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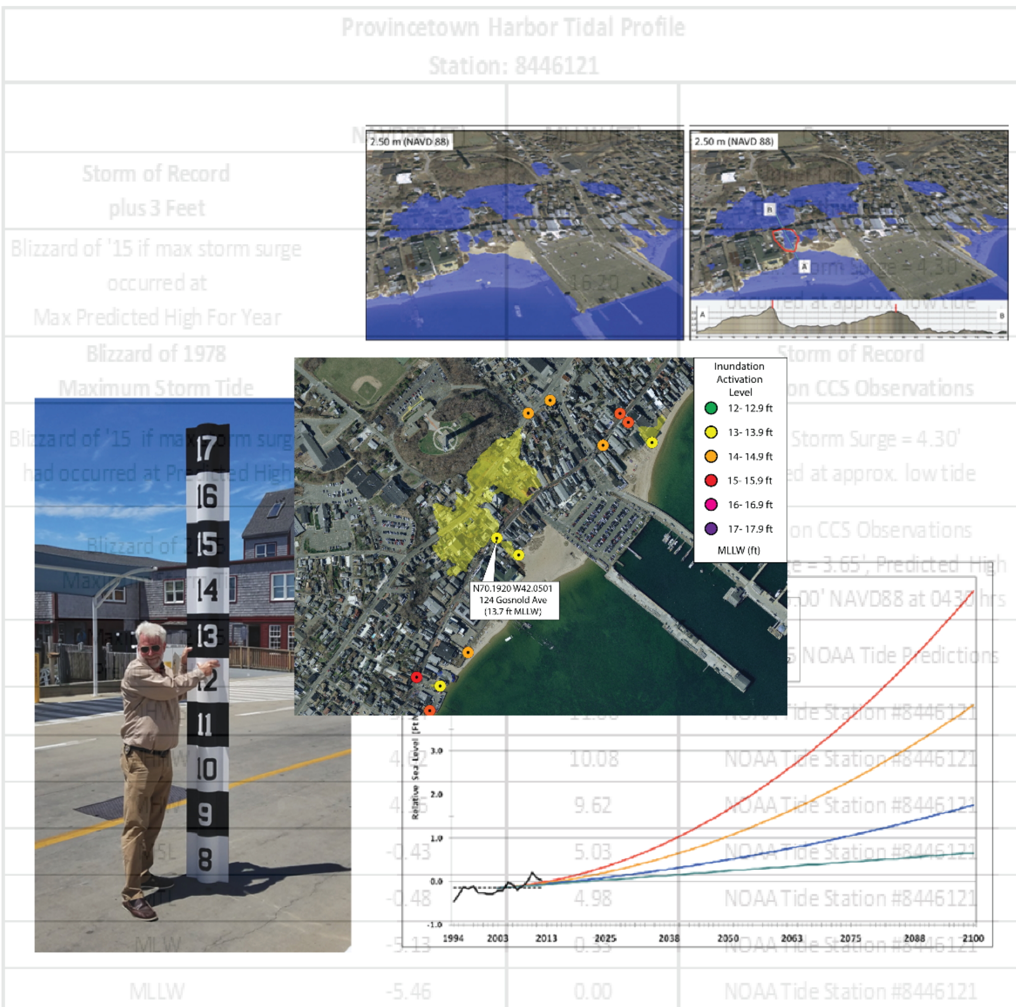
A New Method for Mapping Inundation Pathways to Increase Coastal Resiliency, Provincetown Massachusetts



A report prepared for the Town of Provincetown, Massachusetts
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PROJECT BACKGROUND AND OVERVIEW

The impacts of coastal inundation have historically confronted coastal managers dealing with vulnerabilities to existing infrastructure and planning for future infrastructure improvements. Occurring on multiple temporal and spatial scales, impacts range from chronic encroachment of tides to the episodic destruction associated with coastal storms and flooding. As evidenced by recent storms such as Katrina and Sandy, 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.

Within this context, much attention has been focused on the subjects of climate change and sea level rise. With regard to the latter, many scientists have concluded that sea levels are not only rising, but 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 creates significant issues 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 (and necessarily) 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 recognize potential vulnerabilities and to educate residents and community leaders about the threats associated with coastal inundation has been severely limited by the lack of regional-scale, accurate elevation data. For example, Flood Insurance Rate Maps (FIRMS), produced by the Federal Emergency Management Agency (FEMA), have long been standard 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. Furthermore, these models are typically too coarsely-scaled to inform local decisions, appropriately-scaled studies are critical for coastal managers and municipalities.

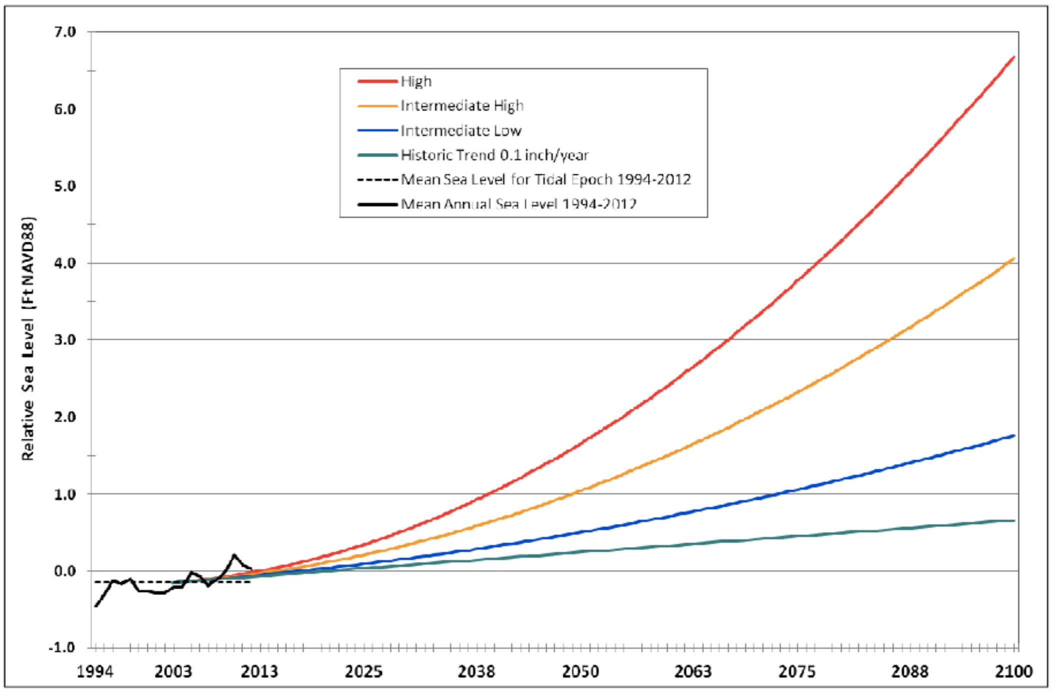

Figure 1. Relative sea level rise scenario estimates (in feet NAVD88) for Boston, MA. Modifed after Figure 5 in, Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning. Massachusetts Office of Coastal Zone Management, December 2013. Available at: http://www.mass.gov/eea/docs/czm/stormsmart/slr-guidance-2013.pdf.)

Based on the long range projections of sea level rise and the catastrophic damages associated with large coastal storms much attention has been placed 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 (GHG) emissions, promote green energy, and 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.

Reflective of the limited financial and technical resources of coastal communities and their unique geography, local responses and strategies to sea level rise and climate change will be more successful particularly in the context of short-term planning horizons and frequently changing leadership. Specifically, the short term planning 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 storm tide elevations may provide a more effective means of characterizing coastal hazard vulnerability for local planning actions. Figure 2 depicts estimates of various historical storm tide elevations for the Boston area (an easterly facing shore) for various storms for the 17^{th} - 21^{st} 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 17^{th} century.

Using historical data to identify potential storm tide heights, coastal flooding extents, and areas of potential vulnerability provides important, high certainty planning information to local communities with several benefits. First, using historical storm tides to identify coastal hazard vulnerabilities removes sea level rise and the disparity of projections (Figure 1) from the discussion of the most appropriate sea level rise elevation to use to develop short term planning responses. Sea level rise notwithstanding, storm tides of these magnitudes

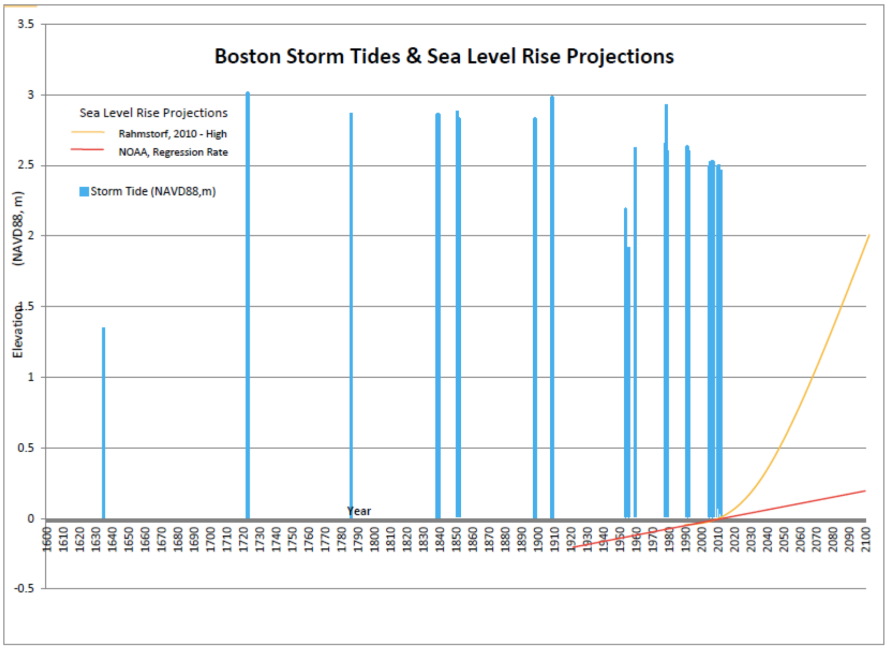

Figure 2. Historical Storm tides and sea level rise.

have been experienced in the past and are very likely 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.

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 source of coastal elevation data. Covering broad geographic areas with horizontal accuracies 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 has historically 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 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.

In 2011, the Natural Resource Conservation Service, United States Department of Agriculture (NRCS) completed terrestrial lidar surveys of Barnstable County, Massachusetts. The horizontal and vertical accuracies [can we say what the reported values are?] of this publically available contemporary elevation data provide a reliable base map and can be used as the foundation for local action planning.

A primary goal of this Provincetown pilot project is to, using lidar as a base level guide, accurately map pathways or areas through which storm tides might pass, threatening vulnerable areas of the town with inundation of varying depths. For purposes of this project, these locations have been termed 'storm tide pathways' or 'inundation pathways'.

The term 'storm tide' refers to the rise in water level experienced during a storm event resulting from the combination of storm surge and 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.

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., storm water system, 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, the study used recorded flood elevations associated with actual coastal storm tides. As discussed below, research of available records and studies indicates that, as for Boston, the best approximation of the storm of record for Provincetown would appear to be storm tide elevation of the Blizzard of '78. This storm tide was recorded by Dr. Graham S. Giese of the Center for Coastal Studies in Provincetown to be 9.36 feet (2.85 meters) 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).

METHODS

Datums: Definition and Uses

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 (Table 1). 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 a 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 1. Common Tidal Datums (Source: NOAA, 2000b).

Identifying existing Inundation pathways (IP) in a dynamic coastal environment is a multi-step process. First, a datum referenced tidal profile is established for the local area. For Provincetown Harbor, existing benchmarks for NOAA CO-OPS tidal station # 8446121 were recovered, occupied by the Center's Real-Time-Kinematic Global Positioning System (RTK GPS) and referenced vertically to the North American Vertical Datum of 1988 (NAVD88). Tidal station # 8446121 was established in Provincetown Harbor on March 5, 2010 and tidal datums referenced to the station datum and reported on the NOAA CO-OPS website [tidesandcurrents.noaa.gov], were then converted to NAVD88 for reference throughout the project. Figure 3 shows the contemporary tidal datums for Provincetown Tidal Station # 8446121 referenced to NAVD88 and Mean Lower Low Water (MLLW). As shown in Figure 3, this tidal profile is compares closely with resemble that for Boston Harbor.

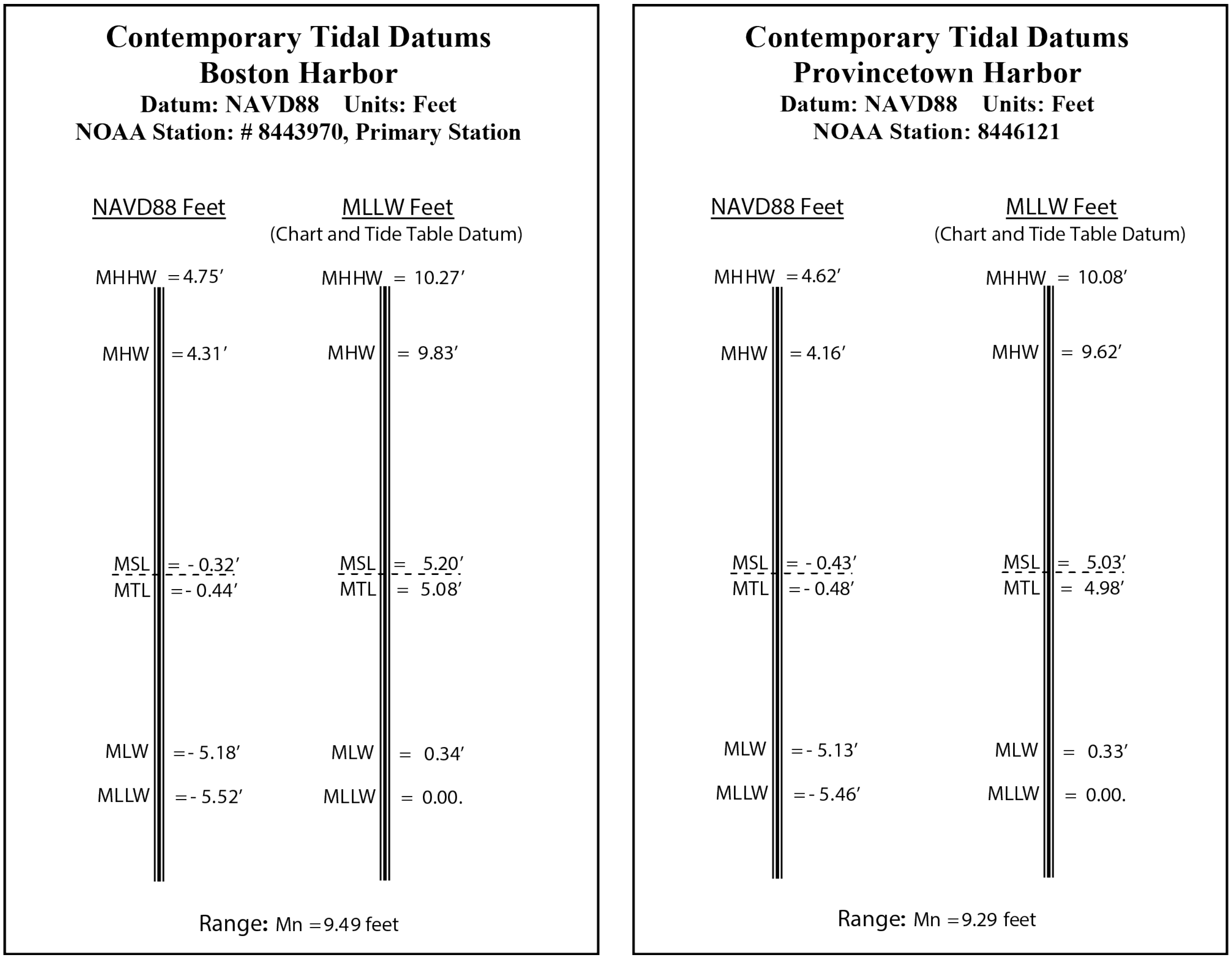

Figure 3. Tidal datum profiles for Boston and Provincetown.

Having established a datum referenced tidal profile, historical coastal storms were then researched to determine significant storm tide (storm surge + astronomical tide) events that have occurred since 1921, the beginning of the continuous tidal record for Boston Harbor. As noted above, the storm of record for this study was identified to be 9.36 feet NAVD88.

In addition to the major inundation that often accompanies coastal storms, many coastal communities are also beginning to experience occasional minor flooding during spring tides as relative sea level continues to rise. Often referred to as nuisance flooding since it is rarely associated with dramatic building and property damage, this type of minor flooding is becoming more common with chronic impacts that include overwhelmed drainage systems, frequent road closures, and the general deterioration of infrastructure not designed to withstand saltwater immersion (NOAA, 2014). A complete discussion of the results of this research is presented below in the Results and Discussion section.

Spatial Analysis

Based on the Provincetown Harbor tidal characterization discussed below, analysis begins in the laboratory. Here, using state-of-the-art software and powerful computers to examine the existing elevation (lidar) data using varying water levels to identify potential IPs.

A list of potential IPs begins with the desktop analysis of the best available synoptic elevation data for the study area. The latest lidar data were downloaded from the NOAA website (https://coast.noaa.gov/digitalcoast/). The website has default settings for horizontal and vertical reference datums, spheroid and projection as well as units (metric vs standard). Metadata for these data indicate horizontal and vertical accuracies of +/- 1.0 m and +/- 0.15 m respectively. Recognizing that previous lidar data sets produced for the area possessed double the vertical uncertainty. it is important to note that use of the most accurate and most recent lidar for the desktop analysis greatly facilitates filed verification of IPs

For the purposes of this study, Center staff altered the default download parameters for ease of use within several software packages. Regardless of the spatial parameters, the positional information within the lidar are not altered. The final data products at the conclusion of the project are reported in feet referenced to the MLLW datum for Provincetown Harbor to simplify use at the local level.

All data are downloaded in a raster format and brought into ESRI's ArcGIS software and the raster is divided into smaller tiles to facilitate data analysis and archiving. These lidar tiles are then brought into QPS's Fledermaus data visualization software. 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 in which 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 with very large data files quickly. Individual files can be multiple GBs in size, yet Fledermaus rapidly moves through the data for visual inspection, ‘fly-throughs’ and similar functions. Horizontal planes, representing an identified potential IP elevations can be added to a Fledermaus project or ‘scene’ and these planes can be increased or decreased to simulate changes in water levels, IP elevations, or storm tide conditions (Figure 4).

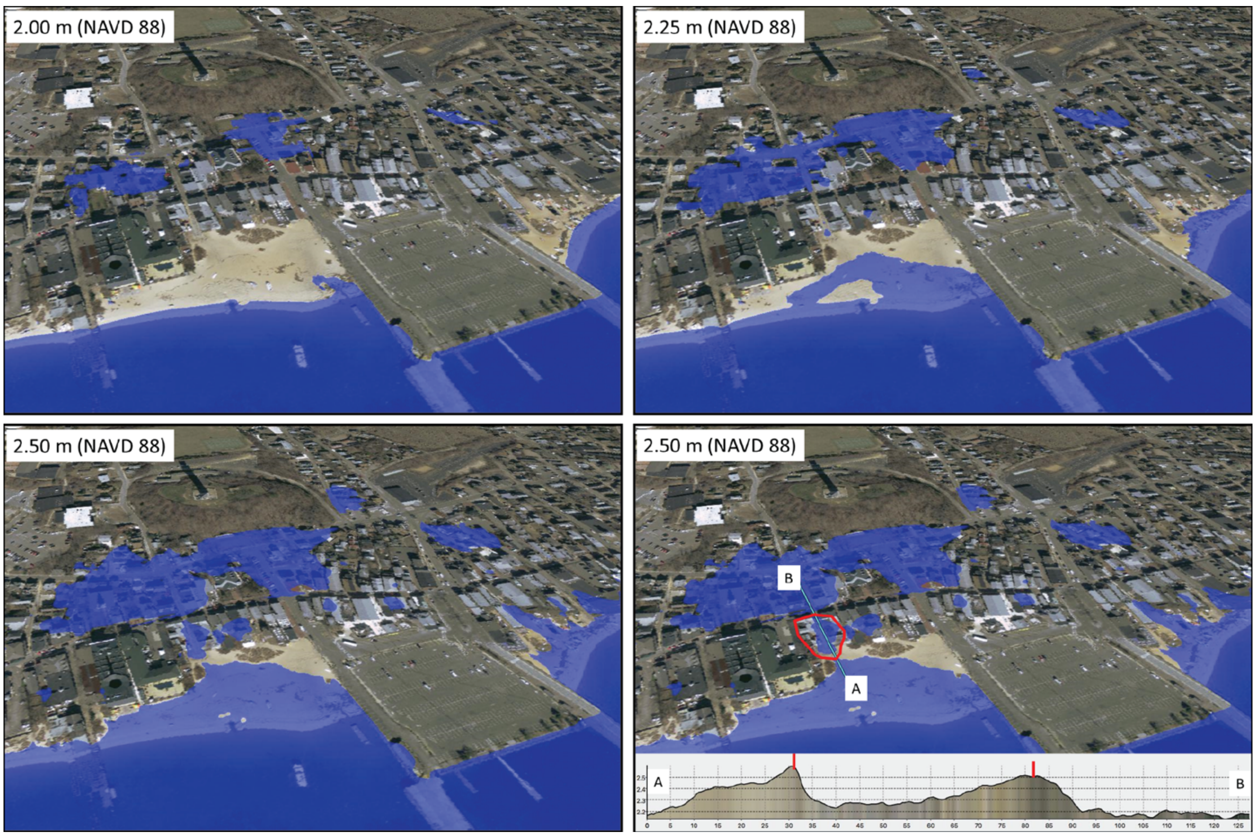

Figure 4. Downtown Provincetown, draped aerial photograph over Lidar surface. Blue areas are horizontal plane created in Fledermaus at increasing elevation. Lower left is example of a storm-tide pathway with accompanying profile. These images were generated before field work to identify potential IPs.

Another invaluable feature of this data visualization software is the ability to drape a 2 dimensional data set such a vertical aerial photograph over a 3D dataset (lidar). This allows the analyst to better document the IP and also to gain valuable information as to the substrate the IP is located in and its landscape setting. For example, an IP found on or near a naturally evolving coastal feature such as a beach or dune would be characterized differently than one atop a concrete wall or other relatively static feature. This is important not only for a final assessment of the most appropriate way to address an IP in a critical area but also serves to inform the field team to more closely examine areas that are naturally evolving and to be vigilant for other to potential IPs in close proximity to the identified point but not present in the lidar. Although as discussed below the GPS was critical for the location of individual IPs, the ability to drape aerial photographs also proved extremely helpful, serving as a quick means of field orientation while placing the potential IP in its broader geographic context. The terrestrial lidar collected in the Spring of 2011 by the NRCS for all of Barnstable county used as the base mapping for the desktop or phase one analysis provided an accurate and extremely useful synoptic elevation dataset that facilitated fieldwork discussed below.

Field Work

Once an inventory of possible IPs was compiled in the desktop exercise, an extensive fieldwork assessment program was conducted to verify the presence or absence of the IP. Further, where the suspected presence of an IP was confirmed, an 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 to setup a terrestrial base station or post-process the GPS data in any way, reducing mobilization and demobilization costs, streamlining the field effort, and maximizing vessel-based survey time.

The Center undertook 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 (error) used to assess and quantify uncertainty. Significantly, there was little difference between the error 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 was a critical component of the IP verification process for several reasons. First, lidar collected via aerial surveys and the post-processing involved can introduce uncertainties that exaggerate or diminish features in three dimensional data and, as a result, obscure or conflate the presence and scale of a storm-tide 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.

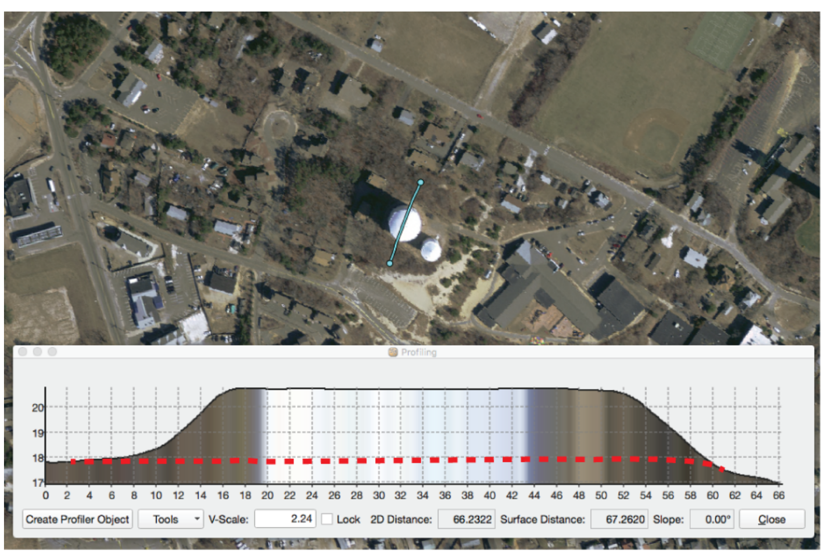

Figure 5. Example of ‘pull up’ near water tower in Provincetown. Dotted line is more representative of elevations at the water tower. Blue line in image is location in profile. Profile units = meters (Vert. NAVD88, Hor. NAD83).

Second, the use of an RTK-GPS instrument affords the high 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 from 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 visible 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 may rapidly out of date in certain dynamic areas. Consequently, the GPS survey 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 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 was inspected by a 3-person team and occupied with the GPS mobile unit. The field team inspected? the lidar data via a laptop in the field in real-time while RTK-GPS data were collected at each location. This served three purposes, first to map the real-world location of the IP identified during the desktop analysis of the lidar data; the second to increase the positional accuracy of the verified IP itself; 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 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 facilitated with 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 cull those points determined not be IPs, incorporate newly identified IPs documented in the field, and provide all IPs with horizontal and vertical position information, substrate and geographic context labels, and other pertinent information for inclusion into a comprehensive database. Once quality controlled, the database was brought into the project GIS for use as an archive of important 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 compilation of the comprehensive IP database, the file was brought into ESRI's ArcGIS to visualize IP locations to provide a working or living archive for local managers to: 1) proactively address IPs prior to storm events; 2) 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 is beyond the scope of the project, the lidar data was used in 2 interactive ways to visualize IP inundation levels and hopefully maximize 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 its 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 1 foot intervals to 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 +1ft; the Storm of Record +2ft; and the Storm of Record +3ft. also provides a useful representation of future sea level rise scenarios that would have practical implications for local managers.

RESULTS AND DISCUSSION

Provincetown Harbor Tidal Profile

As noted above in the Methods section, to document IPs an elevation profile for the community was developed to characterize both storm tides and nuisance flooding within its landscape and landform setting. 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.

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 the astronomical 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 Boston's storm of record and 2 inches below the maximum recorded elevation for the same storm in Provincetown. Recognizing the significance of not only the magnitude of the predicted storm but the time it will occur relative to the stage of the tide, the National Weather Service in Boston, MA maintains an informative website that estimates storm surge and total water level at various stations (http://www.weather.gov/box/coastal) as coastal storms approach New England. Used in conjunction with IPs, this information has the potential to provide valuable short-term response information to emergency managers.

The effects of storm tides on coastal communities are dependent on many factors. These include coastal orientation (e.g., east facing v. south facing shores); the elevations of astronomical tides (e.g., the elevation of mean high water in Boston Harbor is 4.31ft 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 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 – projects). With such variation in physical and cultural characteristics, the initial step in the identification of storm tide pathways for a community is the development of a datum-referenced tidal profile.

Based on conversations with Center staff, on December 31, 2014, the U.S. Geological Survey (USGS) Water Resources installed a datum-referenced (NAVD88, feet) station in Provincetown Harbor. This station now provides a real-time source of 15-minute datum-referenced, water level observations for north Cape Cod Bay. The gage is accessible at the following website: http://waterdata.usgs.gov/ma/nwis/uv/?site_no=420259070105600&PARAmeter_cd=00065,00060.

Prior to 2015, tidal and water level information for Provincetown Harbor was established based on a secondary NOAA tide station (#8446121) established within the Harbor on March 5, 2010 and water level observations recorded for a period of four months from April to July, 2010. The gage was referenced to a station datum memorialized with four benchmarks established around the harbor. Tide station #8443970, the primary tide station located in Boston Harbor and the longest continuously operating station in Massachusetts (since 1921) was used as the control station to publish local tidal datum elevations. These datums represent mean tidal elevations for the 1983 to 2001 National Tidal Datum Epoch (NTDE). Information on the NOAA tide station #8446121 can be found at http://tidesandcurrents.noaa.gov/datums.html?id=8446121.

Recognizing that tidal heights vary with location, the published tidal datums were converted to NAVD88 for reference throughout the project area and for direct comparison with the tidal profiles of other areas. To accurately convert elevations from the Station Datum to NAVD88, the four benchmarks for tidal station # 8446121 were recovered and occupied for 15 minutes each by the Center's RTK GPS to obtain benchmark elevations referenced vertically to NAVD88. Since each benchmark is also referenced to the station datum the published tidal information for # 8446121 was converted to NAVD88. Figure 3 depicts contemporary tidal datums for Provincetown Harbor referenced to NAVD88 and mean lower low water (MLLW), the local tidal or chart datum.

As noted above, NOAA tide station #8443970 located in Boston Harbor is a primary tide station and has been used historically as the control station for published tide information in Cape Cod Bay. Figure 3 depicts the tidal profile for Boston Harbor referenced to NAVD88 and MLLW. Referencing tidal heights to NAVD88 allows for Provincetown and Boston Harbors to be compared directly and as shown in Figure 3 the tidal profiles for the two harbors are very close.

The Provincetown tidal profile was completed with historical research of significant coastal storms to determine, where possible, the elevation of the associated storm tide (astronomical tide + storm surge). APPENDIX A includes a list of references summarizing major coastal storm events and associated storm tide elevations.

With similar tidal profiles, Boston Harbor was used as a proxy for Provincetown Harbor. Table 2 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".

While no tide station was available at this time in Provincetown Harbor, Dr. Graham S. Giese, co-founder of the Center for Coastal Studies, was on scene at MacMillan Wharf to record observations of water height during the Blizzard. Significantly, Dr. Giese referenced the water readings to a 1933 NOAA tidal benchmark, which was recovered as part of this project and occupied with the Center's RTK GPS instrument 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. 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.

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 2. Significant historical storm-tides recorded at the Boston Harbor Tide Station. (#8443970)

Table 3 represents the resulting Provincetown Harbor tidal profile constructed for use in screening potential IPs. As shown by the table, the maximum water level elevation considered in this analysis was the storm tide of record plus 3 feet (12.36ft NAVD88). To evaluate potential nuisance flooding associated with more frequent non-storm tidal 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 3. Provincetown Harbor Tidal Profile

Inundation Pathways

Desktop analysis of the lidar data in phase one yielded 81 potential IPs throughout the study area. Each location was inspected by the 3-person field team. The team incorporated the lidar data via a laptop in the field in real-time while RTK-GPS data were collected at each location. Where necessary, IPs were moved based on field observations when the team determined the 2011 lidar was not representative of the real-world terrain in 2015.

The final IP dataset developed for this project contains 72 storm-tide pathways. There are several types of IPs included in this dataset: standard Storm Tide Pathways (IPs) as discussed above; ‘spillways’ (IP-S); ‘roadways’ (IP-R); and unverified (IP-U) (Table 4). These sub-types, while not initially anticipated, 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)
72	43	15	9	5

Table 4. Summary of Storm Tide 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 6). 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.

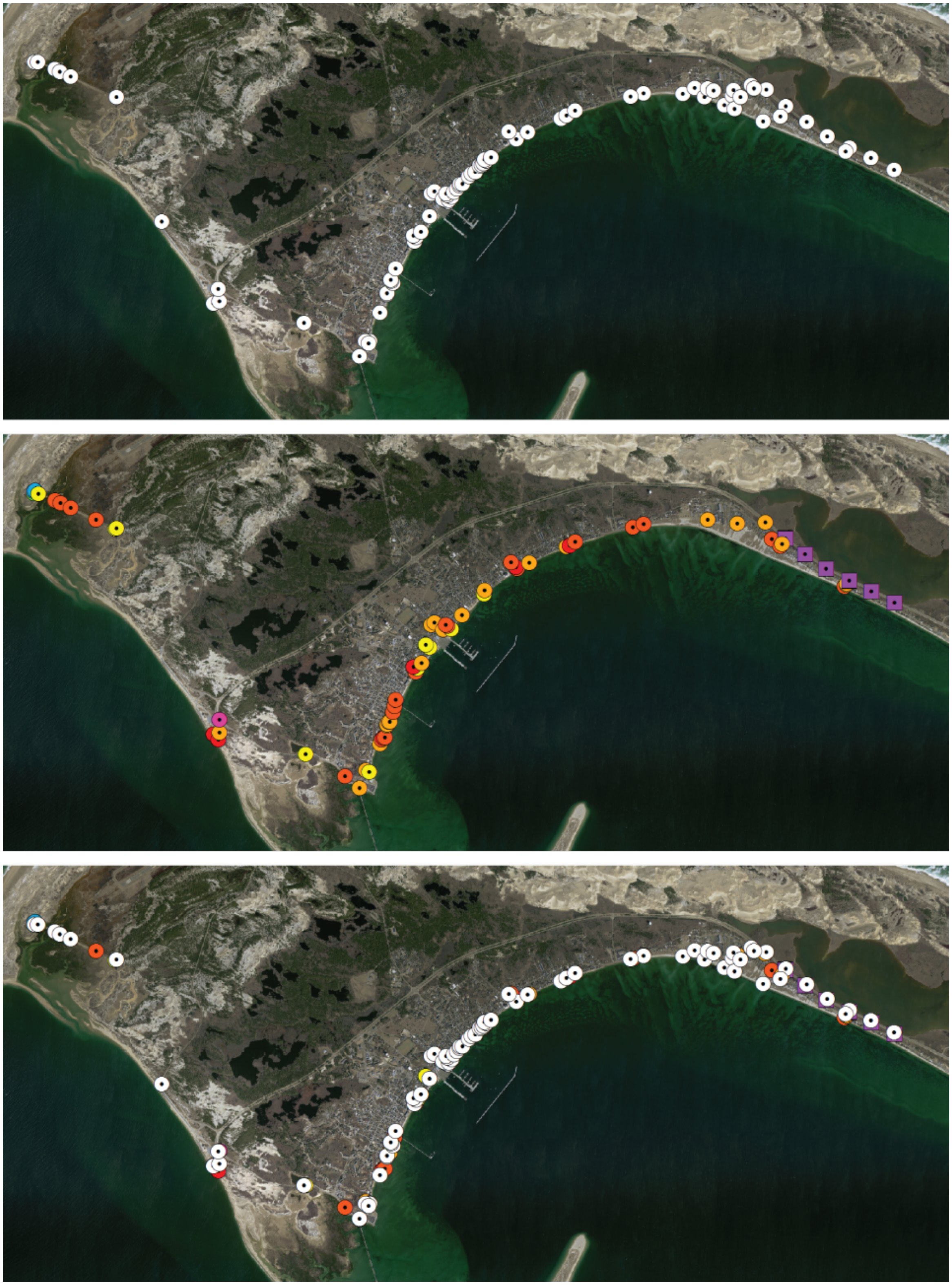

Figure 6. Top: Location of initial locations for IPs based on desktop analysis of lidar. Middle: final location of IPs based on field work. Bottom: pre- and post-fieldwork IPs, several IPs were found based on the fieldwork that were evident in the lidar data.

The roadways IP (IP-R) were delineated as they are associated with those inundation pathways that generally only impact roadways. All nine IP-Rs found in this study were located along Route 6, near East Harbor (Pilgrim Lake). Although relatively low lying (12.2 – 14.2 ft MLLW) the path water would need to take through the IP-Rs would be circuitous and likely occur only when storm surge and wind conditions prevented tidewater from draining over several tidal cycles. As mentioned above, the focus of this study is on identifying and locating storm tide pathways and it does not attempt to quantify the probability of flooding events., Recognizing this, it is likely that, under the right storm conditions, these IP-Rs could receive tidewater flowing from Cape Cod Bay, flooding the gully directly south of Route 6 and then flowing over the road and into East Harbor. While this gully is deep it appears possible that it could fill under certain storm conditions and if deemed critical further analysis could be performed by a qualified coastal engineer.

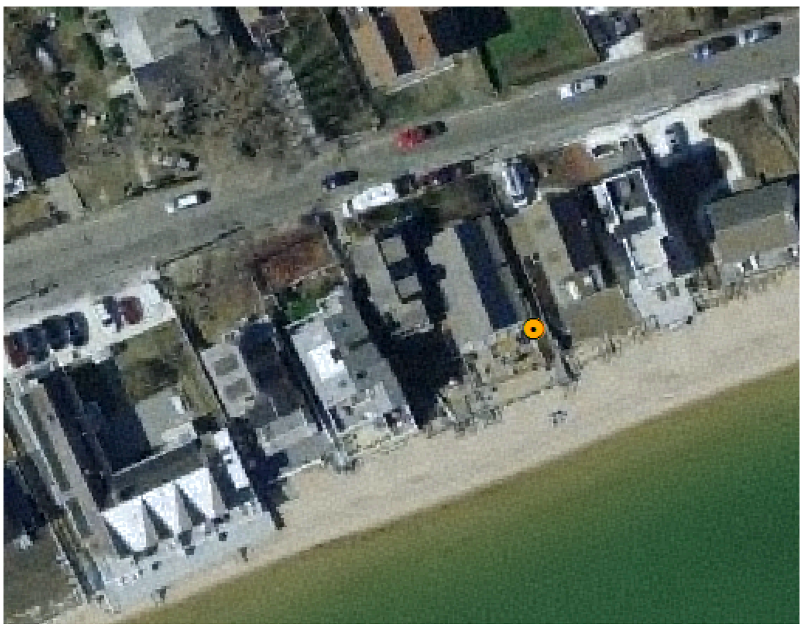

Figure 7. Example of an IP-U. This was an unverified IP as the field team could not lawfully gain access to the exact location of the IP.

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) (IP-U figure) or may in fact have been artifacts of the bare-earth process.

The 5 IP-Us found in this study are in low areas that will experience water flowage but the

Figure 8. Top section of tide staff prior to installation. Pictured, R. McKinsey-Provincetown Harbormaster.

precise location of the IP is unknown. With further analysis the precise location of the IP may be ascertained, but remains beyond the scope of this study.

A tide staff was installed in the harbor at the direction of the Harbormaster. This is a custom-made fiberglass tide staff built to be visible at a distance (Figure 8). This 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 is known to raise ~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 data, as it happens, 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 (Figure 8).

Finally, the tide staff will also provide the public with a more substantial and tangible understanding of coastal inundation and how it relates to their 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.

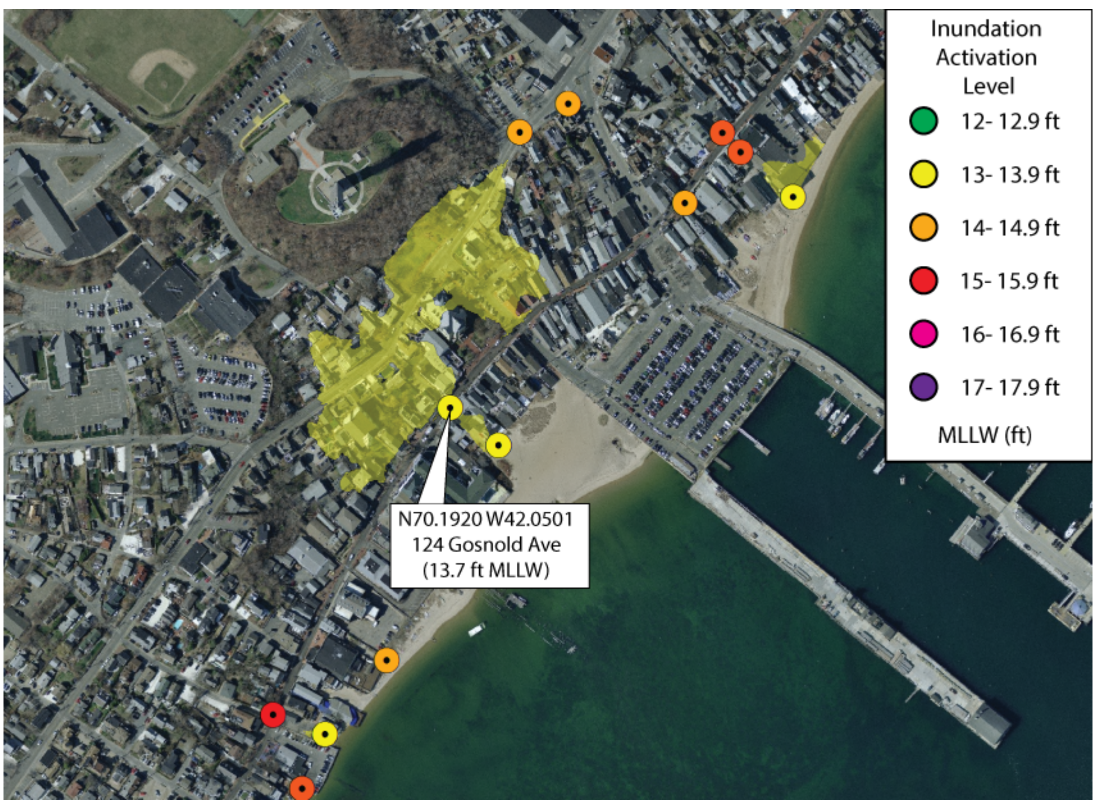

Figure 9. Example of colored coded inundation pathways that match the tide staff elevations in MLLW ft.

This study is deterministic rather than probabilistic, the focus was on creating a high-resolution map of *where* inundation would occur and *when*, or at what water level inundation would begin.

The uncertainties associated with quantifying the *how and why* of coastal flooding, the modelling of storm surge, sea level rise, waves, etc. are prohibitive when dealing with inundation events at the local level by coastal managers. These uncertainties and others are largely removed by the 'where and when' of mapping inundation pathways.

Appendix A

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

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