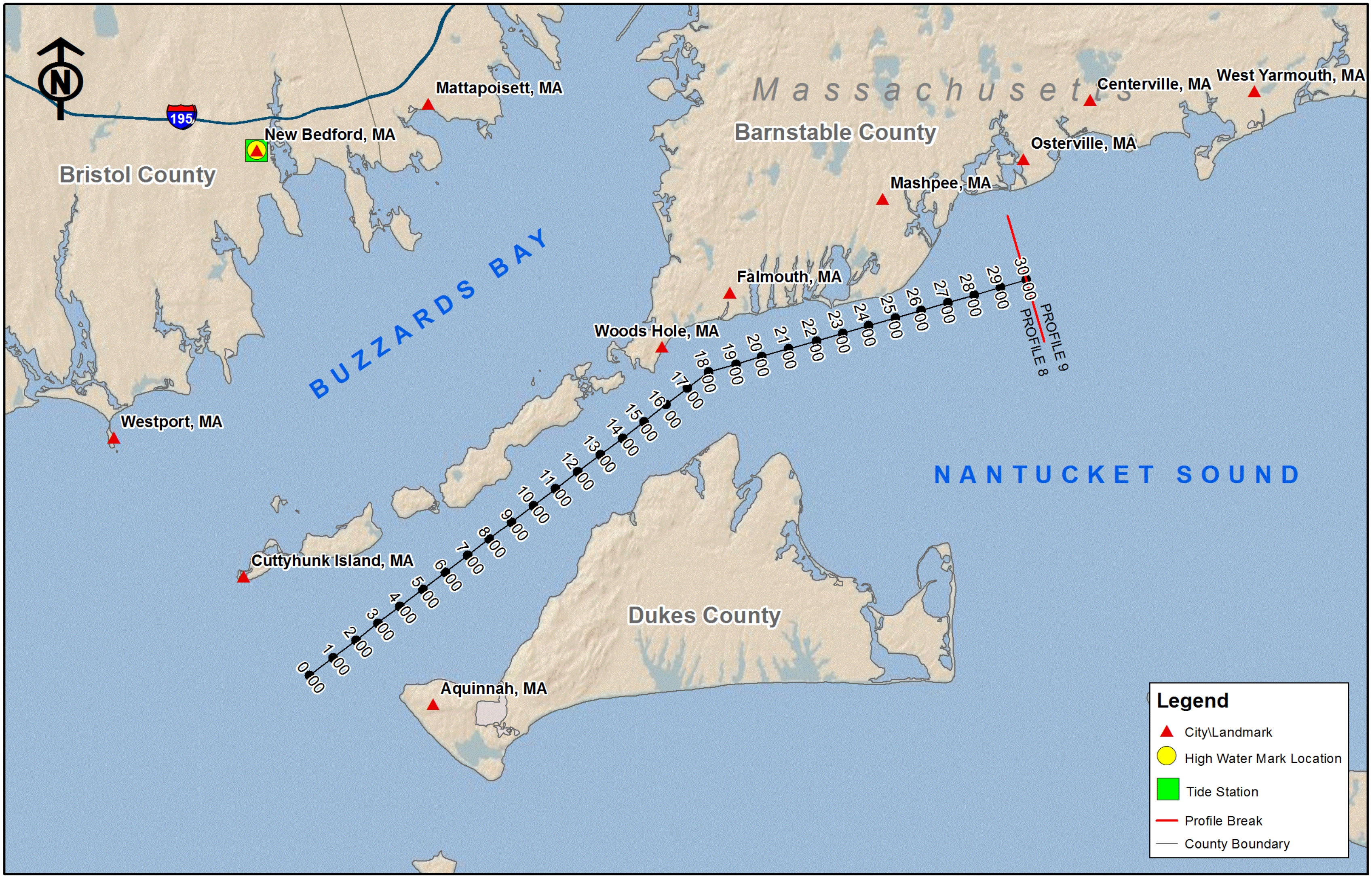


Figure B10. Base Map for Profile 8 from Cuttyhunk Island, MA to Mashpee, MA

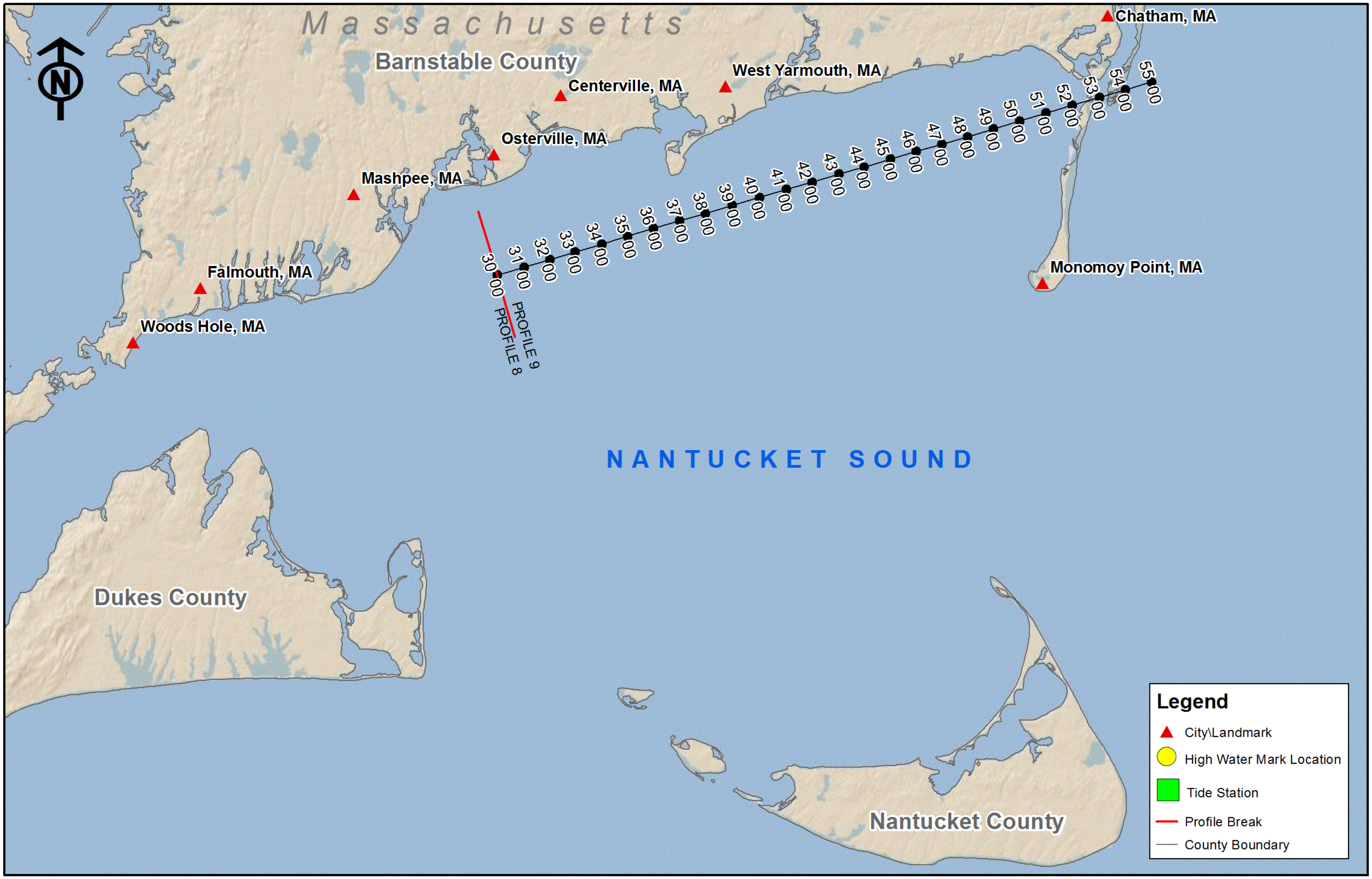


Figure B11. Base Map for Profile 9 from mile 30 to Chatham, MA

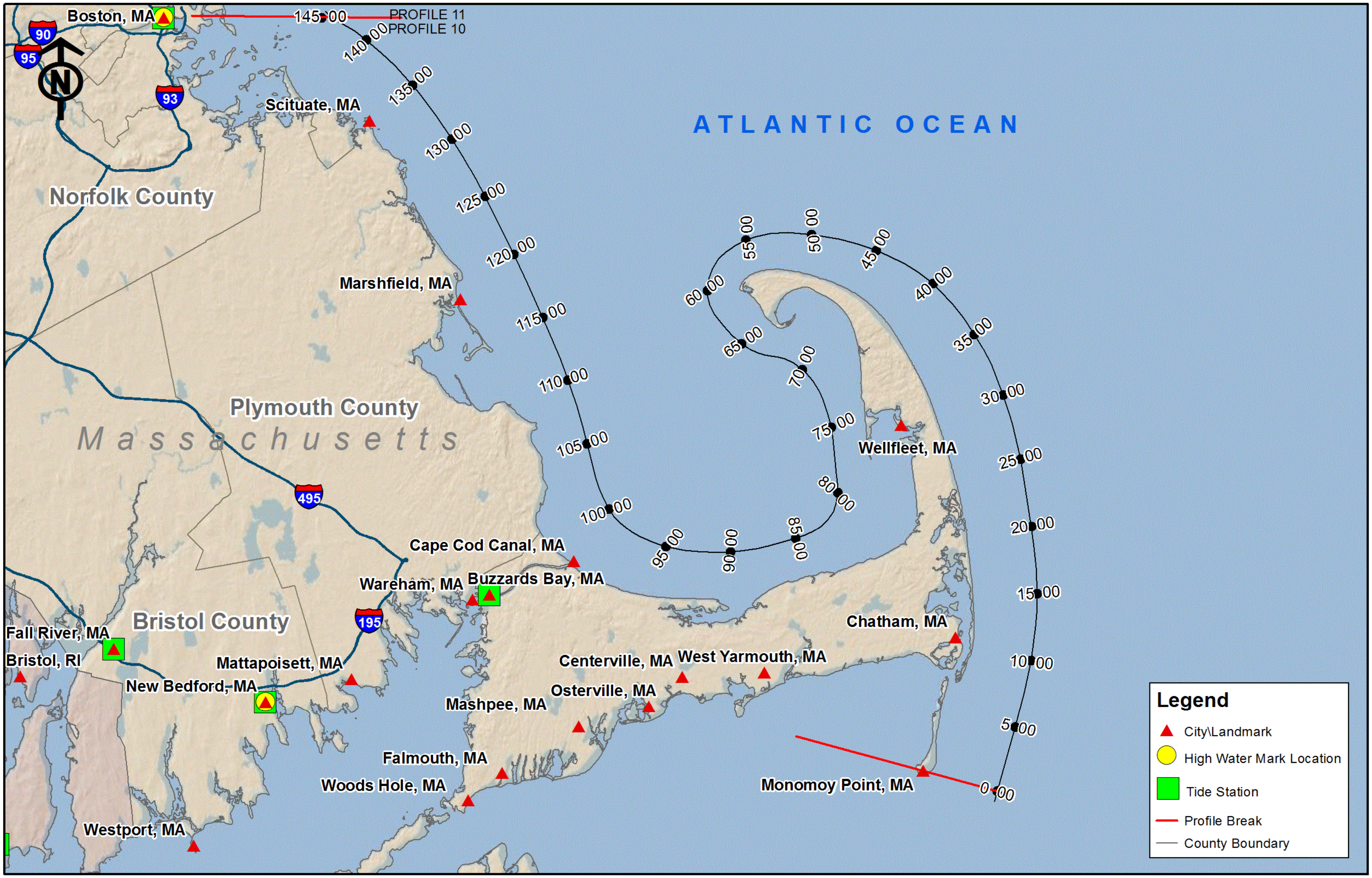


Figure B12. Base Map for Profile 10 from Monomoy Point, MA to Boston, MA

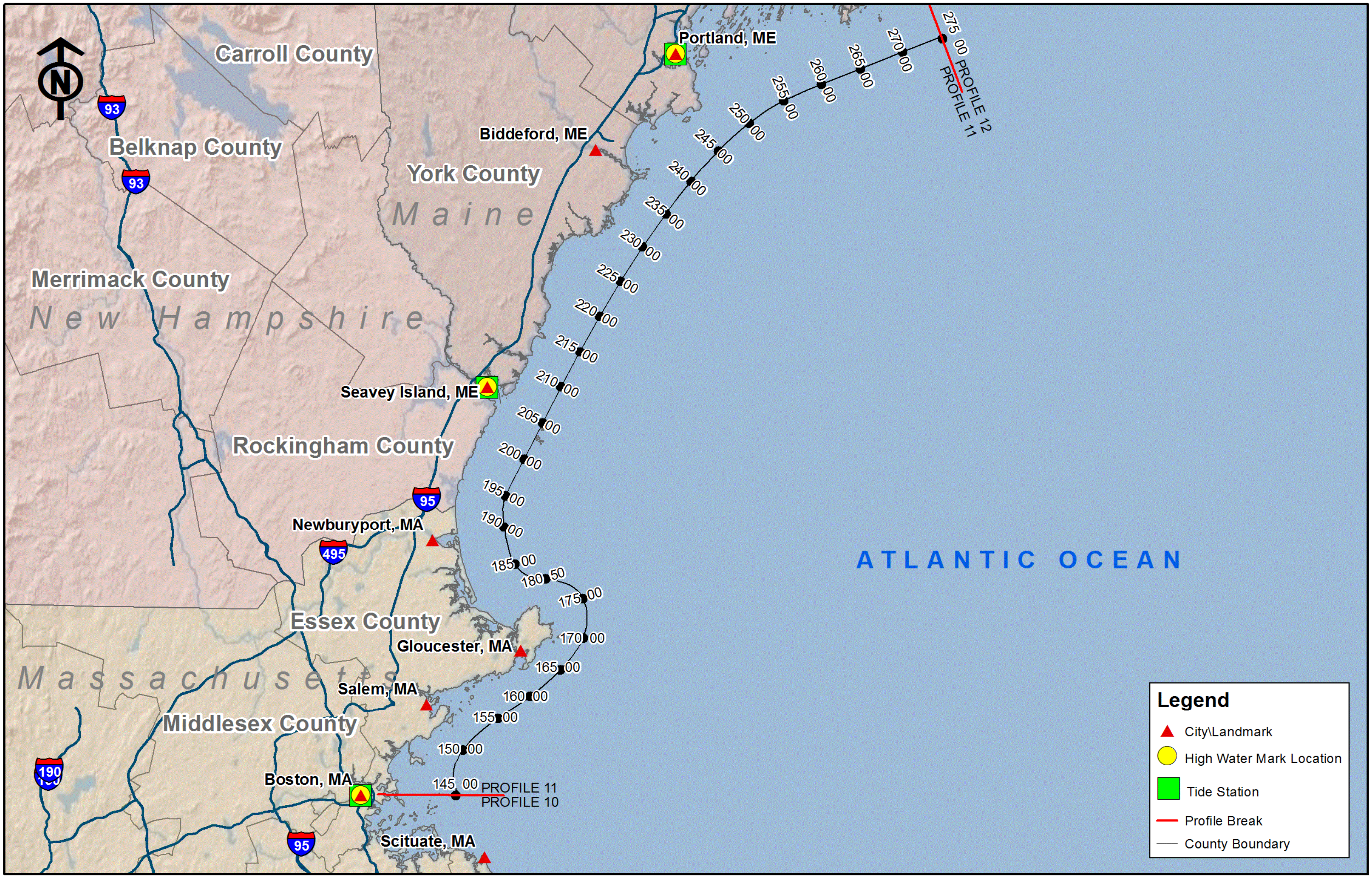


Figure B13. Base Map for Profile 11 from Boston, MA to mile 275

Figure B14. Base Map for Profile 12 from mile 275 to mile 370

Figure B15. Base Map for Profile 13 from mile 370 to Eastport, ME

Appendix C: Flood Profiles

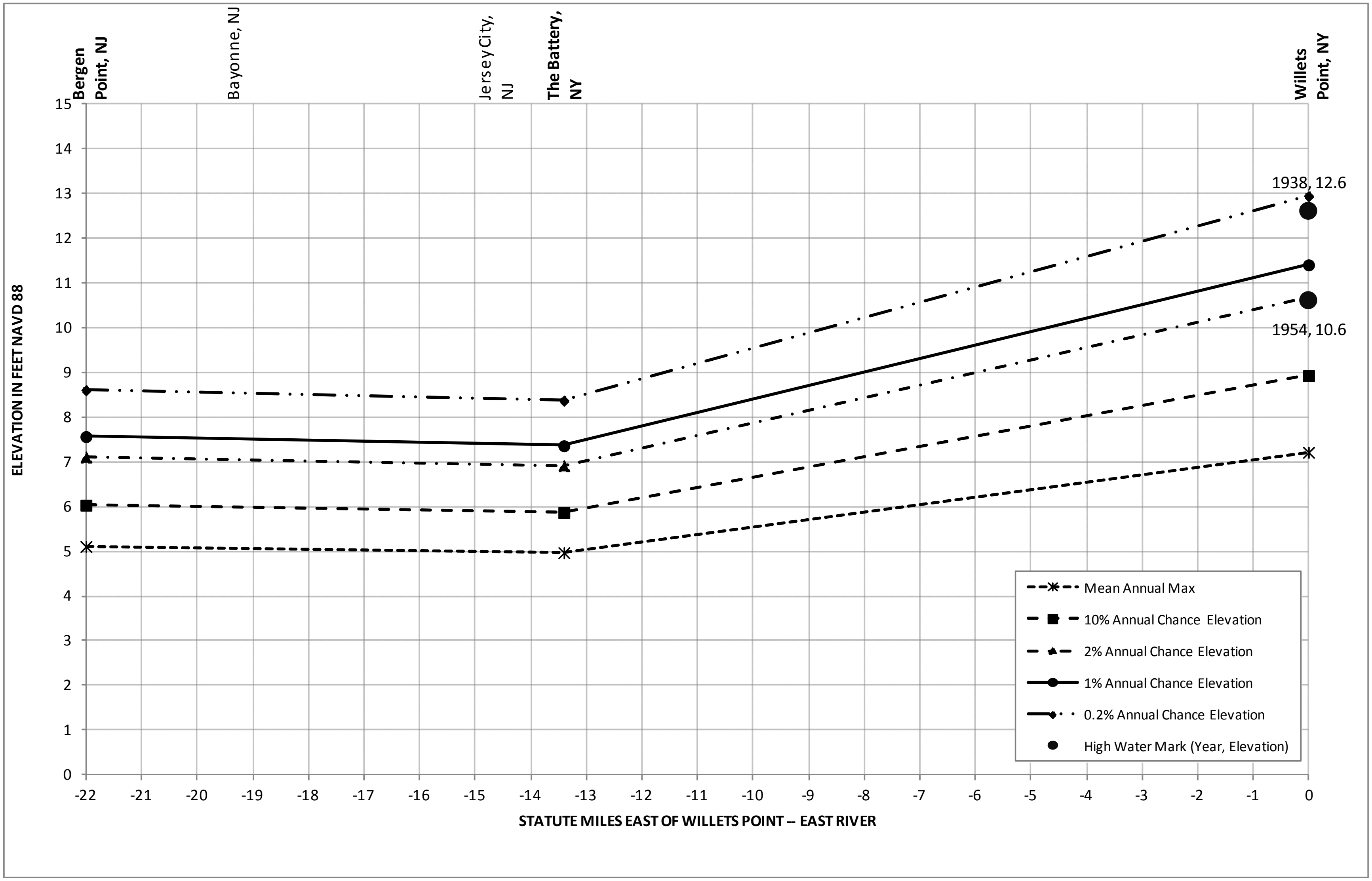


Figure C1. Tidal Flood Profile 1A from Bergen Point, NY to Willets Point, NY

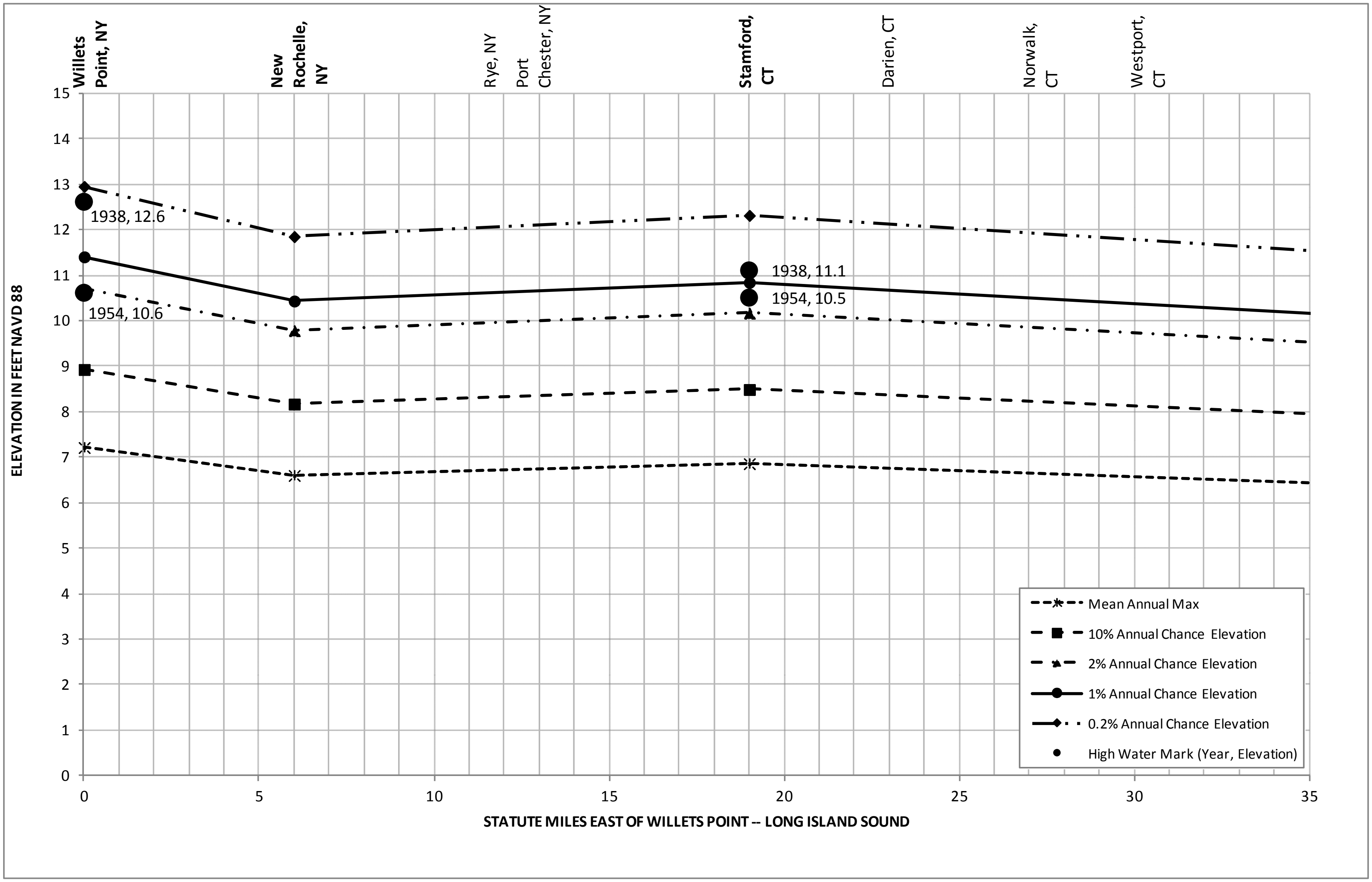


Figure C2. Tidal Flood Profile 1 from Willets Point, NY to mile 35

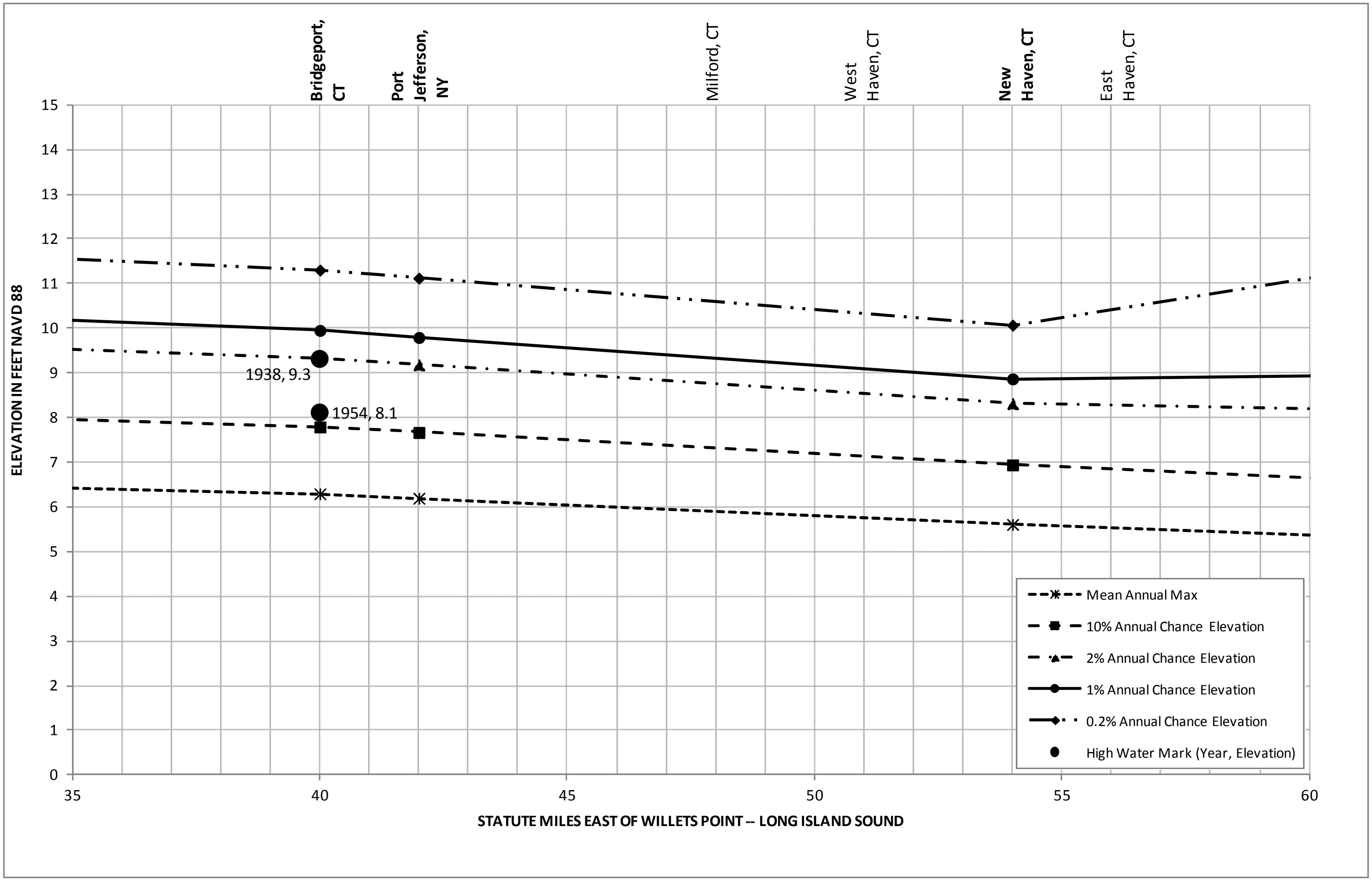


Figure C3. Tidal Flood Profile 2 from mile 35 to mile 60

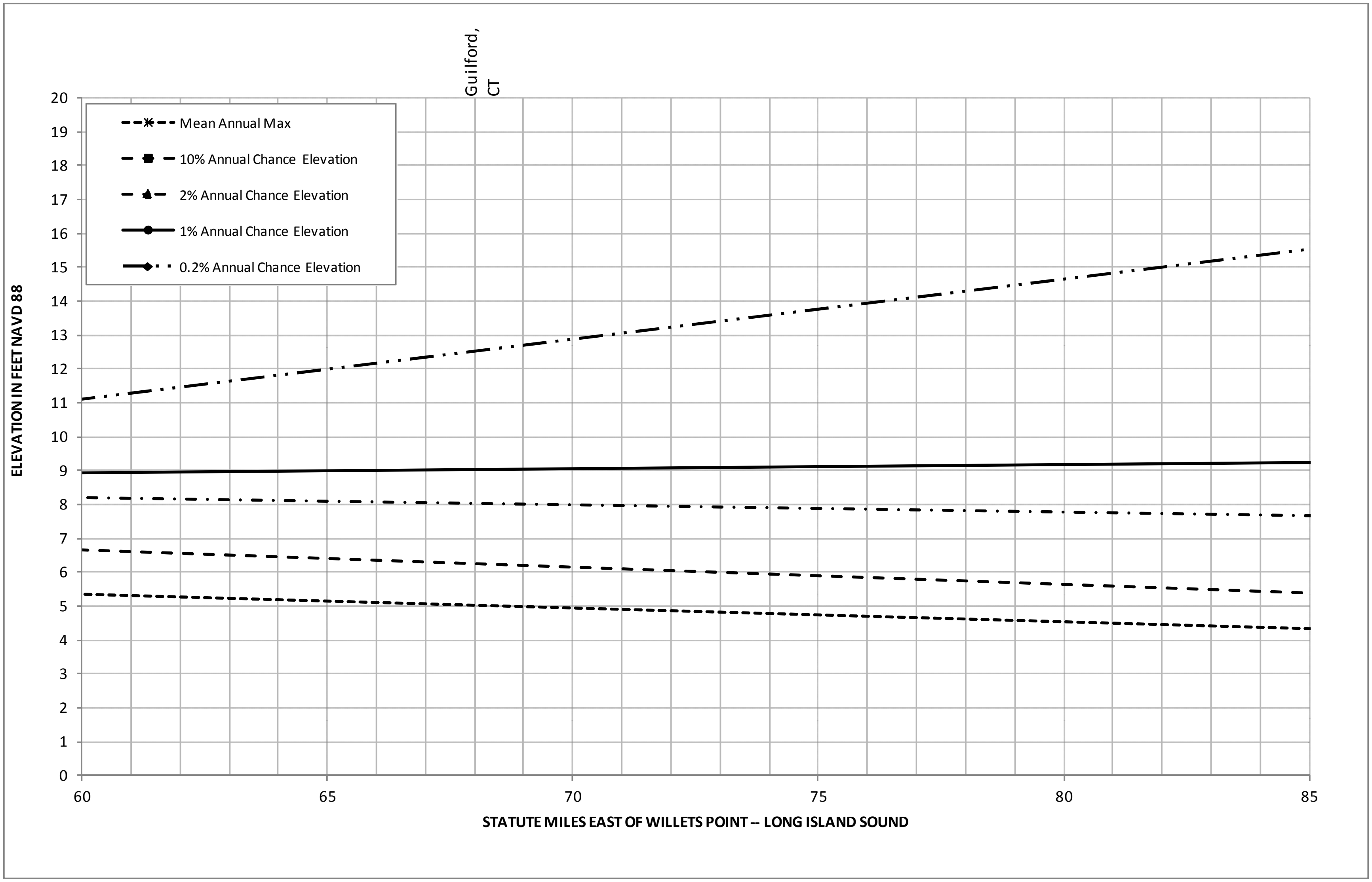


Figure C4. Tidal Flood Profile 3 from mile 60 to mile 85

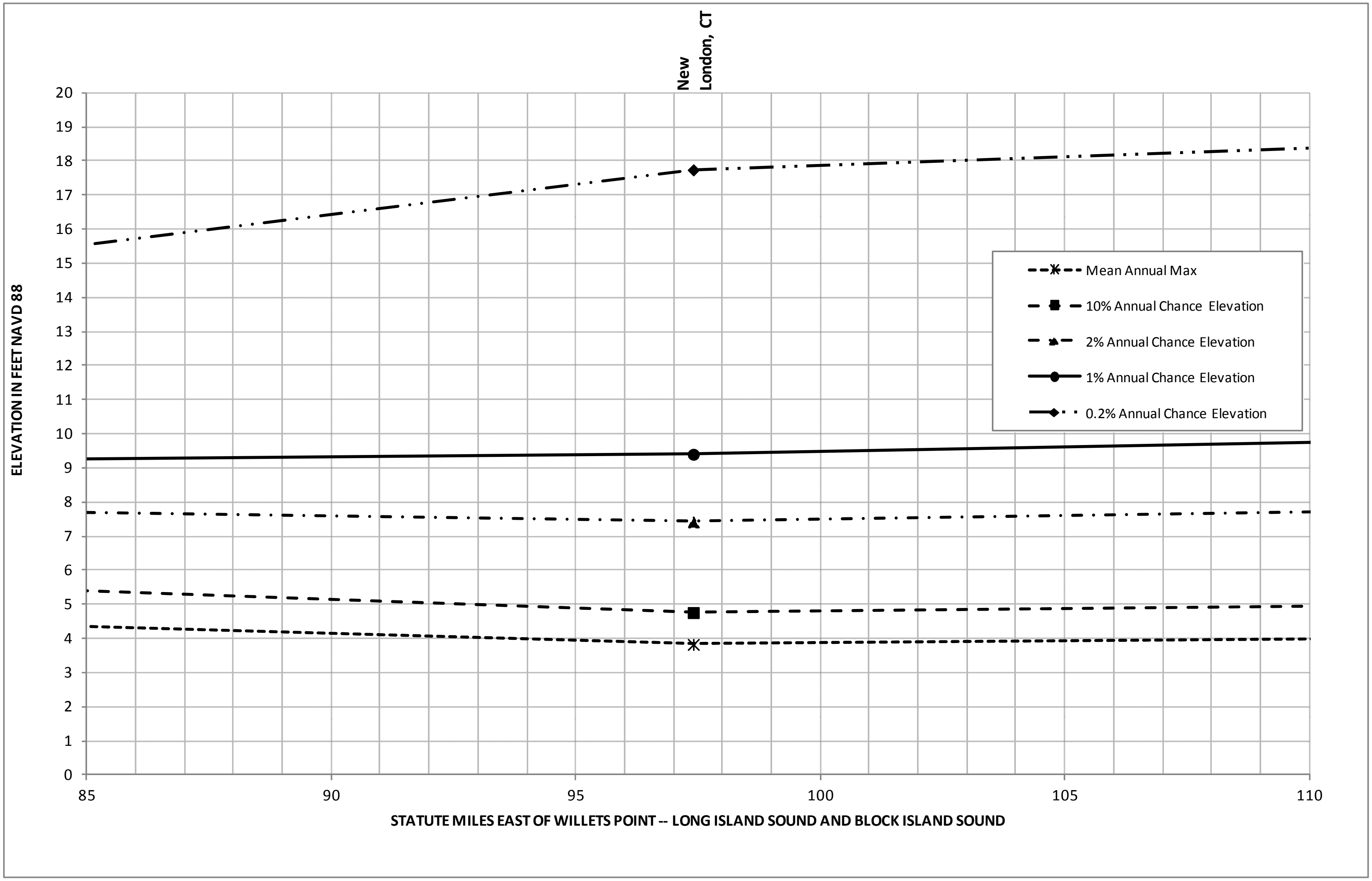


Figure C5. Tidal Flood Profile 4 from mile 85 to mile 110

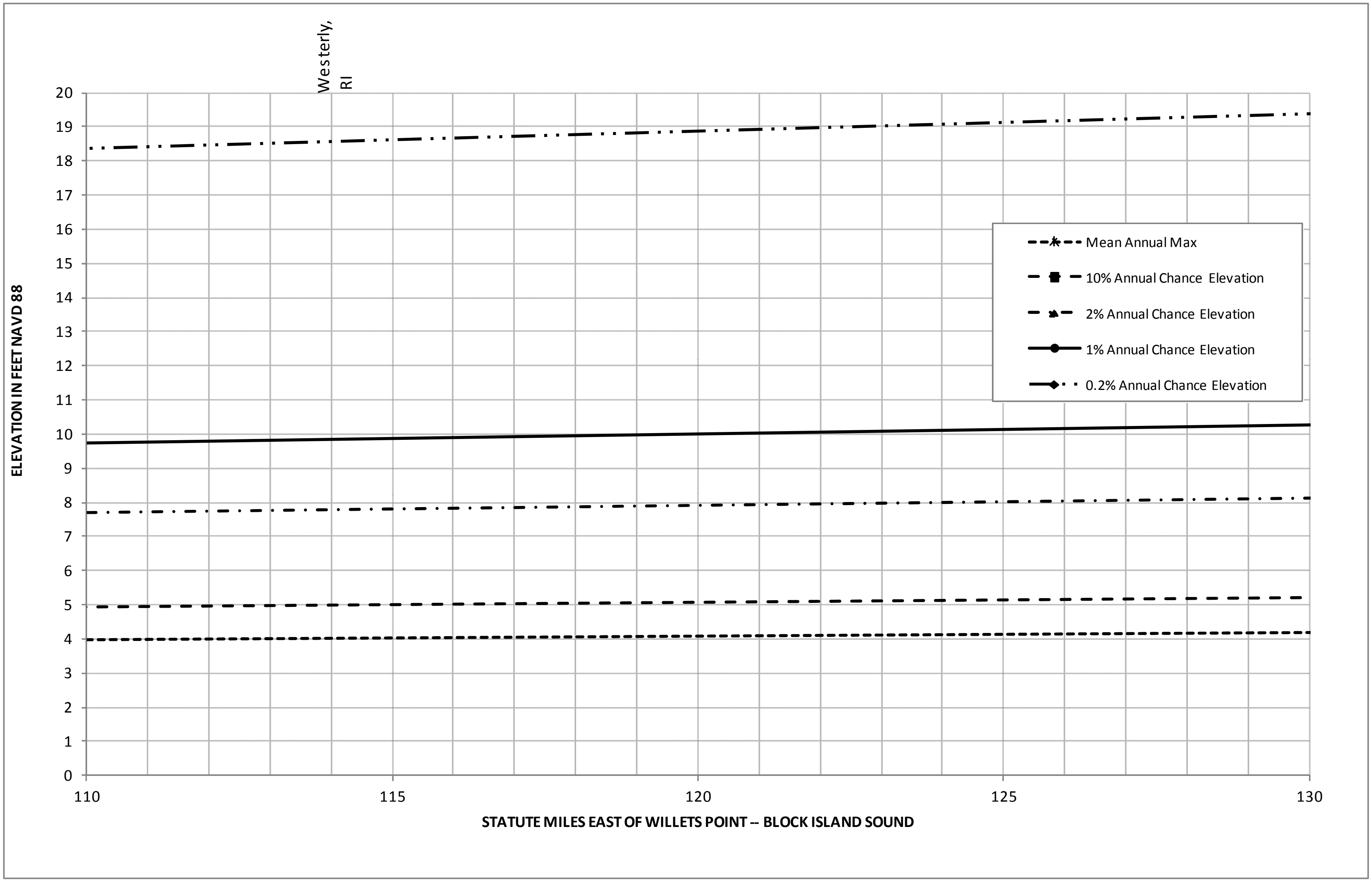


Figure C6. Tidal Flood Profile 5 from mile 110 to mile 130

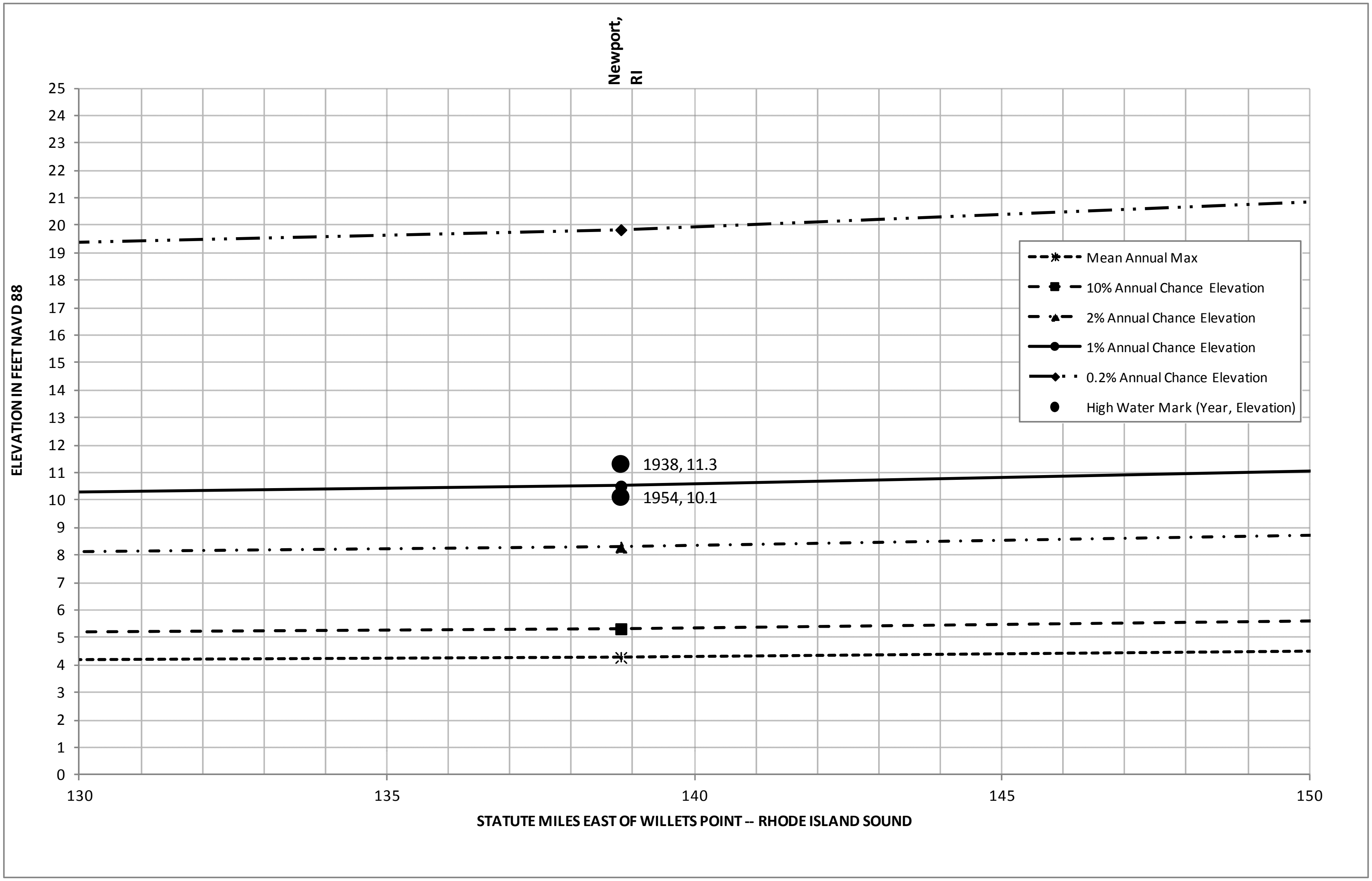


Figure C7. Tidal Flood Profile 6 from mile 130 to mile 150

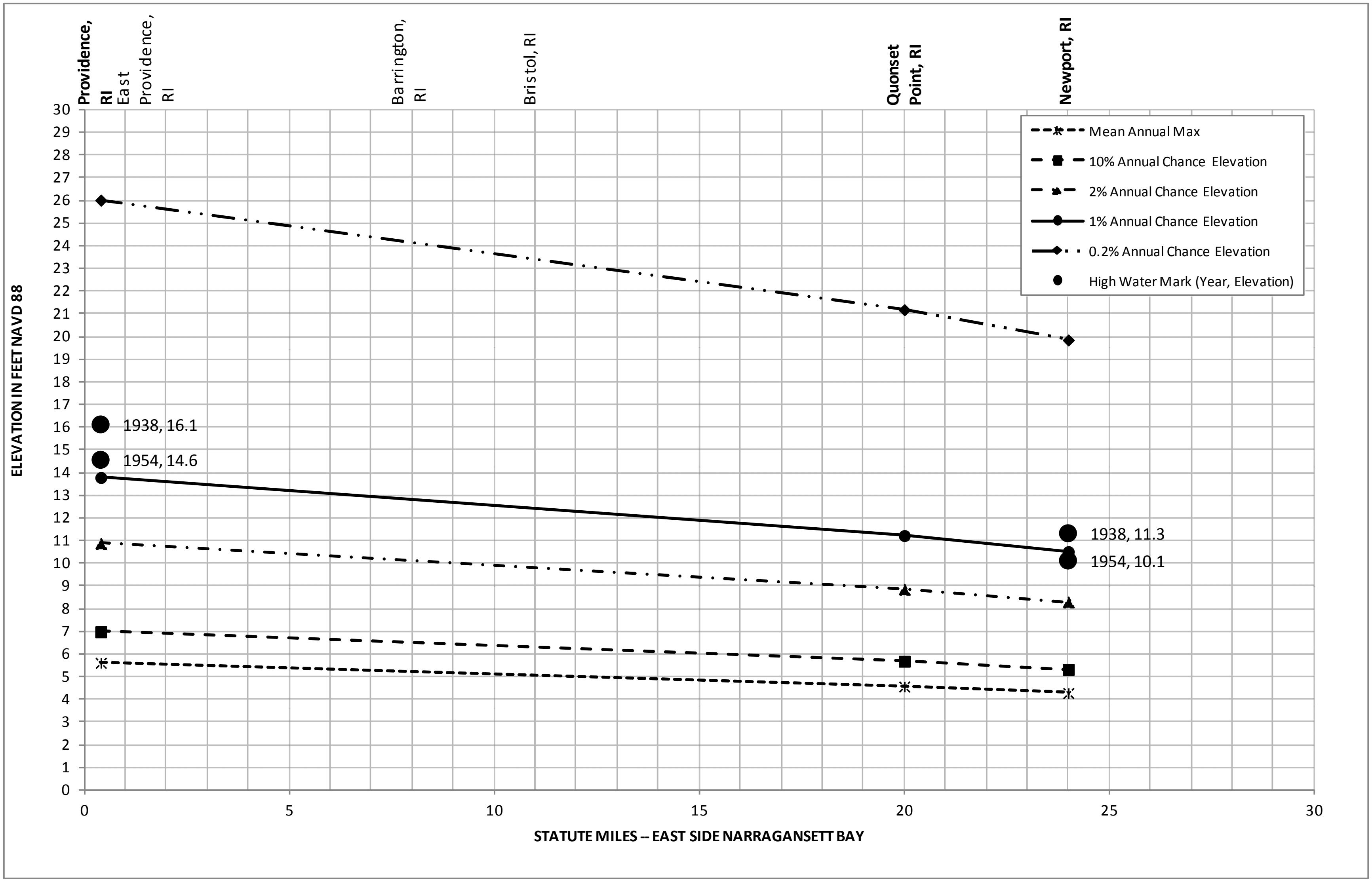


Figure C8. Tidal Flood Profile 6A from Providence, RI to Newport, RI

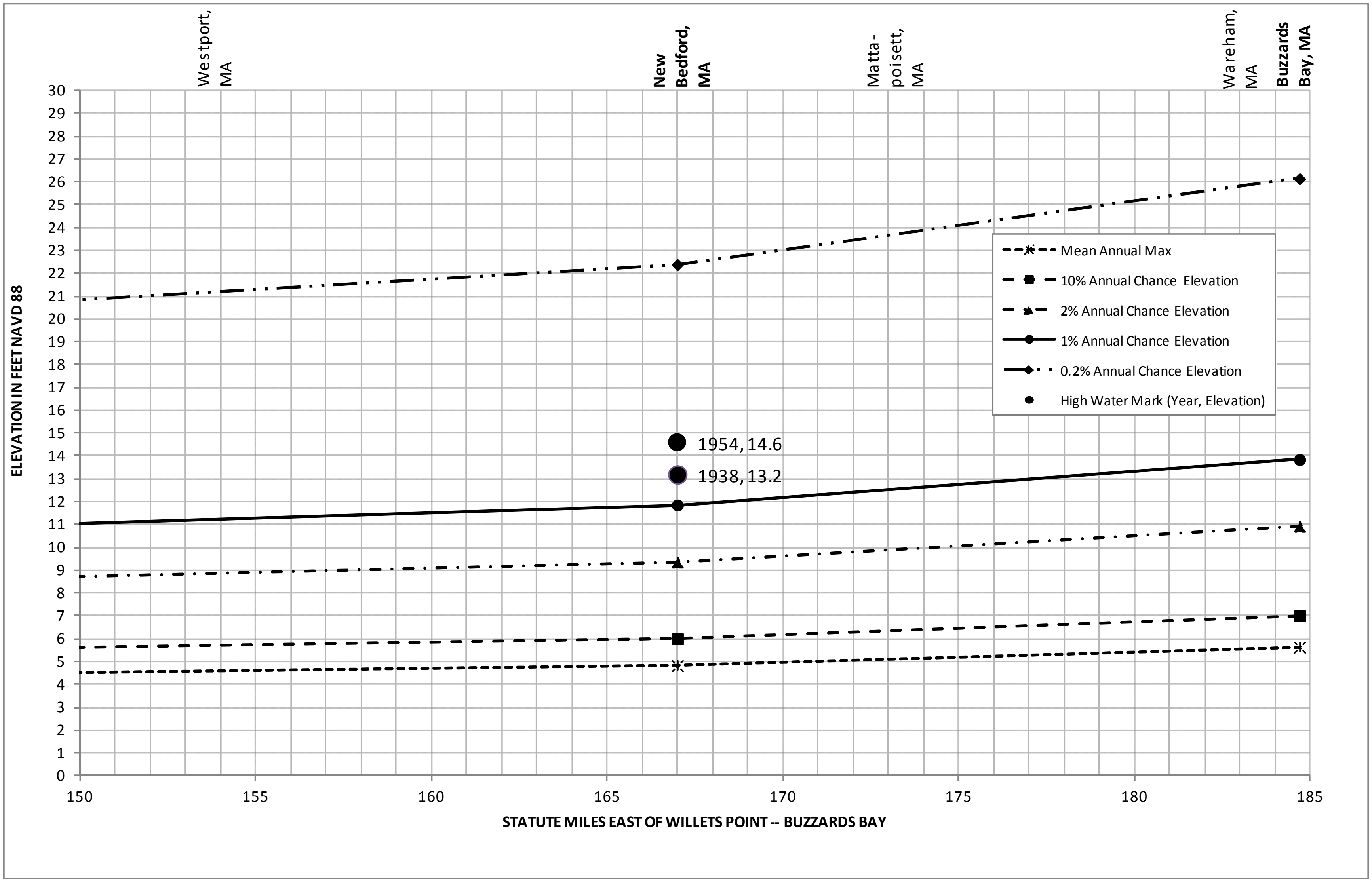
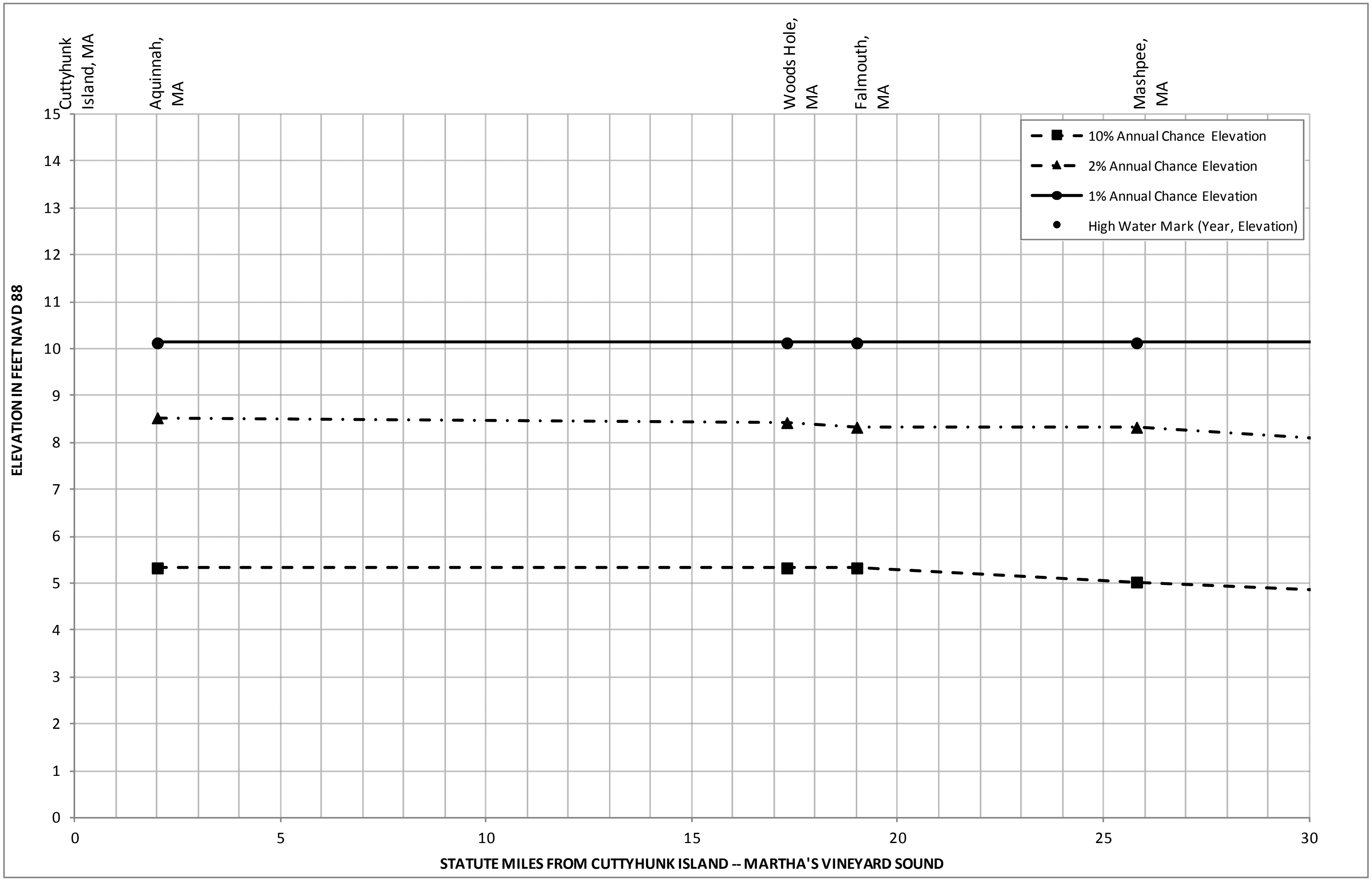
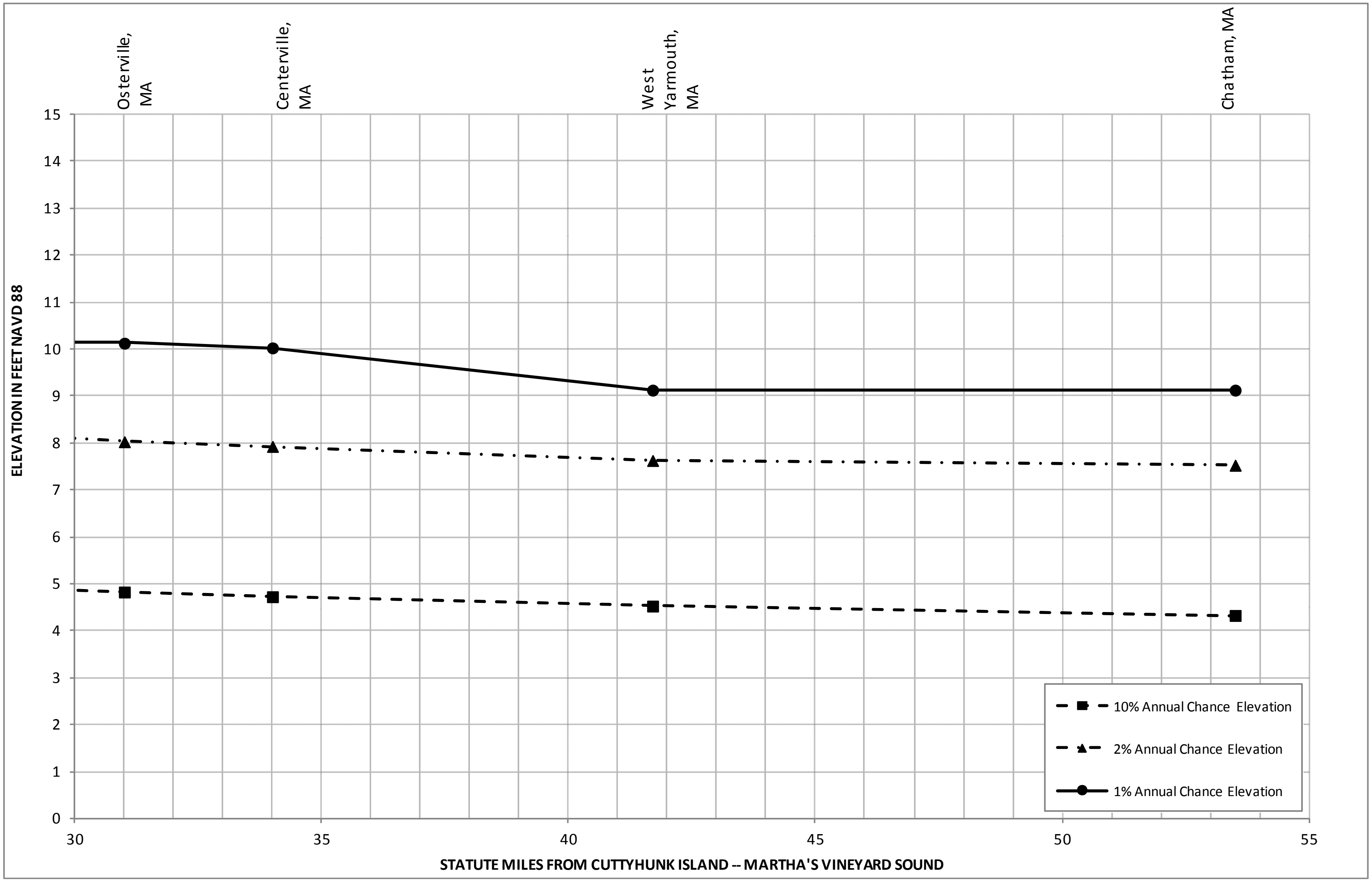


Figure C9. Tidal Flood Profile 7 from mile 150 to Buzzards Bay, MA



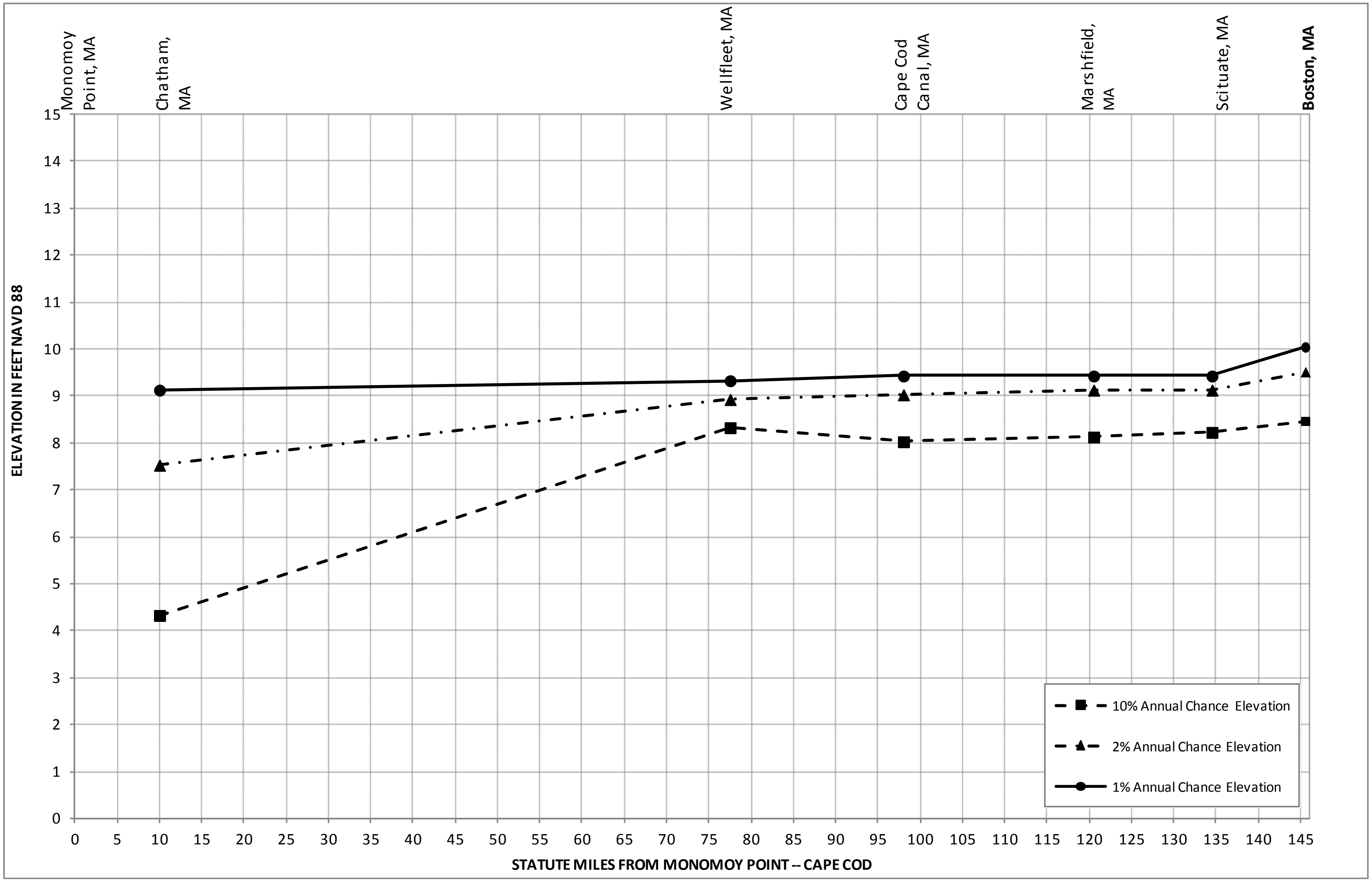
*Values for the x % annual chance elevation were obtained from the 1988 U.S. Army Corps Tidal Flood Profiles

Figure C10. Tidal Flood Profile 8 from Cuttyhunk Island, MA to Mashpee, MA



*Values for the x % annual chance elevation were obtained from the 1988 U.S. Army Corps Tidal Flood Profiles

Figure C11. Tidal Flood Profile 9 from mile 30 to Chatham, MA



*Values for the x % annual chance elevation were obtained from the 1988 U.S. Army Corps Tidal Flood Profiles
(For Boston, MA see Figure C13 for the Updated Tidal Flood Profile 11)

Figure C12. Tidal Flood Profile 10 from Monomoy Point, MA to Boston, MA

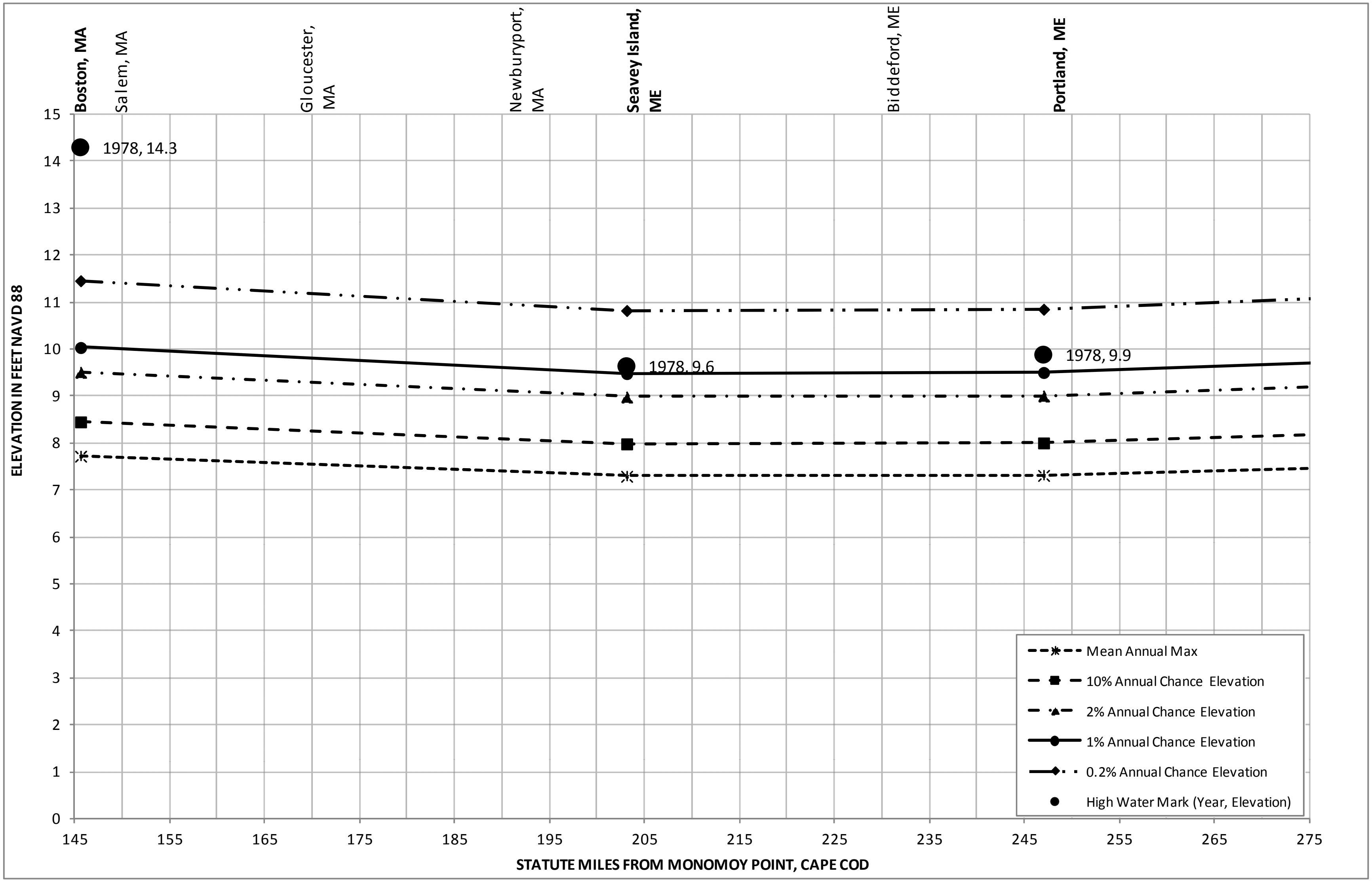


Figure C13. Tidal Flood Profile 11 from Boston, MA to mile 275

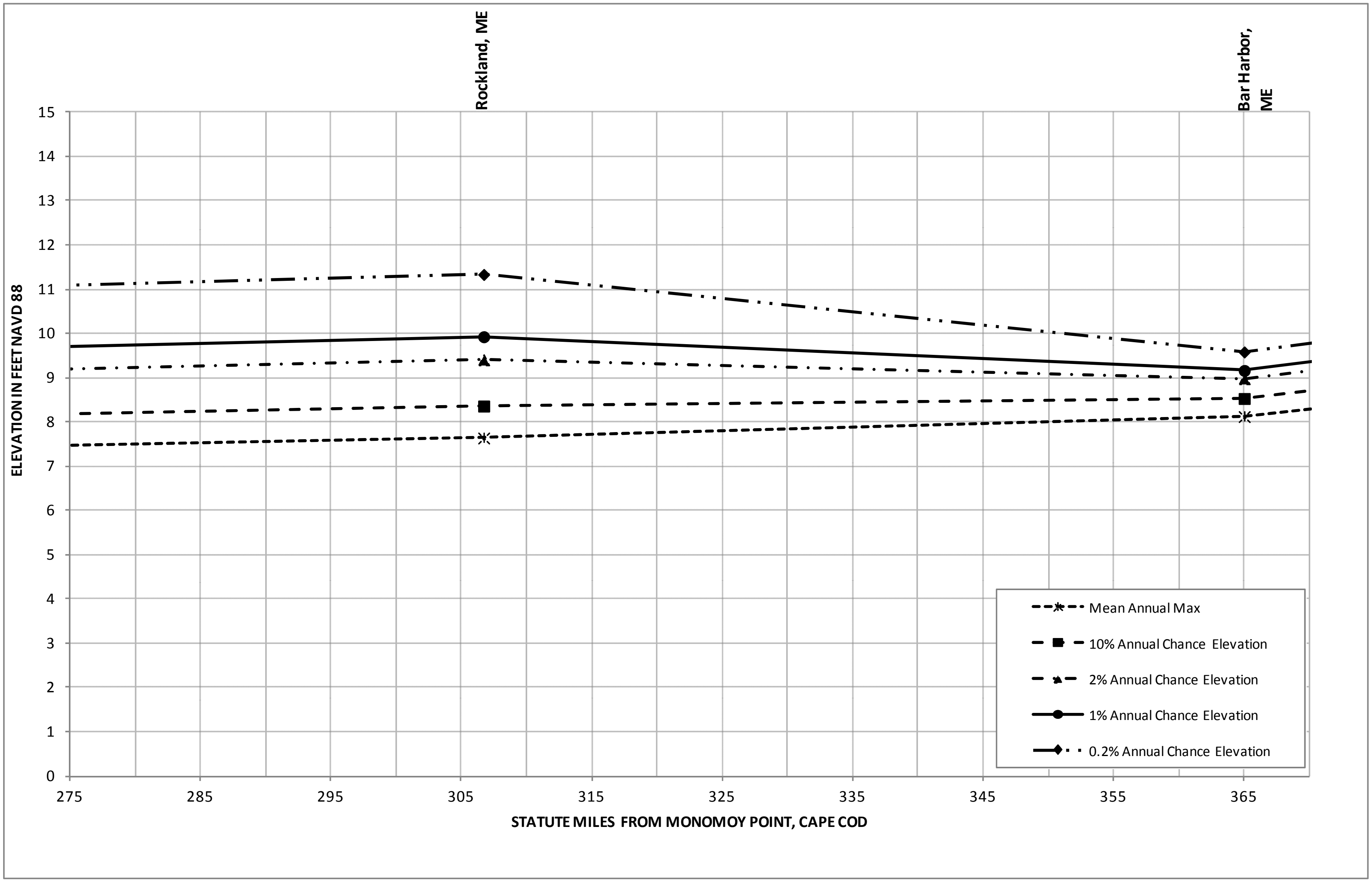


Figure C14. Tidal Flood Profile 12 from mile 275 to mile 370

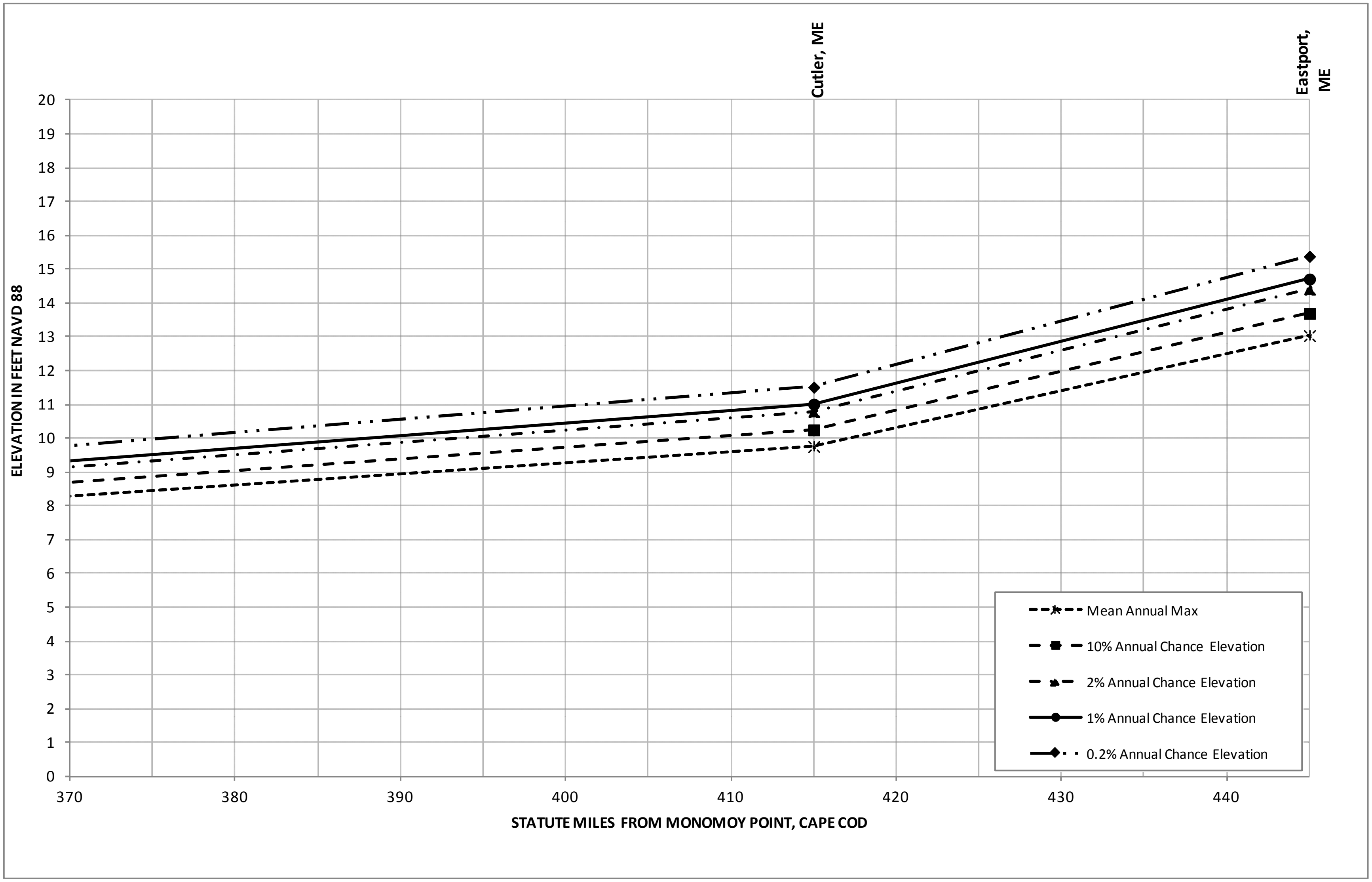


Figure C15. Tidal Flood Profile 13 from mile 370 to Eastport, ME