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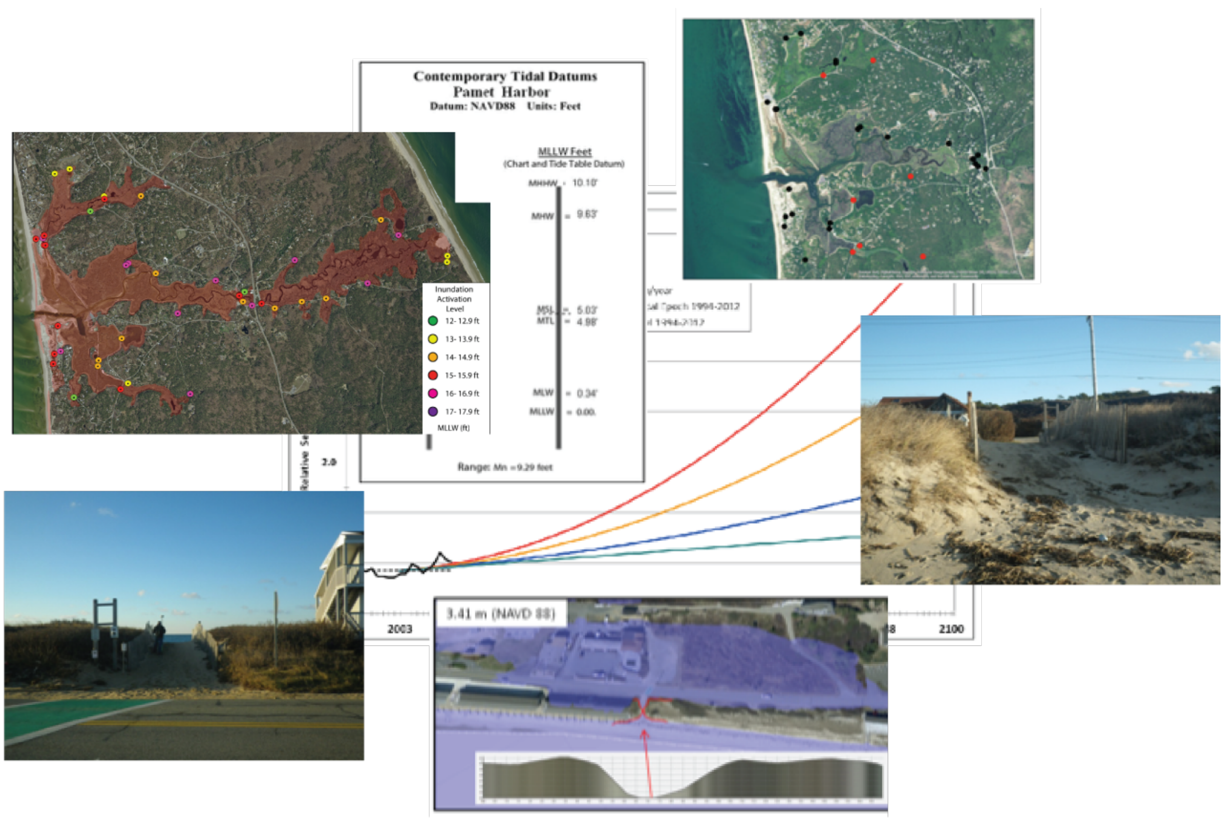
Mapping Inundation Pathways
to Provide Communities with Real-time Coastal Flood Forecasts:
A Pilot Project with the National Weather Service



A report prepared for the Town of Truro, Massachusetts
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EXECUTIVE SUMMARY

This project consisted of two phases, each the product of multiple components. Phase 1 focused on the development of inundation pathway maps and associated GIS data for the town of Truro. Phase 2 combined this data with similar information developed for the town of Provincetown in a previous CZM Resiliency Grant (FY2016) and, in collaboration with the Southern New England Weather Forecast Office of the National Weather Service (SNEWFO-NWS), the incorporation of these data into the NWS Coastal Flood Threat and Inundation Mapping webpage (http://www.weather.gov/box/coastal)

The methodology for the initial phase built on the successes and lessons learned from two CZM-funded pilot projects in Provincetown and Nantucket (FY16) and used the best available, high-resolution, three-dimensional spatial datasets to map inundation pathways for contemporary and future storm events. Field work necessary to verify and locate pathways accurately was conducted in December of 2016. A total of 41 pathways were identified in the initial desktop analysis and, after field surveys, 38 pathways were included in final GIS data layer for the project. Of the 38 final pathways, the location of 26 pathways (68%) were moved more than 1 m horizontally based on field surveys.

Working with the SNEWFO-NWS, Center for Coastal Studies (CCS) staff combined data from phase 1 with that developed for Provincetown and the resulting data set incorporated into the NWS Coastal Flood Threat and Inundation Mapping website. This website now combines NWS storm surge forecasts with accurate elevation data and storm tide pathway locations to provide municipalities with reliable information of the severity of coastal inundation events. These improved and easily accessible data will help communities to avoid, mitigate and prepare for these increasingly severe flooding events.

PROJECT BACKGROUND AND OVERVIEW

Low-lying coastal municipalities have historically been vulnerable to inundation associated with coastal storms and flooding. Rising sea levels further exacerbate flooding events by increasing the frequency and magnitude of nuisance flooding as well as superimposing those rises in sea level onto water elevations (storm surge, wave set up, etc.) during coastal storms. As evidenced by recent storms such as Katrina, Sandy, and the more local January 2015 Blizzard, management challenges are becoming more acute as current climate conditions appear to be producing higher intensity or longer duration storms accompanied by large storm surges that result in significant coastal flooding events.

With projections of continued climate change and accelerated sea level rise much attention has been focused on efforts that enhance adaptation and increase resiliency. Consensus among scientists indicates that sea levels are rising at an increasing rate. As shown in Figure 1, projections vary from a low of 0.15 meters (0.5 feet) to a high of 2 meters (>6 feet) by the end of this century. Such a broad range of projected sea level rise creates significant uncertainty for coastal managers faced with identifying potential hazards to, and vulnerabilities of property and infrastructure, prioritizing response actions, and demonstrating to local governments the need to undertake actions in spite of the unavoidable uncertainties inherent in century-scale sea level rise projection scenarios. Traditionally shorter planning horizons are not easily defined within the context of sea level rise discussions and effective response actions, implementable at the local level, are difficult to identify.

In addition to the issue of defining a suitable planning horizon, the ability of coastal managers to effectively and efficiently identify potential vulnerabilities and to educate residents and community leaders about the threats associated with coastal inundation has been severely limited by the lack of accurate elevation data at a scale that is usable at the community level. For example, Flood Insurance Rate Maps (FIRMS), produced by the Federal Emergency Management Agency (FEMA), have long been standard planning resources for coastal communities, however, these maps were intended to facilitate the determination of flood insurance rates and historically have lacked the topographic detail necessary for focused planning efforts. Until recently the accuracy of relatively low-cost elevation data has been appropriate only for general planning at regional scales and not appropriate for identifying inundation and flooding impacts over timeframes that meet the needs and budgets of most municipalities. Numerical modeling of storm surge, sea level rise, waves, or sediment transport (coastal erosion) can be effective for regional efforts to understand coastal evolution, but can also be cost prohibitive. Typically, the vertical uncertainties associated with these models are often too coarsely-scaled to inform site-specific decisions expected of local coastal managers.

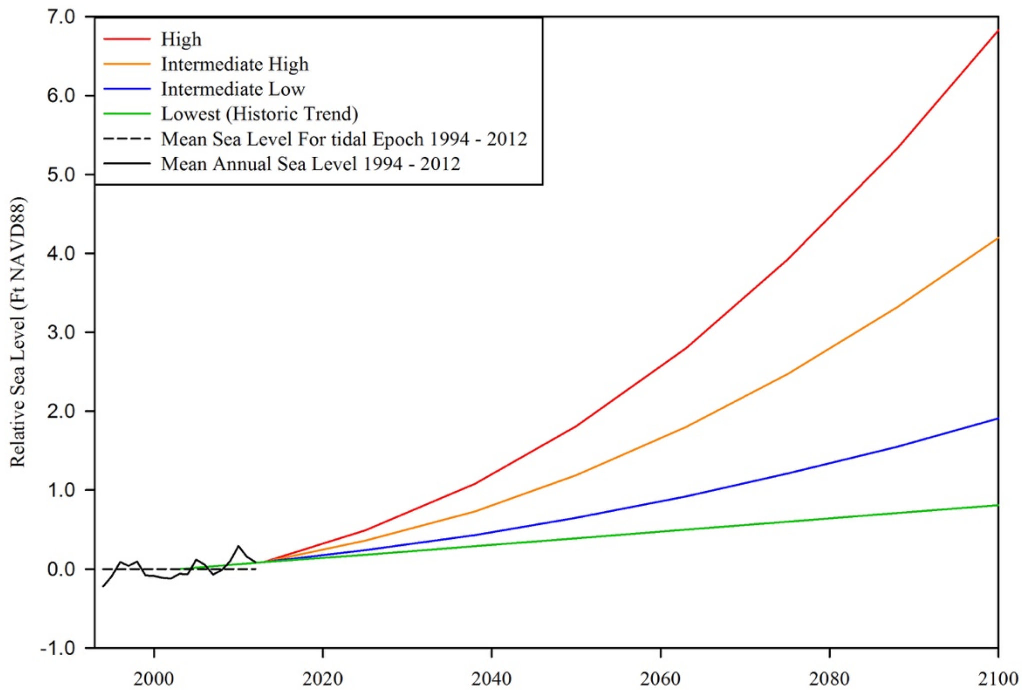

Figure 1. Relative sea level rise scenario estimates (in feet NAVD88) for Boston, MA. Modifed after Figure 5 in, Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning. Massachusetts Office of Coastal Zone Management, December 2013. Available at: http://www.mass.gov/eea/docs/czm/stormsmart/slr-guidance-2013.pdf.)

Based on the long range projections of sea level rise, and the catastrophic damages associated with large coastal storms, much attention is focused on long term strategies to reverse current climate trends and slow the rate of, or reverse sea level rise. Strategies to reduce Green House Gas emissions, to promote green energy, and to deal with rising temperatures, glacial ice melt, and thermal expansion of sea water over the next hundreds of years are being discussed and debated at the international, national, and state levels. Clearly the planning and costs to confront these issues are long term and capital intensive. Lost in these discussions are viable hazard planning strategies that can be adopted and implemented at the local level within the shorter planning horizons and financial means of local municipalities.

Recognizing the limited financial and technical resources of coastal communities and their unique geography, local responses and strategies to sea level rise and climate change need to operate effectively in the context of short-term planning horizons and frequently changing leadership. Specifically, short term planning efforts should identify actions or responses that are:

1) Achievable within an appropriate time frame (e.g., 30 years)
2) Implementable with current technology
3) Financially feasible
4) Politically viable (i.e., not extreme – e.g., wholesale retreat)
5) Adaptable to future scenarios
6) Focused on both infrastructure and natural resources

While sea level rise projections are clearly critical for longer term planning considerations, particularly for large scale efforts, actual past, present, and future storm tide elevations may provide a more effective means of characterizing local coastal hazard vulnerabilities for community level planning actions. Figure 2 depicts estimates of historical storm tide elevations for the Boston area (an easterly facing shore) for various storms for the 17th - 21st centuries. The current projections for the highest sea level rise scenario and the NOAA regression rate scenario based on current tide gauge data obtained from the Boston tide gauge are shown through the year 2100.

Not surprisingly, the graph illustrates that in recent history the storm of record for Boston and areas to the north of Cape Cod was the "Blizzard of '78". Significantly, this plot indicates that the storm tides and associated flooding for Boston reached an elevation of approximately 1 meter (~3 feet) above that of the highest sea level rise projection for the year 2100. The plot further reveals that earlier estimates of storm tide heights have probably equaled or exceeded the 1978 maximum numerous times since the 17th century.

Using historical data to identify potential storm tide heights, coastal flooding extents, and areas of potential vulnerability provides several benefits to coastal communities. First, using actual historical storm tides data to identify coastal hazard vulnerabilities increases the certainty of planning efforts by removing sea level rise and the disparity of projections (Figure 1) from the discussion of the most appropriate sea level rise elevation upon which to base short term planning responses. Sea level rise notwithstanding, storm tides of significant magnitude have been experienced in the past and will continue to be experienced again in the future. Second, storms of record provide an accurate, actual (i.e., indisputable) reference elevation that towns can plan for when history repeats itself. Finally, as discussed below, using emerging data gathering technologies to identify inundation impacts, will yield valuable information that can be used by coastal communities to plan and implement ground level strategy in response to sea level rise.

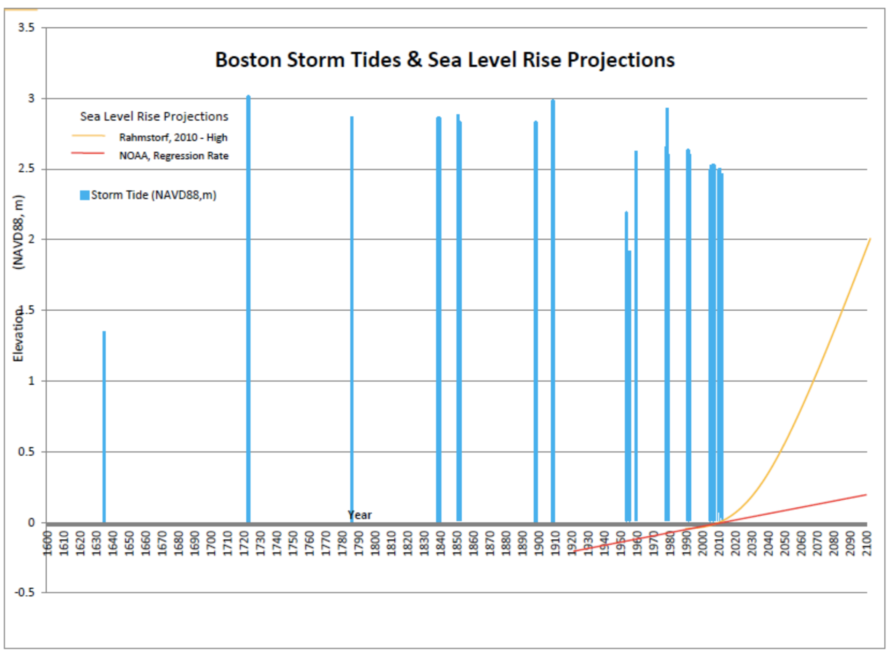

Figure 2. Historical Storm tides and sea level rise.

Accurate Elevation Data, Record Inundations and Potential Pathways

Over the past ten years, **li**ght **d**etection **a**nd **r**anging (lidar) surveys have emerged as a cost-effective and constantly improving source of coastal elevation data. Covering broad geographic areas with horizontal accuracies typically on the order of 3 meters (~10 feet) and vertical accuracies on the order of 15-30 cm (0.5-1.0 feet), this relatively high resolution topographic information is a valuable initial resource for coastal managers developing inundation scenarios that can be used to begin to visualize threats associated with coastal storms. Despite improvements in vertical accuracy, the use of lidar alone to map areas of storm vulnerability and to develop community response strategies, however, has been limited. Recognizing data limitations, current guidelines for inundation modeling using lidar elevation data sets with vertical accuracies of 15 cm (0.5 feet) recommend analyses be performed at increments of 58.8 cm (~2.0 feet), a resolution clearly too coarse for the development of short-term, local action items. This base level information, however, when supplemented with area-specific high resolution elevation data to reduce uncertainties, can be used to identify and prioritize potential coastal hazards at the local level in a cost-effective manner.

For this project, recently available elevation data (the 2013-14 USGS "Sandy Project" lidar data) and state-of- the-art software (Fledermaus™) was used as the basis for the initial screening to identify potential IPs for further analysis. These pathways are subsequently investigated in the field using centimeter-scale GPS survey equipment to verify its horizontal and vertical location. Continuing to use the lidar as a base map to be verified in the field, this process is repeated as an iterative sensitivity analysis to identify threshold pathways associated with key historical storms and higher or lower storm- tide elevations to provide a foundation for local action planning actions.

A primary goal of this pilot project is to supplement the lidar base map with more accurate GPS survey data to map the routes through which '*storm tides'* (discussed in more detail below) will pass, threatening vulnerable areas of the town with inundation of varying depths. For purposes of this project, these locations have been termed 'inundation pathways'.

Generally, inundation pathways, by virtue of their elevation relative to the elevation of the storm tide, provide a direct connection between coastal waters and low lying inland areas. Examples of pathways that may serve as direct hydraulic connections include: low spots in built environment (e.g., roads, walkways, dikes, seawalls, etc.); and low spots in natural topography (e.g. low lying earthen berms, barrier beaches, and dune systems susceptible to erosion and breaching). Low-lying infrastructure can also serve as unintended conduits (e.g., stormwater systems, sanitary sewers, electrical/utility conduits), however, analysis of potential conduit hydraulics should be evaluated by a qualified engineer to accurately assess potential vulnerabilities.

As discussed above, to minimize the uncertainties associated with sea level rise projections and to provide information that is reliable within a 30-year planning horizon, this study relies on documented elevation records associated with the flood elevations of actual coastal storm tides. Research of available records and studies indicates that, as for Boston, the storm of record for Provincetown would appear to be the Blizzard of '78. The associated storm tide was recorded by Dr. Graham S. Giese of the Center for Coastal Studies in Provincetown and found to be 9.36 feet (2.85 meters) referenced to the North American Vertical Datum of 1988 (NAVD88). This elevation represents an actual storm tide elevation that is approximately 5 feet above contemporary mean higher high water (MHHW) and approximately 11 feet above contemporary mean sea level (MSL) for Provincetown harbor. As discussed below, based on actual tide readings obtained by CCS for Pamet Harbor, the Blizzard of '78 can also be used as the storm of record for the Cape Cod Bay Shores of Truro within the context of this study.

METHODS

Characterizing Coastal Inundation

As relative sea level continues to rise, many coastal communities are beginning to experience occasional minor flooding with the higher tides of the month (e.g., spring tides). Often referred to as *nuisance flooding* since it is rarely associated with dramatic building and property damage, this type of flooding is becoming more frequent resulting in chronic impacts that include overwhelmed drainage systems, frequent road closures, and the general deterioration of infrastructure not designed to withstand saltwater immersion (Sweet, *et. al.,* 2014).

In addition to minor monthly inundation, many coastal communities are beginning to experience damaging flooding associated with relatively short duration, high intensity coastal storms. The term *storm tide* refers to the water level experienced during a storm event resulting from the combination of the rise in water level from the *storm surge* on top of the astronomical (predicted) tide level. Storm tides are referenced to datums, either to geodetic datums (e.g., NAVD88 or NGVD29) or to local tidal datums (e.g., mean lower low water (MLLW)). *Storm surge* refers to the increase in water level associated with the presence of a coastal storm. As the difference between the actual level of the storm tide and the predicted tide height, *storm surges* are not referenced to a datum.

In addition to storm surge magnitude, the time at which the maximum surge occurs relative to the stage of the astronomical tide is a critical component of the maximum storm tide elevation experienced during any particular storm. The significance of this relationship is illustrated by the following example.

The storm of record for the Boston Tide Gauge (#8443970) occurred on February 7, 1978 with a maximum storm tide elevation of 9.59ft NAVD88. Occurring at approximately the time of the predicted or astronomical high tide, the storm surge was approximately 3.5 feet. By comparison, the maximum storm tide elevation experienced during the blizzard of January 27, 2015 was 8.16ft NAVD88. Occurring shortly after the astronomical high tide, this elevation resulted from the combination of an astronomical tide height of 4.79ft NAVD88 and a storm surge of 3.37 feet. Significantly the maximum storm surge for this event was observed to be 4.5 feet, however, because it occurred close to the time of low water the corresponding storm tide elevation was only -1.1ft NAVD88. Had the maximum storm surge occurred approximately 6 hours earlier at the time of the astronomical high tide, the resulting storm tide elevation would have been 9.2ft NAVD88, approximately 5 inches below the elevation of the storm of record.

Recognizing the significance of not only the magnitude of the predicted storm surge but the time it will occur relative to the stage of the tide, the National Weather Service (NWS) in Taunton, MA maintains an informative website that estimates storm surge and total water level at various Massachusetts locations (http://www.weather.gov/box/coastal) as coastal storms approach New England. This project builds on the lessons learned from the Nantucket and Provincetown CZM Resiliency projects and leverages the work by the NWS Taunton office to complete a pilot project that incorporates accurately mapped storm tide pathways into the NWS coastal storm surge website. This project reduces the uncertainty and improves the utility of storm tide inundation forecasts for Truro and Provincetown, two towns located in the northeast corner of Cape Cod Bay.

Creating a Tidal Profile for Truro, Massachusetts

The effects of storm tides on coastal communities are dependent on many factors. These include the landscape setting of the community (e.g., east facing v. south facing shores); the elevations of astronomical tides (e.g., the elevation of mean high water (MHW) in Boston Harbor is 4.31 feet NAVD88 v. the elevation of mean high water for Woods Hole is 0.56ft NAVD88); general characteristics of astronomical tides (e.g., the average range (MHW minus MLW) of Boston Harbor tides is 9.49 feet while that of Woods Hole tides is only 1.79 feet); topography (e.g., the elevation of the land relative to the community tidal profile); nearshore bathymetry (e.g., the deeper the water relative to shore, the greater the potential wave energy); topographic relief (i.e., a measure of the flatness or steepness of the land with flatter areas more sensitive to small changes in water levels); the nature of coastal landforms (e.g., the rock shorelines of the North shore v. the dynamic sandy shorelines of Cape Cod); and the vertical relationship between historical community development and adjacent water levels (e.g., development in Boston began in the early 17th century with the water levels at that time influencing the elevation of not only pile supported structures but large scale land-making – filling – efforts).

As discussed in the Methods section of this report, with such variation in physical characteristics, the initial step in the identification of storm tide pathways for a community is the development of a datum-referenced tidal profile that characterizes average tidal heights, nuisance flooding, and storm tides. In addition to the more common tidal datums of mean high water springs (MHWS), mean higher high water (MHHW), mean high water (MHW), and mean sea level (MSL), to be useful this tidal profile includes datum referenced storm tides of the past, including the elevation of the maximum storm tide experienced (i.e., the storm of record) for the area. In light of the increasing sea level elevations, an estimate of potential future storm tides is provided by adding three feet to the storm of record (Zervas, 2009).

On June 1, 2016, the Center for Coastal Studies installed a datum referenced (NAVD88, meters) HOBO™ U20 water level logger in Pamet Harbor located on the westerly shore of Truro, MA. (Legare, 2016). Part of a larger Cape Cod National Seashore Project, tidal elevations were collected every six minutes from June 1 to June 30, 2016. At the end of the collection period, the highest high water (HHW), lowest high water (LHW), highest low water (HLW), and lowest low water (LLW) daily values were identified and monthly averages for these values calculated.

Following standard NOAA-COOP procedures, these values were used to translate one month of datum-referenced tidal observations into 1983 – 2001 National Tidal Datum Epoch (NTDE) values for direct comparison with NOAA stations #8443970 (Boston Harbor) and #8446121 (Provincetown Harbor) (NOAA, 2003).

An NTDE represents a specific 19-year period adopted by the National Ocean Service (NOS) as the official period over which tide observations are taken and reduced to obtain mean elevations of tidal datums (e.g., mean lower low water, etc.) at various tidal stations along the East, West and Gulf Coasts (Gill & Schultz,. 2001). A nineteen year period is used to compute tidal datums because it is the closest full year to the 18.6-year nodal cycle, the period required for the regression of the moon's nodes to complete a circuit of 360 degrees of longitude (Gill & Schultz, 2001; NOAA, 2003). The NTDE is used as the fixed period of time for the determination of tidal datums because it includes all significant tidal periods, is long enough to average out the local meteorological and seasonal temperature effects on sea level, and by specifying the NTDE, a uniform approach is applied to the tidal datums for all stations.

The present NTDE is for the period 1983-2001 and as with all epochs, tidal data is reviewed annually for possible revision. Regardless of any annual changes, NTDE values or each tidal station are actively reviewed for revision approximately every 25 years (NOAA, 2003). Since for comparative and reporting purposes tidal datums are specified with regard to the current 19 year NTDE, tidal datums computed from month long tidal readings for Pamet Harbor were translated to the 1983-2001 NTDE. This was achieved by using the *Modified-Range Ratio Method* as described in NOAA, 2003.

NOAA tide station #8443970 located in Boston Harbor is a primary tide station with tide readings beginning on May 3, 1921 and it has been used historically as the control station for published tide information for Cape Cod Bay. Figure 3 depicts tidal profiles referenced to NAVD88 and MLLW, the local tidal or chart datum, for Boston Harbor based on 96 years of observations, and Pamet Harbor, based on June 2016 tidal readings adjusted to the 1983-2001 NTDE. Referencing tidal heights to NAVD88 allows for Pamet and Boston Harbors to be compared directly and as shown in this figure the tidal profiles for the two harbors are very close.

The uncertainty associated with tidal datums computed from a short series of record (i.e., 1-month versus the 19 year tidal epoch) is estimated to be 0.13 feet (3.96 cm) (Bodnar, 1981).

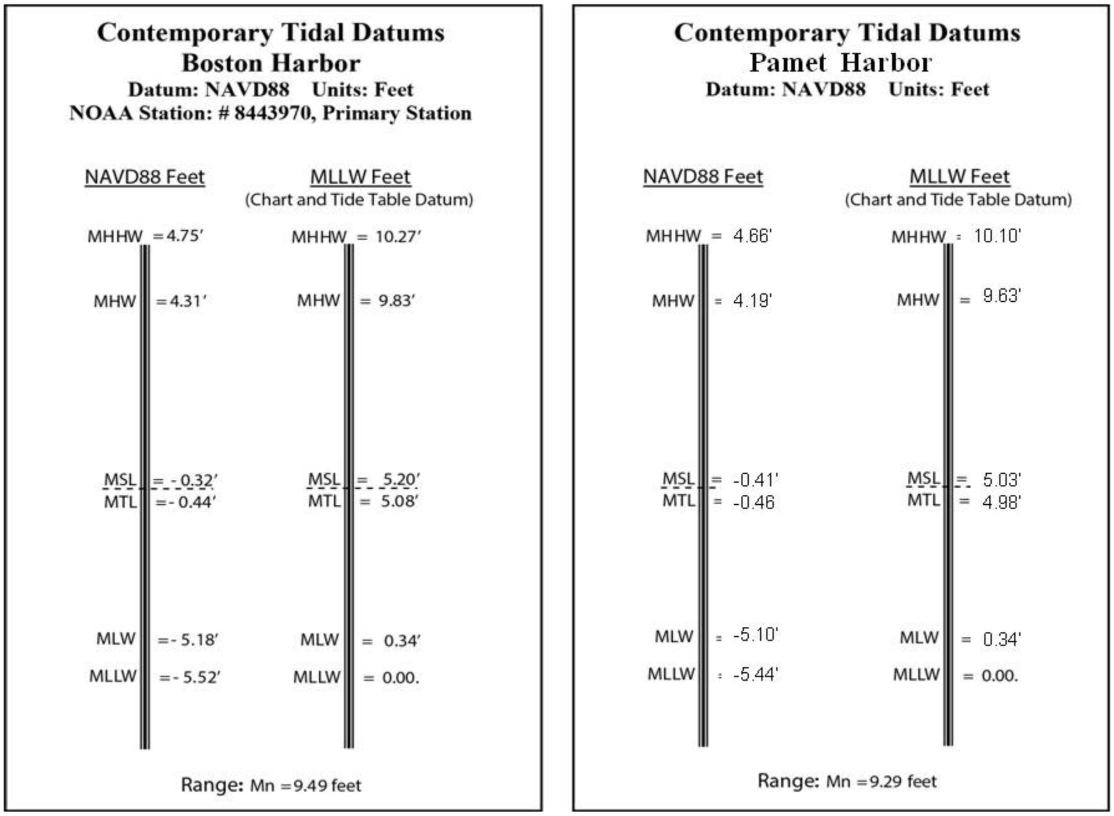

Figure 3. Tidal datum profiles for Boston and Pamet Harbors.

Developing the Truro Tidal Profile

As shown by Figure 4, the values of the tidal datums for Provincetown and Pamet Harbors are extremely close with the values for Pamet Harbor marginally below (0.03ft $\pm$) those of Provincetown Harbor**.** Due to these similarities in tidal profile and geographic orientation, the Boston Harbor storm record developed for the CZM Provincetown Resiliency Grant was used as a proxy for Pamet Harbor and the Cape Cod shores of Truro. Table 1 summarizes the highest water levels for Boston Harbor since May 3, 1921 when tidal station #8443970 was installed. Since this time, the maximum water level for Boston Harbor was observed to be 9.59ft NAVD88 on February 7, 1978 during the "Blizzard of '78".

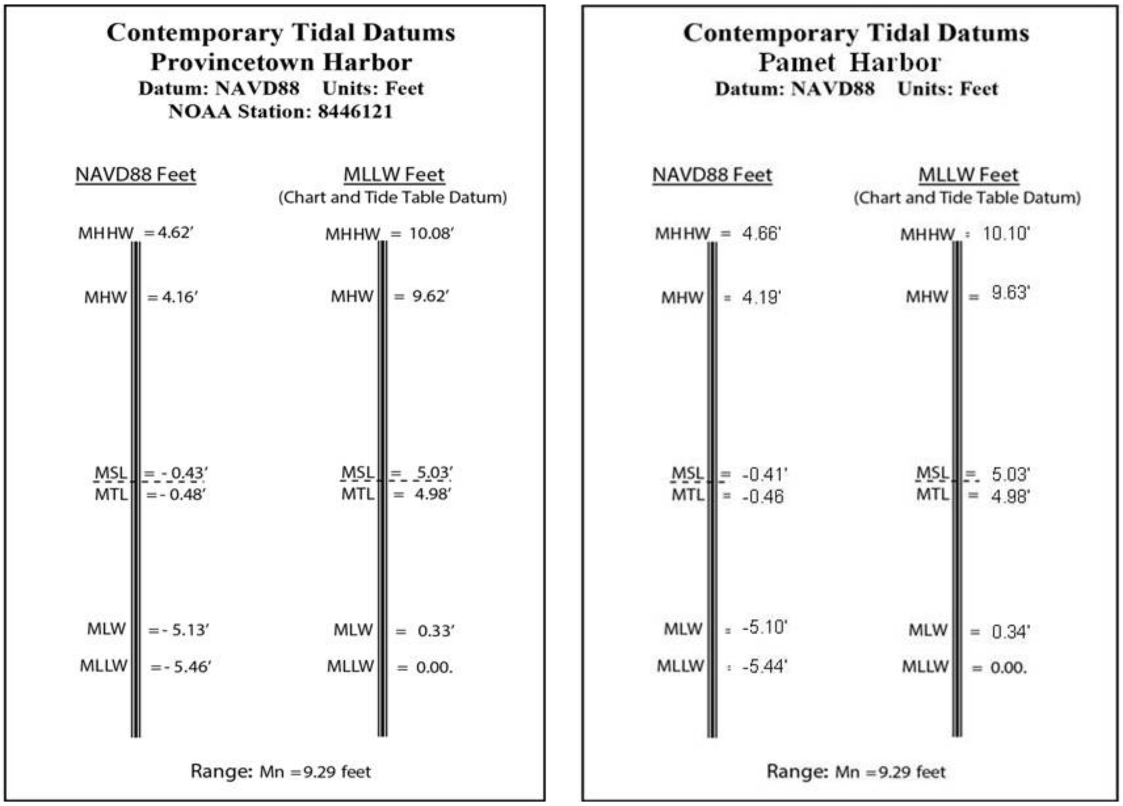

Figure 4. Tidal datum profiles for Provincetown and Pamet Harbors.

The information in Table 1 was used to develop the elevation of various storm tides (astronomical tide + storm surge). While no storm of record has been documented by a tide station in Pamet Harbor, Dr. Graham S. Giese, co-founder of the Center for Coastal Studies, was on scene at MacMillan Wharf in Provincetown Harbor to record observations of water height during the Blizzard of ’78 (Giese, 1978). Significantly, Dr. Giese referenced the water readings to a 1933 NOAA tidal benchmark, which was recovered as part of the CZM Provincetown Resiliency Grant and occupied with the Center’s RTK GPS to convert water level readings to NAVD88. Based on this work, the elevation of the Blizzard of ’78 storm tide for Provincetown Harbor was determined to be 9.36ft NAVD88. This compared well with the USACE New England Tidal profiles. Interestingly, this was found to be 0.71 feet above the maximum water level of 8.65ft NAVD88 measured by CCS during the January 27, 2015 blizzard. APPENDIX A includes a list of additional references summarizing major coastal storm events and associated storm tide elevations for the section of Cape Cod Bay.

Boston Harbor (Station #8443970) Highest Recorded Water Levels			
Rank	**Date**	**NAVD88 (Ft.)**	**MLLW (Ft.)**
1	2/7/1978	9.59	15.11
2	1/2/1987	8.69	14.21
3	10/30/1991	8.66	14.18
4	1/25/1979	8.53	14.05
5	12/12/1992	8.52	14.04
6	12/29/1959	8.49	14.01
7	4/18/2007	8.29	13.81
8	5/25/2005	8.27	13.79
9	2/19/1972	8.19	13.71
10	12/27/2010	8.19	13.71
11	5/26/2005	8.16	13.68
12	1/27/2015	8.13	13.65
13	5/26/1967	8.11	13.63
14	6/5/2012	8.07	13.59
15	3/4/1931	7.97	13.49
16	11/30/1944	7.87	13.39
17	1/20/1961	7.85	13.37
18	4/21/1940	7.83	13.35

Table 1. Maximum Water Levels for Boston Harbor since May 3, 1921

As noted above, the maximum storm tide elevation experienced during the blizzard of January 27, 2015 in Boston Harbor was 8.16ft NAVD88. The same elevation reached on May 26, 2005 (ranked 11th), Table 1 was not updated to include this storm. For Provincetown Harbor, the recently installed USGS tide gauge recorded a maximum storm tide elevation of approximately 8.66 feet NAVD88, approximately 4.5’ above mean high water and 0.7 feet below the recorded Blizzard of ’78 elevation.

Table 2 represents the tidal profile constructed for Provincetown Harbor, and used in this work to determine potential IPs within the town of Truro. As shown by the table, the maximum storm tide elevation considered in this analysis is the storm tide of record plus 3 feet (12.36ft NAVD88). To evaluate potential nuisance flooding associated with more frequent non-storm tide events, the lowest elevation considered in the IP analysis was that of the maximum predicted high tide for 2015 (6.44ft NAVD88). A review of the NOAA tide charts for Provincetown Harbor indicated that the maximum astronomical high water predicted for 2015 was 6.44ft NAVD88.

Provincetown Harbor Tidal Profile Station: 8446121			
	NAVD88 (FT)	**MLLW (FT)**	**Comments**
Storm of Record plus 3 Feet	**12.36**	**17.82**	**Upper Limit of Storm Tide Pathway Analysis**
Blizzard of '15 if max storm surge occurred at Max Predicted High For Year	10.74	16.20	Max. Storm Surge = 4.30' occurred at approx. low tide
Blizzard of 1978 Maximum Storm Tide	**9.36**	**14.82**	**Storm of Record Based on CCS Observations**
Blizzard of '15 if max storm surge had occurred at Predicted High	9.19	14.65	Max. Storm Surge = 4.30' occurred at approx. low tide
Blizzard of 2015 Maximum Storm Tide	8.65	14.11	Based on CCS Observations Storm Surge = 3.65', Predicted High Tide El. = 5.00' NAVD88 at 0430 hrs
Maximum 2015 Predicted High	6.44	11.90	From 2015 NOAA Tide Predictions
MHWS	5.54	11.00	NOAA Tide Station #8446121
MHHW	4.62	10.08	NOAA Tide Station #8446121
MHW	4.16	9.62	NOAA Tide Station #8446121
MSL	-0.43	5.03	NOAA Tide Station #8446121
MTL	-0.48	4.98	NOAA Tide Station #8446121
MLW	-5.13	0.33	NOAA Tide Station #8446121
MLLW	-5.46	0.00	NOAA Tide Station #8446121

Table 2. Provincetown Harbor Tidal Profile, which because of its closeness to the Pamet Harbor Tidal Profile was used to complete the storm tide analysis for the Truro IP Project

A Word About Datums

A datum is a reference point, line, or plane from which linear measurements are made. Horizontal datums (*e.g*., the North American Datum of 1983 (NAD83)) provide a common reference system in the x,y-dimension from which a point's position on the earth's surface can be reported (*e.g.,* latitude and longitude). Similarly, vertical datums provide a common reference system in the z-direction from which heights (elevation) and depths (soundings) can be measured. For many marine and coastal applications, the vertical datum is the height of a specified sea or water surface, mathematically defined by averaging the observed values of a particular stage or phase of the tide, and is known as a tidal datum (Hicks, 1985).[1] It is important to note that as local phenomena, the heights of tidal datums can vary significantly from one area

[1] The definition of a tidal datum, a method definition, generally specifies the mean of a particular tidal phase(s) calculated from a series of tide readings observed over a specified length of time (Hicks, 1985). Tidal phase or stage refers to those recurring aspects of the tide (a periodic phenomenon) such as high and low water.

to another in response to local topographic and hydrographic characteristics such as the geometry of the landmass, the depth of nearshore waters, and the distance of a location from the open ocean (Cole, 1997).[2]

As almost every coastal resident knows, tides are a daily occurrence along the Massachusetts coast. Produced largely in response to the gravitational attraction between the earth, moon and sun, the tides of Massachusetts are semi-diurnal - *i.e*., two high tides and two low tides each tidal day.[3] Although comparable in height, generally one daily tide is slightly higher than the other and, correspondingly, one low tide is lower than the other. Tidal heights vary throughout the month with the phases of the moon with the highest and lowest tides (referred to as spring tides) occurring at the new and full moons. Neap tides occur approximately halfway between the times of the new and full moons exhibiting tidal ranges 10 to 30 percent less than the mean tidal range (NOAA, 2000a.)

Tidal heights also vary over longer periods of time due to the non-coincident orbital paths of the earth and moon about the sun. This variation in the path of the moon about the sun introduces significant variation into the amplitude of the annual mean tide range and has a period of approximately 18.6 years (a Metonic cycle), which forms the basis for the definition of a tidal epoch (NOAA, 2000a). In addition to the long-term astronomical effects related to the Metonic cycle, the heights of tides also vary in response to relatively short-term seasonal and meteorological effects. To account for both meteorological and astronomical effects and to provide closure on a calendar year, tidal datums are typically computed by taking the average of the height of a specific tidal phase over an even 19-year period referred to as a National Tidal Datum Epoch (NTDE) (Marmer, 1951). The present NTDE, published in April 2003, is for the period 1983-2001 superseding previous NTDEs for the years 1960-1978, 1941-1959, 1924-1942 and 1960-1978 (NOAA, 2000a).

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[2] For example, the relative elevation of MHW in Massachusetts Bay is on the order of 2.8 feet higher than that encountered on Nantucket Sound and 3.75 feet higher than that of Buzzards Bay.

[3] A tidal day is the time or rotation of the earth with respect to the moon, and is approximately equal to 24.84 hours (NOAA, 2000a). Consequently, the times of high and low tides increase by approximately 50 minutes from calendar day to calendar day.

Tidal Datum	Abbreviation	Definition
Mean Higher High Water	MHHW	Average of the highest high water (or single high water) of each tidal day observed at a specific location over the NTDE*
Mean High Water	MHW	Average of all high water heights observed at a specific location over the NTDE*
Mean Sea Level	MSL	Arithmetic mean of hourly tidal heights for a specific location observed over the NTDE*
Mean Tide Level	MTL	Arithmetic mean of mean high and mean low water calculated for a specific location
Mean Low Water	MLW	Average of all low water heights observed at a specific location over the NTDE"
Mean Lower Low Water	MLLW	Average of the lowest low water (or single low water) of each tidal day observed at a specific location over the NTDE*

Table 3 Common Tidal Datums (Source NOAAs, 2000b)

NGVD29 v. NAVD88

Frequently, tidal datum elevations are correlated to a fixed reference surface known as a geodetic datum. Two common reference systems adopted as standard geodetic datums for vertical measurements are the National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Vertical Datum of 1988 (NAVD88). NGVD29 was derived from mean sea level observations at twenty-one (21) tide stations in the United States, including Boston Harbor, and five (5) in Canada. It is important to note that although it is often referred to as Mean Sea Level of 1929, the relationship between NGVD29 and local mean sea level is not consistent from one location to another and, therefore, NGVD29 should not be confused with local mean sea level.

NAVD88, is a similar fixed vertical reference system, derived from the height of a primary tidal bench mark located at Father Point, Rimouski, Quebec, Canada. NAVD88 is slowly replacing NGVD29 as the official vertical datum for most federal and state agencies in the United States and as a geodetic datum can be used to compare elevations directly (heights and soundings) at different geographic locations.

Although the NGVD29 and NAVD88 reference surfaces are not parallel, resulting in differences that vary geographically across the country, the relationship between the two surfaces for eastern Massachusetts can be described generally by the following equation:

$$\text{Elevation feet}_{NGVD29} + -0.85 \text{ feet} = \text{Elevation feet}_{NAVD88}$$

$$\text{Elevation m}_{NGVD29} + -0.24\text{m} = \text{Elevation m}_{NAVD88}$$

While this relationship holds true for most applications, care should be exercised when converting from NGVD29 to NAVD88 and verified depending on the purpose of the work. This is particularly true when doing work on Cape Cod requiring direct conversions from NGVD29 to NAVD88 due to documented problems with the establishment of the former geodetic datum on the Cape in the 1930s.

Spatial Analysis

Based on the tidal characterization for the town of Truro, analysis begins in the laboratory where state-of-the-art software and powerful computers were used to examine the best available elevation data for the Bay shoreline and adjacent low-lying areas in Truro. The goal of this desktop analysis was to develop an initial working database of potential IPs. Using this preliminary compilation, the location and elevation of each potential IP was verified in the field and a final IP database compiled from the GPS survey.

The terrestrial lidar used as the base map for the desktop analysis was collected by the United States Geological Society in 2013-14. This data was downloaded from the NOAA website (https://coast.noaa.gov/digitalcoast/). The website has default settings for horizontal (NAD83) and vertical (NAVD88) reference datums, spheroid and projection as well as units (metric vs standard). Metadata for these data report a horizontal accuracy of 0.42 m at 95% confidence level. The data have a Consolidated Vertical Accuracy (CVA) of 0.189 m at 95% confidence level. These vertical accuracy values are based on different ground covers and range from a low of 0.096 m over ‘Bare-Earth’ up to 0.257 m over ‘Urban Land Cover’. It is important to note that use of the most accurate and most current lidar for the desktop analysis greatly facilitates field verification of IPs. The final elevation data products for this project are reported in feet referenced to NAVD88 (a geodetic datum) and to the MLLW (the local tidal datum) to simplify use with local navigation charts, tide tables, and the NWS website.

All lidar data are downloaded in a raster format, brought into ESRI's ArcGIS software, and divided into smaller tiles to facilitate data analysis and archiving. These lidar tiles are then brought into QPS's Fledermaus data visualization software for initial IP screening. While acquired by CCS as an integral component of its Seafloor Mapping Program, the Fledermaus software package has proven to be an ideal platform for the initial desktop identification of IPs where the accuracy of the initial analysis is limited primarily by the uncertainty and resolution of the lidar itself.

The power of Fledermaus lies in its ability to work quickly with very large data files. Although individual files can be multiple GBs in size, Fledermaus moves rapidly through the data for visual inspection, 'fly-throughs' and similar functions. Using the Fledermaus software, horizontal planes representing incrementally higher flood levels are created and used to identify the corresponding potential IP elevation. These planes are added to a Fledermaus project or 'scene' and form the basis for the initial IP identification. (Figure 5).

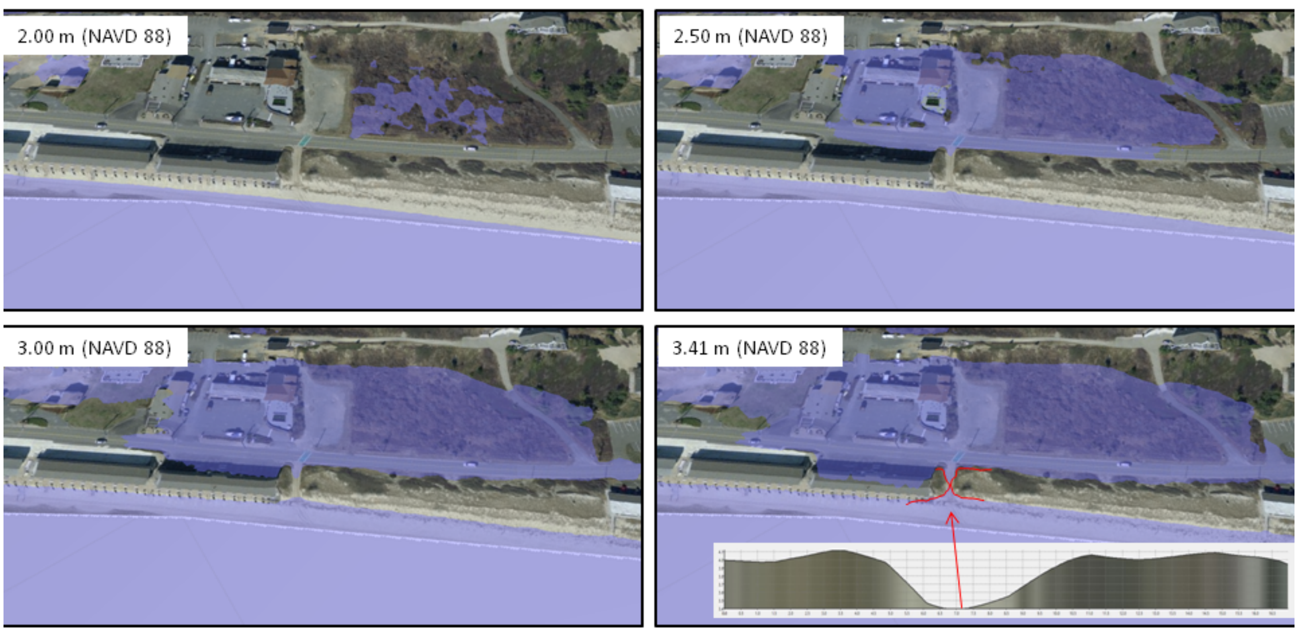

Figure 5. Draped aerial photograph over Lidar surface in North Truro. Blue areas are horizontal planes created in Fledermaus at increasing elevations. Lower right is example of a storm-tide pathway with accompanying profile. These images were generated before field work to identify potential IPs.

Another invaluable feature of this data visualization software is the ability to drape 2-dimensional data, such as a vertical aerial photograph, over a 3D dataset (lidar). This allows the analyst to better document the IP and also acquire information about the substrate on which the

IP is located and its landscape setting. For example, an IP found on or near an ephemeral coastal feature such as a sandy beach or dune is characterized differently than one atop a concrete wall or other relatively static feature. In addition to providing managers with information on how to address an individual IP, these characterizations also inform the field team to more closely examine areas that are naturally evolving and to inspect the area for other to potential IPs that might not have appeared in the now dated lidar. The ability to drape aerial photographs proved extremely helpful for conducting the GPS field work, serving as a quick means of orientation and placing the potential IP in its broader geographic context.

Field Work

Once a preliminary inventory of potential IPs was compiled in the desktop analysis, an extensive fieldwork assessment program was conducted to verify the presence or absence of the IP. When the presence of an IP was confirmed, the accurate horizontal and vertical location was obtained.

A Trimble® R8 GNSS receiver utilizing Real-Time-Kinematic GPS (RTK-GPS) was used for all positioning and tide correction fieldwork. The Center subscribes to a proprietary Virtual Reference Station (VRS) network (KeyNetGPS) that provides virtual base stations via cellphone from Southern Maine to Virginia. This allows the Center to collect RTK-GPS without the need for a terrestrial base station or to post-process the GPS data, streamlining the field effort and increasing field work efficiency.

The Center performed a rigorous analysis of this system to quantify the accuracy of this network (Mague and Borrelli, in prep). Over 25 National Geodetic Survey (NGS) and Massachusetts Department of Transportation (DOT) survey control points, with published state plane coordinate values relating to the Massachusetts Coordinate System, Mainland Zone (horizontal: NAD83; vertical NAVD88), were occupied. Control points were distributed over a wide geographic area of the Cape and Islands.

Multiple observation sessions, or occupations, were conducted at each control point with occupations of 1 second, 90 seconds, and 15 minutes. To minimize potential initialization error, the unit was shut down at the end of each session and re-initialized prior to the beginning of the next session. The results of each session (i.e., 1 second, 90 second, and 15 minute occupations) were averaged to obtain final x, y, and z values to further evaluate the accuracy of short-term occupation. Survey results from each station for each respective time period were then compared with published NGS and DOT values and the differences used to assess and quantify uncertainty. Significantly, there was little difference between the values obtained for the 1 second, 90 second, and 15 minute occupations. The overall uncertainty analysis for these data yielded an average error of 0.008 m in the horizontal (H) and 0.006 m in the vertical (V). An RMSE of 0.0280 m (H) and 0.0247 m (V) and a National Standard for Spatial Data Accuracy (95%) of 0.0484 m (H) and 0.0483 m (V).

The ability to conduct accurate fieldwork is a critical component of the IP verification process for several reasons. First, post processing of lidar collected via aerial surveys can introduce uncertainties that exaggerate or diminish features in three-dimensional data and, as a result, can obscure or conflate the presence and scale of an inundation pathway. These effects have been shown to be associated with ‘bare earth’ models where elevations tend to be “pulled up” adjacent to areas where buildings have been removed and “pulled down” in areas where bridges and roads cross streams or valleys (Figure 6).

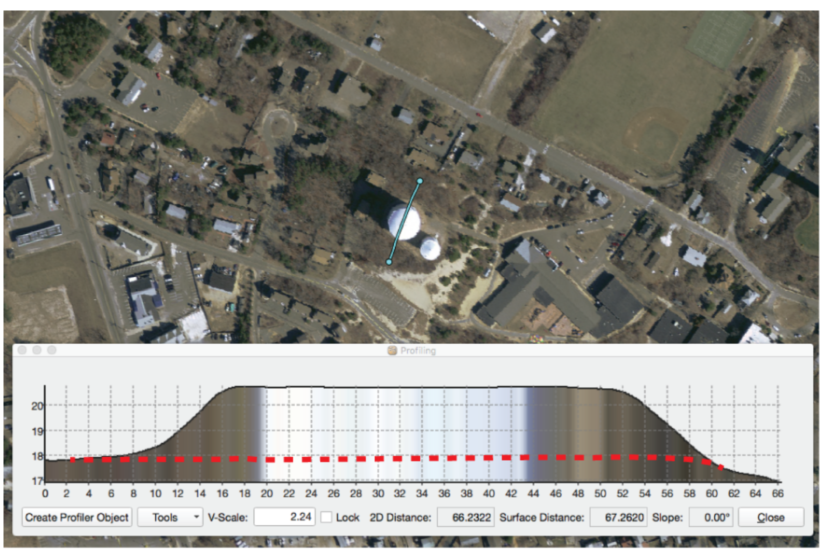

Figure 6. Example of ‘pull up’ near a water tower. Dotted line is more representative of elevations at the water tower. Blue line in image is location in profile. Profile units = meters (Vert. NAVD88, Hor. NAD83).

Second, the use of an RTK-GPS instrument provides the accuracy necessary for acquiring and verifying 3-dimensional positional data. In this way GPS data is used to corroborate or eliminate the presence of IPs identified in the desktop lidar analysis. Third, due to the dynamic nature of coastal environments, visual assessment conducted as part of the field work sometimes reveals IPs that are not revealed in a desktop analysis of lidar data. Lastly, and also related to the ephemeral characteristics of the areas proximate to the shoreline, even the most current lidar is frequently out of date in dynamic areas. Consequently, the GPS survey, coupled with field observation of each IP, provides real time information to eliminate IPs that may have appeared in the lidar but no longer exist due to changes in landform.

At the completion of the desktop analysis, all potential IPs were compiled into a spatial database with x, y, z coordinates and uploaded into the Center's GPS. Using the "stakeout" function and aerial photographs to navigate to the precise location identified with the lidar, each potential IP location, and the adjacent area, was inspected by a 3-person team and occupied with the GPS mobile unit. the lidar data via a laptop in the field in real-time While RTK-GPS data were collected, lidar data in the area of each potential IP was inspected on a field laptop. This served three purposes, first to map the real-world location of the IP identified during the desktop analysis; second to increase the positional accuracy of the verified IP itself; third, to verify consistency with the current landscape setting; and lastly to confirm the positional accuracy of the lidar data.

Significantly, using the GPS instrument to navigate to the location of a potential IP also afforded the field crew the opportunity to investigate potential alternative or additional IPs based on visual inspection of the area. Many coastal sites have very low relief (relatively flat) and verifying whether an IP existed, its exact location, and the direction of water flow required professional judgment and experience in the principles and practices of land surveying as well as a thorough knowledge of coastal processes.

After the field work was completed, the team returned to the laboratory to remove those points determined not be IPs from the database, incorporate newly identified IPs documented in the field, and provide all IPs with horizontal and vertical position information, substrate and geographic context labels, photograph links, and other pertinent information for inclusion into a comprehensive database. Once the information was quality controlled, the database was brought into the project GIS for use as an interactive archive of final IP information. Importantly, the database was annotated to note those areas where the lidar was found to correlate poorly with current conditions or real-world position as determined by the GPS observations and professional judgment was necessary to accurately represent the IP.

With the final compilation of the IP spatial database, the file was brought into ESRI's ArcGIS to provide a working or living archive for local managers: 1) to proactively identify and prioritize which IPs to address prior to storm events; 2) to prepare for approaching storms; and 3) to plan for longer-term improvements to mitigate other IPs.

Although field delineation of inundation extents for each IP was beyond the scope of the project, the lidar data was used in 2 interactive ways to visualize IP inundation levels with the goal of maximizing the utility of the final product. The first depiction is referred to as the Pathway Activation Level (PAL). The PAL represents the elevation at which water begins to flow over an IP. To visualize the PAL, the inundation extent was delineated as a continuous contour derived from the lidar elevation data. For example, based on the GPS fieldwork, an IP with a PAL of 13.6 feet MLLW indicates that the moment the water level reaches 13.6 feet MLLW water will begin to flow inland via the IP. Using the data visualization software, a water elevation of 13.6 feet MLLW was then used to trace the area that would hypothetically be inundated (assuming storm tide water levels are maintained long enough for the entire area to become flooded). If a storm tide recedes after reaching the PAL, then this depiction can be viewed perhaps as a "best" case scenario for impacts associated with a specific storm tide. If water levels were to continue to rise above the PAL, higher than 13.6 feet MLLW, however, obviously more area would be inundated leading to the need for a second means of visualizing IPs.

For this reason and to increase the utility of the IP data and make visualizations more user friendly for local mangers, Inundation Ranges (IRs) were developed for the entire study area rather than creating PALs for every IP and all potential flood elevations. After several attempts at visualizing IPs and recognizing that floodplain mapping was not a goal of the project, it was felt that the use of IRs would be the clearest way of making the data useful while addressing the associated with the lidar. The IR visualizations were based on a series of iterations of potential inundation scenarios, including nuisance flooding. After reviewing the various scenarios, the lower end of the IR range was begun at the highest Spring tide of the year. Inundation ranges were developed in 0.5 foot intervals to a maximum elevation of the Storm of Record plus three feet and inundation planes extracted for each range. In addition to providing an upper limit to project elevations, it was felt that using the Storm of Record plus 3 feet provides a useful representation of future sea level rise scenarios that would have practical implications for local managers.

RESULTS AND DISCUSSION

Truro Tidal Profile

As discussed earlier, to document IPs an elevation profile for Truro was developed to characterize both storm tides and nuisance flooding. In addition to the more common tidal datums of mean high water springs (MHWS), mean higher high water (MHHW), mean high water (MHW), and mean sea level (MSL) this tidal profile also includes datum referenced storm tides of the past, including the elevation of the maximum storm tide experienced (i.e., the storm of record), and an estimate of potential future storm tides reflected by adding three feet to the storm of record. These elevations and the elevations used in the Truro analysis are summarized in Table 2 above.

Inundation Pathways

Desktop analysis of the lidar data yielded 41 potential IPs throughout the Truro study area. Each location was inspected by the 3-person field team. Where necessary, IPs were moved based on field observations when the team determined the 2013-2014 lidar was not representative of the real-world terrain in 2016.

The final IP dataset developed for this project contains 38 inundation pathways. There are several types of IPs included in this dataset: standard Inundation Pathways (IPs) as discussed above; ‘spillways’ (IP-S); ‘roadways’ (IP-R); and unverified (IP-U) (Table 4). These sub-types were developed to reflect different on-the-ground morphologies and techniques needed to identify and/or describe potential inundation at these locations.

Pathways	Standard (IP)	Spillway (IP-S)	Roadway (IP-R)	Unverified (IP-U)
38	31	0	7	8

Table 4. Summary of Inundation Pathways

The ‘standard’ IP can be described as a relatively narrow low-lying area where flowing water would be directed inland by the natural topography (Figure 5, lower right panel). The term ‘spillway’ was developed as a way to reflect to reflect the low relief of the area. The IP-S are situated in very flat areas and are representative of long broad weir-like formations as opposed to the discrete point-like nature of the standard IPs. Actions planned to mitigate spillway IPs generally require action along a broad area and detailed topographic surveys in order to minimize associated flooding during future events. While difficult to visualize, these areas may be of great concern precisely because of the characteristic that makes them a spillway, a broad flat area of inundation with no clear, narrow pathway for flood waters to enter. Although no IP-Ss were present in the Truro dataset there were 15 in the Provincetown dataset. The roadways IP (IP-R) were delineated as they are associated with those inundation pathways that generally only impact roadways (Figure 7).

Of the 38 IPs mapped in Truro, 26 were moved by the field survey team suggesting that the lidar did not accurately represent the existing conditions at the time of collection, or at the time of the field survey. This highlights the need to field check all remotely sensed data.

Finally, an unverified IP (IP-U) was defined to be an IP that was identified during the lidar analysis, but was unable to be located and occupied by the field team. The lidar used for this study is a ‘bare earth’ lidar data set, which is typical for these types of analyses. As discussed above, during the processing of these data the vegetation, (tress, bushes, beach grass, salt marsh, etc.) and structures (houses, buildings, etc.) are removed from the data, hence the ‘bare earth’ name. Therefore, certain low spots found in the lidar analysis could not be accessed or were otherwise inaccessible (private property) or may in fact have been artifacts of the bare-earth process. The 8 IP-Us found in this study are in low areas that will experience water flowage but the precise location of the IP is not identifiable using solely the methods of this study.

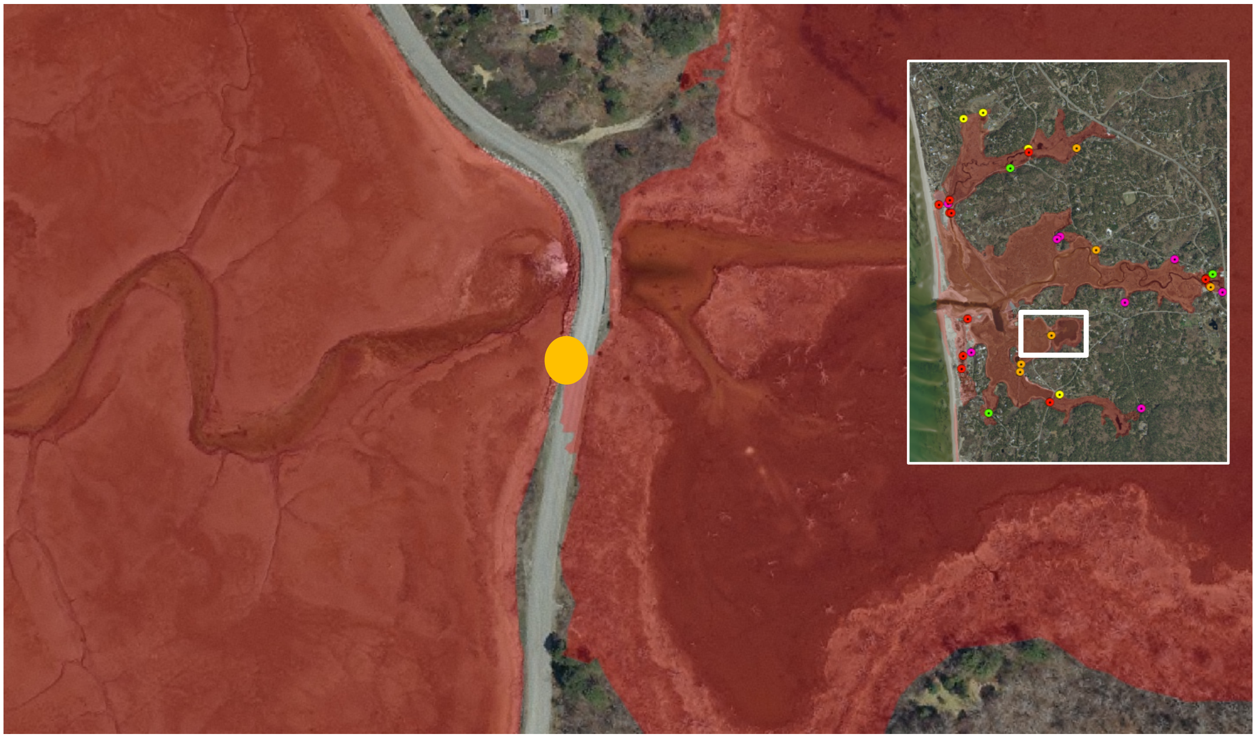

Figure 7. Example of Inundation Pathway-Road (IP-R). The red represents the approximate extent of water during an inundation event. This pathway only leads to flooding along the road, however it is a critical route for emergency vehicles.

A tide staff will be installed in the harbor at the direction of the Harbormaster. This custom-made fiberglass tide staff built to be visible at a distance will serve several purposes: first, it will link the elevation of the inundation pathways to a visual water level for the Harbormaster's office. During storm events the actual level of the water will be easily noted from the safety of the Harbormaster's office. Then action items can be developed based on present water levels, peak of upcoming high tide and other considerations. For example, an elevation of 11.7 ft (MLLW) is seen at the tide staff, but high tide is still 1 hour away and, based on the NWS website, is predicted to rise ~2 feet in that one hour. Town managers can prepare for a 13.7 ft (MLLW) flood event. The storm surge may lessen, winds may change direction, but the town now has reliable real-time data upon which to base storm preparations and response.

The tide staff will also provide the critical, real-time connection between the water levels in the harbor with the map of inundation pathways. Following the example above, if the harbormaster anticipates a 13.7 ft (MLLW) inundation event then all of the IPs that are at or near that level will have to be addressed in some way.

Finally, the tide staff will also provide the public with a more substantial and tangible understanding of coastal inundation and how it relates to preconceived notions of water levels. For example, the general public typically is not aware that the difference between a 10-year storm and a 100-year storm can be as little as 12-18 inches (FEMA, 2014). By reinforcing that relatively minor changes in water level can dramatically alter the impact of coastal storms have can be useful not only in improving the understanding of storms, but the vulnerability of low-lying coastal areas to small changes in water levels. This will also be useful for putting sea level rise projections of, for example, 1 foot over a given time-period into its proper context. A 1-foot rise in sea level or storm surge can have profound impacts on the vulnerability of coastal areas not only from storms or sea level rise but also from the increasing frequency of nuisance flooding and the extent of the associated flooding.

Coastal Flood Threat and Inundation Mapping webpage

SNEWFO-NWS maintains a webpage (https://www.weather.gov/box/coastal) with tide and storm surge forecasts for numerous stations throughout southern New England. As coastal storms approach, viewers can manipulate the webpage to depict the approximate extent and depth of flooding based on the predicted tide stage and forecasted storm surge. As noted on the webpage these layers are based on 'static water surface elevations' and are shown in 0.5 ft increments. Wave modeling is not incorporated into these storm-related forecasts. Using a DEM with 5-meter grid cell, location-specific water level data, and the results of storm surge forecasting the webpage provides users with a 'total water level' forecast and projects potential inundation threats as a coastal storm approaches a given coastal area (e.g. Provincetown Harbor).

Using the newly available, high resolution 2013-2014 lidar data, the Center updated the inundation layers, or Inundation Ranges, (IR) for the Provincetown/Truro area of Cape Cod Bay. The ranges provided to the SNEWFO-NWS begin at the highest high tide of the year and increase to an elevation equal to the 1978 storm of record plus 3 feet in 0.5 foot increments (12 – 17.5 ft MLLW) over 12 inundation layers. The additional 3 ft of IRs were included to account for the potential effects of sea level rise on nuisance and storm flood conditions. These data were then grouped into the three flooding categories used by NWS in its forecast: *Minor* (12.5ft MLLW), *Moderate* (13.5ft MLLW) and *Major* (14.5ft MLLW).

Combining the results of two CZM Resiliency Grants, a total of 110 pathways were identified for areas located along the Provincetown/Truro Cape Cod Bay shoreline (Figure 8). Shapefiles of the PALs were generated for each pathway at the moment of 'activation' (i.e., when water reaches the pathway elevation) and for 0.5 ft intervals (12.5 MLLW to 17.5 MLLW) throughout the study area. Working with staff at SNEWFO-NWS, these shapefiles were imported into the Coastal Flood Threat and Inundation Mapping website and color coded to correspond to NWS Minor and Moderate and Major flooding categories. The updated webpage using these project data, when internal NWS review is completed, can be viewed at https://www.weather.gov/box/coastal.

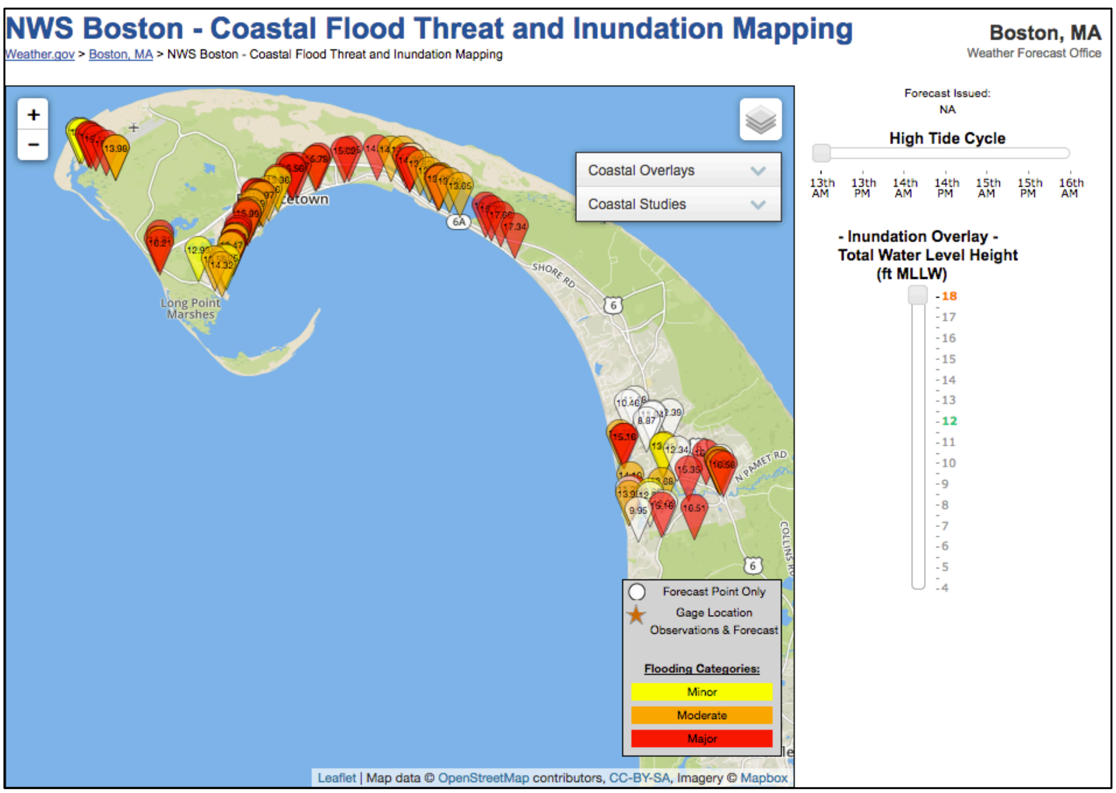

Figure 8. Screenshot of the 110 Inundation Pathways in Provincetown and Truro as depicted on the Southern New England Weather Forecast Office of the National Weather Service.

In addition to providing an effective tool for storm preparedness and response, the ability to view GIS files containing the IRs and the IPs together or separately (Figure 9) also can assist short, medium and long-term planning. Given municipal resource and budget limitations, these datasets will assist staff with the prioritization of short-term storm preparation and response actions as well as the development and implementation of longer term design solutions. For example, these data could help Department of Public Works staff determine potential flooding events immediately prior to an approaching storm and place temporary sandbags in areas with a great deal certainty. Longer term, town planners can use the same data to help identify areas of nuisance flooding that occurs presently 5 or 6 times a year but with expected sea level rise will likely begin to flood more frequently. Finally, as seal level continues to rise, the same data can be used by towns to help evaluate and plan proactively for addressing more catastrophic events associated with storm of record or higher pathways.

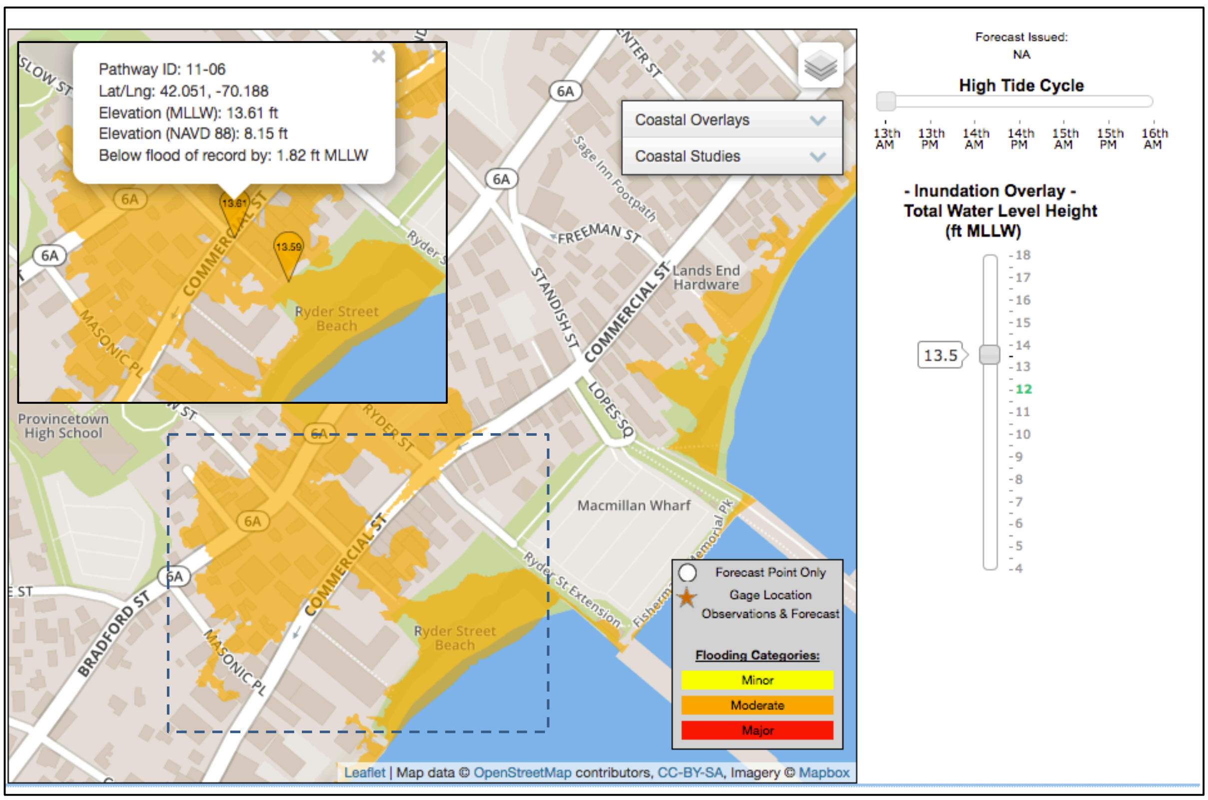

Figure 9. Screenshot from the Coastal Flood Threat and Inundation Mapping webpage (SNEWFO-NWS). Inset in upper right (dotted line indicates area) shows pathway with information window that pops up when the used holds mouse over the IP.

Finally, the mapping of inundation pathways in areas where SNEWFO-NWS provides storm surge forecasting provides useful information to not only municipalities but also county, regional and state entities. Specifically, the integration of real-time coastal storm forecasting with reliable mapping of inundation pathways makes it possible to implement storm preparedness and response measures in advance of storm tides with the goal of minimizing disruption, damage, post-storm cleanup efforts, and cost.

Appendix A

A Summary of References Concerning Major Coastal Storm Events, Associated Storm Tide Elevations, and Tidal Datums

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