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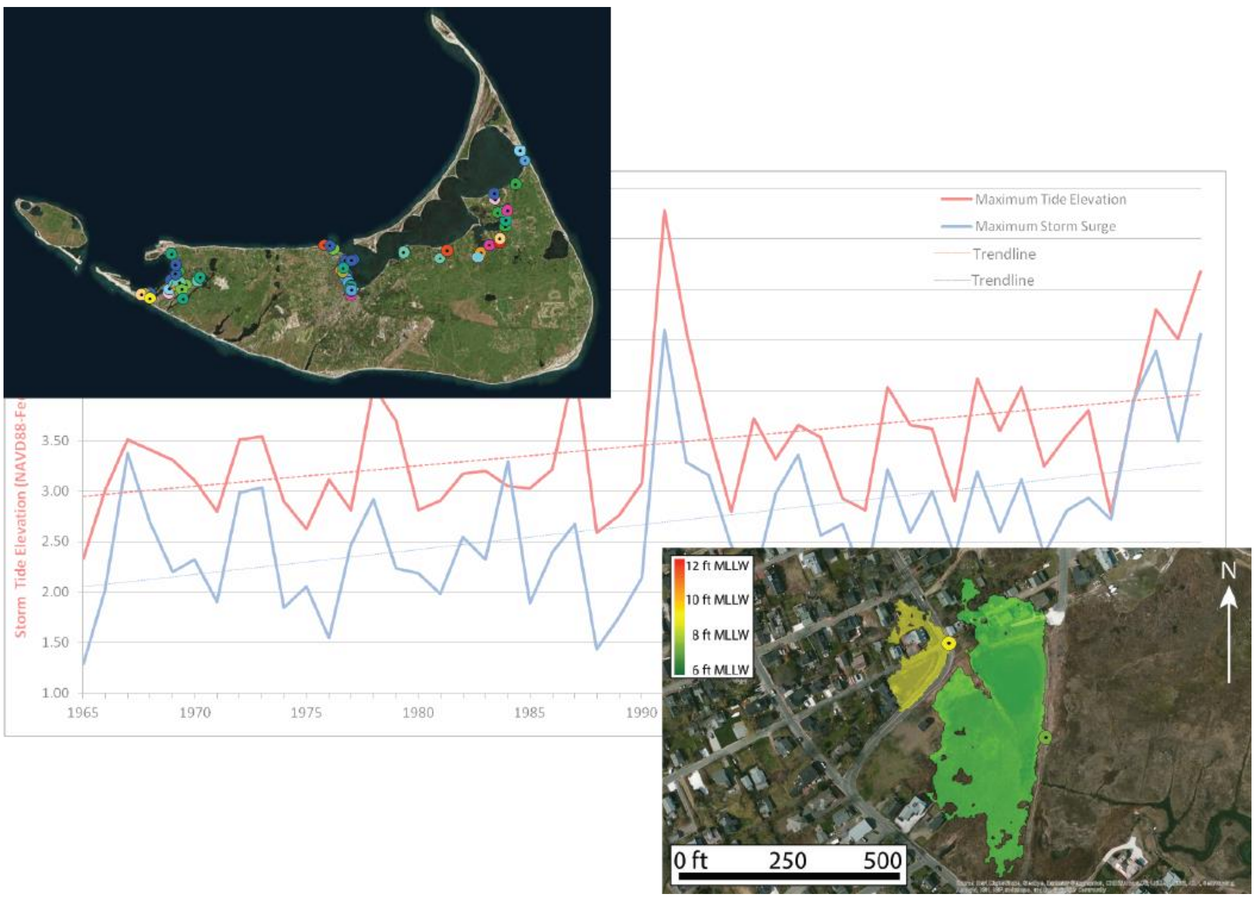
Empowering Coastal Communities to Prepare for and Respond to Sea Level Rise and Storm-related Inundation: A Pilot Project for Nantucket Island



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PROJECT BACKGROUND AND OVERVIEW

The need for coastal managers to be better prepared for low frequency storm-related inundation from such events as Sandy and Katrina, as well as periodic nuisance flooding associated with increasing astronomical tides was the impetus for this project. Recognizing that many coastal municipalities often do not have the resources or expertise to manage and maintain a complicated Geographic Information System (GIS), this project uses existing topographical information and actual water levels from historical storm events to identify pathways through which coastal floodwaters may be carried. With results linked to local tide levels, in conjunction with National Weather Service (NWS) storm surge forecasts, one goal of this study is to provide information that local emergency managers can use to take action in preparation for, and response to, coastal storm threats.

The second objective of this project is to provide managers with information that will help identify longer term local planning needs in response to changing and uncertain environmental conditions. As coastal populations, both seasonal and year-round, continue to increase, 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 protection actions; and the need to undertake actions in the face of the unavoidable uncertainties inherent with century-scale sea level rise projection scenarios. Traditionally (and necessarily) short-term actions and effective responses, implementable at the local level, are not easily defined within the context of sea level rise discussions. Significantly, the results of this study are by design independent of the various sea level rise scenarios and can be used, therefore, to develop action plans within the planning horizon of most communities.

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 storm tides (the combination of storm surge and the astronomical tide level) and flooding 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 a standard planning resource for coastal communities. These maps, however, were intended to facilitate the determination of flood insurance rates and lack the planimetric detail necessary for focused planning efforts. Until recently the accuracy of relatively low cost topographic data has been appropriate only for general planning at regional scales and not for identifying storm-tide 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 often too coarsely-scaled to inform local decisions facing coastal managers and municipalities.

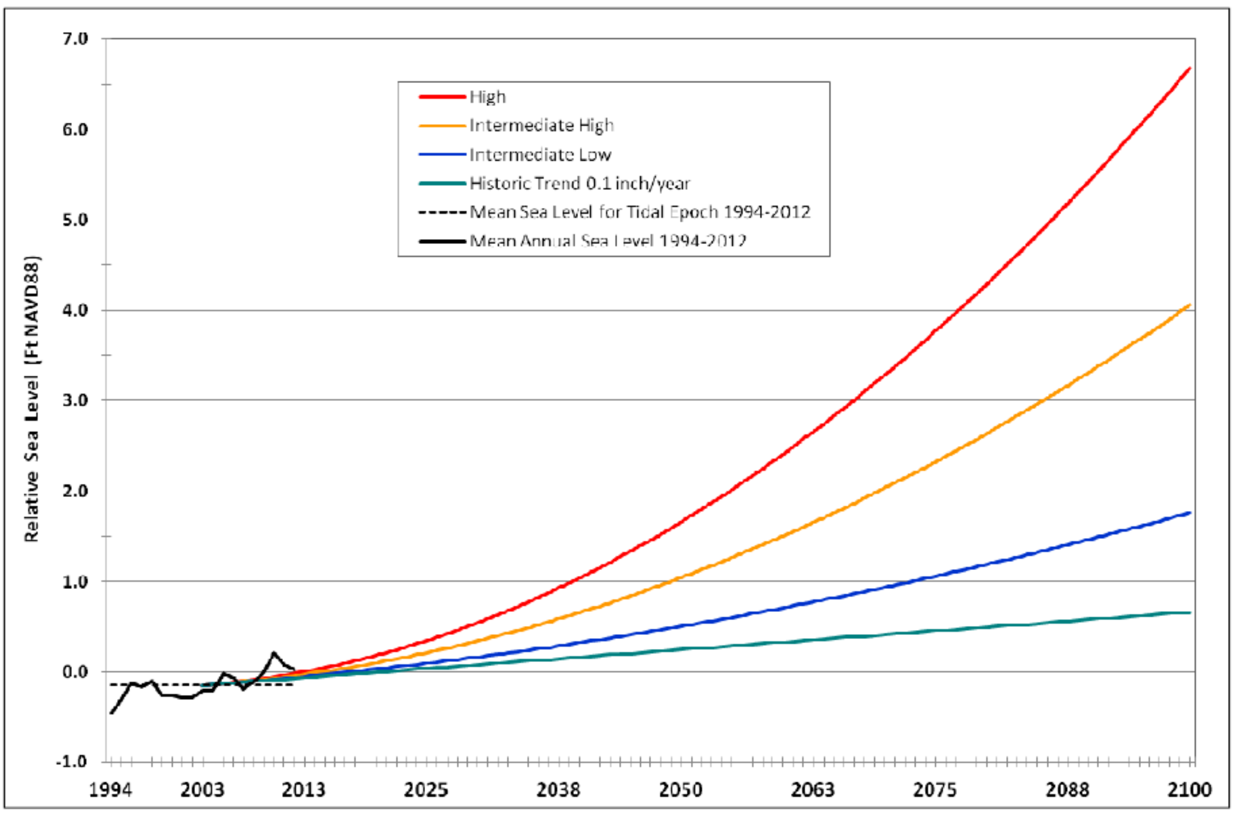

Figure 1. Relative sea level rise scenario estimates (in feet NAVD88) for Boston, MA. Taken from, *Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning. Massachusetts Office of Coastal Zone Management, December 2013. Available at: http://www.mass.gov/eea/docs/czm/stormsmart/slr-guidance-2013.pdf.)*

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 to slow the rate of, or reverse, sea level rise. Strategies to reduce Green House Gas (GHG) emissions and promote green energy to deal with rising temperatures, glacial ice melt, and thermal expansion of seawater 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 when considered in the context of short-term planning horizons, limited financial and technical resources, 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 can provide an effective means of characterizing coastal hazard vulnerability for local planning actions. 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 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 storm tide 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 Storm Tides 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 can be used by coastal managers as the initial basis for developing inundation scenarios that communicate threats associated with coastal storms. Although continuing to improve in vertical accuracy, the use of lidar alone to map areas of storm vulnerability and to develop community response strategies remains limited. Recognizing these 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, can be used to accurately identify and prioritize potential coastal hazards at the local level in a cost effective manner.

This project began in the fall of 2014, at that time the best available lidar data suited for the purposes of this study was from 2010; FEMA collected lidar data in Coastal Massachusetts and Rhode Island. The horizontal and vertical accuracies of this publicly accessible contemporary elevation data provide a reliable base map and can be used as the foundation for local action planning. All of the desktop analysis had been completed using the 2010 lidar. During the course of this study the United States Geological Survey (USGS) collected lidar data on Nantucket as part of the "Sandy Project'. This project involved collecting data in and around areas effected by Hurricane Sandy. These data were of better quality and wider coverage than the 2010 lidar data. After the USGS data were released all of our work was checked against the old lidar and it was determined that all of the final spatial (elevation) data would come from the newer, more accurate lidar data. This involved duplicating almost the entire desktop analysis portion of the study, but was done to provide Nantucket with the best available elevation data in the final product.

Using lidar data to guide accurate fieldwork, this study mapped the low-lying locations through which the elevated water levels associated with coastal storms might flow into Nantucket, Massachusetts. These locations are referred to herein as "storm tide 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. Another contemporaneous study funded through the same grant program uses the term "inundation pathways', this term is interchangeable with storm tide pathways (STP).

Generally, STPs, by virtue of their elevation relative to the elevation of the storm tide, provide a direct hydraulic 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.); low lying infrastructure that can serve as unintended conduits (e.g., storm water system, sanitary sewers, electrical/utility conduits); 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.

PROJECT METHODOLOGY

Spatial Analysis

Based on the characterization of the Nantucket Harbor tidal profile discussed below, the analysis begins in the lab by using state-of-the-art software to superimpose various water levels on the existing elevation (lidar) data in three dimensions to identify potential STPs. To compile a list of potential STPs this desktop analysis relies on best available synoptic elevation data to serve as the study are base map for the project GIS.

For this purpose, the latest lidar data were downloaded from the NOAA website (https://coast.noaa.gov/digitalcoast/). This website has default settings for horizontal and vertical reference datums, spheroid and projection parameters, and units (metric vs standard). For the purposes of this study CCS 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 and the final data products are referenced to MLLW datum for Nantucket Harbor, to simplify use at the local level and for quick and direct comparison with NOAA's real time tide station located in Nantucket Harbor.

The data are downloaded in a raster format and brought into ESRI's ArcGIS software where the raster is divided into smaller tiles. 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 STPs with the accuracy of the initial analysis 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 very rapidly moves through the data for visual inspection ('fly-throughs') and similar functions. A horizontal plane, representing a specific water elevation can be added to a Fledermaus project or 'scene' and that plane can be changed to simulate the increase or decrease in water level until it first reaches an STP.

Another invaluable feature of the data visualization software is the ability to drape a 2-dimensional data set, such as a vertical aerial photograph, over a 3D dataset (lidar). This helps the analyst to better document the STP and also to gain valuable information as to the substrate conditions and landscape setting in which the potential STP is located. For example, an STP found on or near a naturally evolving coastal feature such as a beach or dune is characterized differently than one atop a concrete wall or other relatively static feature. This observation serves to inform the field team to examine naturally evolving areas closely and to be vigilant for other potential STPs that may be in close proximity to the identified point but, due to the dynamic nature of the area, not present in the lidar. This characterization is also important for a final assessment of the most appropriate way to address an STP in a critical area.

As an accurate and synoptic dataset, the terrestrial lidar collected in 2010 by FEMA was selected to be the base map for the desktop analysis and STP identification phase. With metadata reporting horizontal and vertical accuracies of +/- 1.0 m and +/- 0.15 m respectively, this dataset proved to be a reliable source from which to compile the initial STP base map and facilitated the fieldwork phase discussed below. Again, as discussed above, the 2013-2014 USGS lidar was used to produce the final datasets.

Field Work

At the completion of the desktop analysis, all potential STPs were compiled into a database with x, y, z coordinates, uploaded into the Center's GPS, and an extensive fieldwork assessment program conducted to verify the presence or absence of each STP. The stored coordinate file and GPS were used to navigate to each potential STP and when confirmed by visual inspection of the three-person team, an accurate horizontal and vertical location obtained. With the collection of GPS data, lidar data loaded into a laptop to assist with fieldwork were inspected for each point in real-time. This served three purposes: first to compare the real-world position of the STP with that found during the desktop lidar analysis; the second to verify the positional accuracy of the STP itself; and lastly to serve as a qualitative check on the positional accuracy of the lidar data.

Significantly, using the GPS instrument to navigate to the location of a potential STP also afforded the field crew the opportunity to investigate alternative or additional STPs based on visual inspection of the area. Many coastal sites have very low relief (relatively flat) and verifying whether an STP 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.

A Trimble® R8 GNSS receiver utilizing Real-Time-Kinematic GPS (RTK-GPS) was used for all positioning and tide correction field work. 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 establish a terrestrial base station or to post-process the GPS data, reducing mobilization and demobilization costs and streamlining the field effort.

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 were occupied with published coordinate values relating to the Massachusetts Coordinate System, Mainland and

Island Zones (horizontal: NAD83; vertical NAVD88). Control points were distributed over a wide geographic area of Cape Cod and Nantucket.

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).

This fieldwork program is a critical step for several reasons. First, lidar collected via low flying aerial surveys and the post-processing involved can introduce uncertainties that exaggerate or diminish features in three dimensional data that could obscure or conflate the presence and scale of a storm-tide pathway. This has been shown to be particularly evident in cases of ‘bare earth’ models where elevations tend to be “pulled up” in areas adjacent to where buildings are removed and “pulled down” in areas of bridges or where roads cross streams or creeks (Figure 2).

Second, the use of an RTK-GPS instrument provides the best possible accuracy for acquiring and verifying 3-dimensional positional data, such as lidar. Thus the GPS data can corroborate, or refute the presence of STPs identified in the desktop analysis. Further, due to the dynamic nature of coastal environments, fieldwork and careful visual inspection are critical steps to ensure that potential STPs not identified by the desktop analysis are documented while in the field.

Finally, due to the ephemeral characteristics of the areas proximate to the shoreline, even the most current lidar is rapidly out of date in certain areas. Consequently, GPS fieldwork is critical to identify preliminary STPs that appeared in the lidar but no longer exist due to changes in landform.

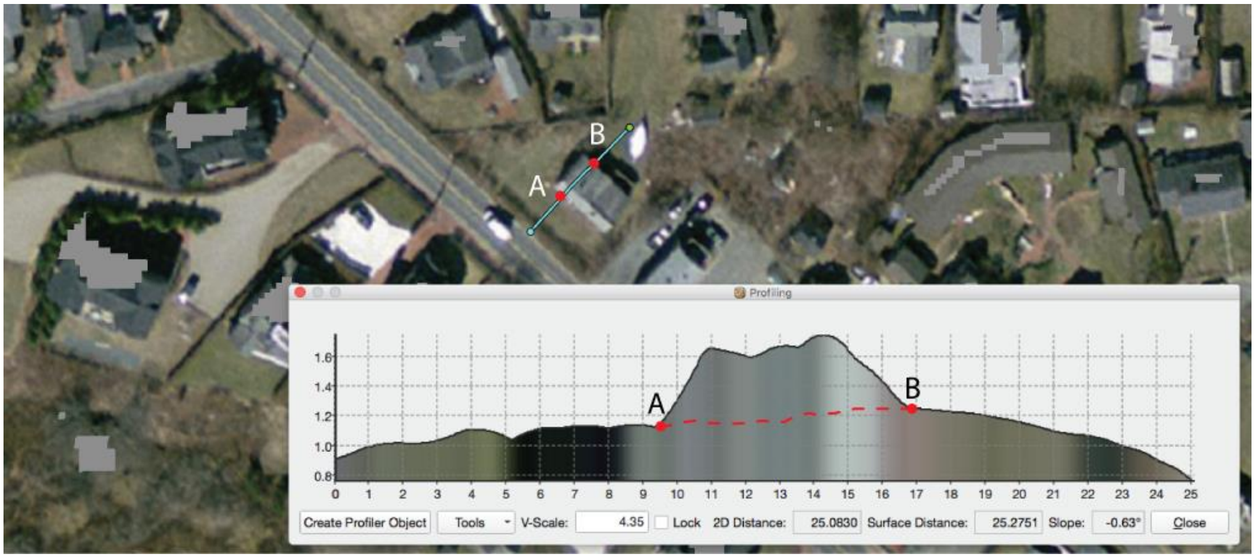

Figure 2. Example of 'pull-up'. The image is an aerial photograph draped over the 2010 lidar for Nantucket. The area above the red dotted line should have been removed by the 'Bare Earth' algorithm but a remnant still remains. The 20-40 cm remnant is a small fraction of the building height but still represents 67 – 133 years of sea level rise (at the current rate of 3 mm/yr).

With the completion of the fieldwork, the team returned to the lab to remove points determined not be STPs and to add new STPs identified and documented as part of the fieldwork. In addition, the database was expanded to incorporate labels for all STPs including position, elevation, substrate condition, and other pertinent descriptive information. This comprehensive database, associated with individual STP shapefiles, was then incorporated into the project GIS for further analysis. 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 STP.

With the compilation of the comprehensive STP database, the file is brought into ESRI's ArcGIS to visualize STP locations and provide a working tool for local managers to: 1) proactively address STPs prior to storm events; 2) prepare for approaching storms; and 3) to plan for longer-term improvements to mitigate other STPs.

Recognizing that accurate field delineation of the extent of inundation for each STP is beyond the scope of the project (i.e., GPS mapping of a flood zone for each STP), the USGS lidar data were used in 2 interactive ways to provide additional utility by visualizing STP inundation levels. The first depiction is referred to as the Pathway Activation Level (PAL). This data layer is developed to show the approximate extent of inundation for the elevation at which water begins to flow over an STP. It is delineated as the contour representing the STP elevation as extracted from the lidar. For example, based on the GPS fieldwork, an STP with a PAL of 8.6' MLLW implies that the moment the water reaches this elevation water will begin to flow inland via the STP. Using the data visualization software, a water elevation of 8.6' MLLW is then used to trace the area that is hypothetically 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, (i.e., higher than 8.6' MLLW), however, obviously more area would be inundated leading to the need for a second way to visualize STPs.

For this reason and to increase the utility of the STP data and make visualizations more user-friendly inundation levels were grouped into ranges. Referred to as Inundation Ranges (IRs), these layers were representing ranges of water levels for the entire study area rather than creating PALs for every STP and all potential flood elevations. The IR visualizations are based on a series of iterations of potential inundation scenarios, including nuisance flooding. Reviewing various scenarios, that the lower end of the IR range reflects the highest Spring tide of the year. Due to low tide range (approx. 3.0 feet) and the relatively low relief of Nantucket's coastal areas, range elevations reflect 0.5' foot intervals. The IR visualizations can be used to approximate conditions up to a maximum elevation of the Storm of Record plus three feet. In addition to providing an upper limit to project elevations, it was felt that extending half foot ranges to his elevation the provides a useful representation of future sea level rise scenarios with practical implications for local managers. The development of Inundation Ranges for the entire Island of Nantucket was not included in the project description but it was felt that this would be an invaluable product for the coastal managers and was included in the final deliverables.

NANTUCKET HARBOR TIDAL PROFILE

As discussed above there is a clear need for reliable sea level rise projections to inform long-term planning efforts and public policy decisions. For shorter term community planning decisions and real-time decisions required by Emergency Managers, Public Works Departments, Harbormasters and Coastal Resource Managers, however, historical data and measurements obtained from actual coastal storms and related storm tides can provide an important source of baseline information.

In addition to major inundation that often accompanies coastal storms, as relative sea level continues to rise, many coastal communities are also beginning to experience minor flooding associated 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 inundation is becoming more frequent 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).

As noted in the Methods section, the first step in assessing IPs involves the development of a tide profile for the community of interest that characterizes elevations of local astronomical tides, historical storm tides, and the possibility of 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 should include datum referenced storm tides of the past, including the elevation of the maximum storm tide experienced (i.e., the storm of record), and capture potential future storm tides (and sea level rise) by adding four feet to the storm of record.

As mentioned above 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.

In addition to the magnitude of a storm surge, 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 when the maximum storm surge occurs relative to the stage of the astronomical tide is illustrated by the following example.

Based on fifty years of readings, the storm of record for the Nantucket Tide Gauge (#8449130) occurred on October 30, 1991 (Halloween Gale of '91) at approximately 5:00 p.m. with a maximum storm tide elevation of 7.87' MLLW (5.78' NAVD88). Occurring approximately an hour before the time of the predicted or astronomical high tide, the contributing storm surge was approximately 4.2 feet. Although the maximum storm surge for this storm was 4.6 feet because it occurred at 3:00 p.m. while the tide was still rising, the associated water elevation was "only" 7.18' MLLW or approximately 0.7' lower than the eventual storm of record.

By comparison, the maximum storm tide elevation recorded on the same gauge during the blizzard of January 27, 2015 (Coastal Storm Juno) was 10.25' MLLW (8.16' NAVD88). Occurring shortly after the predicted high tide, this elevation resulted from the combination of an astronomical tide height of 6.88' MLLW (4.79' NAVD88) and a storm surge of 3.37 feet. Although the maximum storm surge for this event was observed to be approximately 4 feet, because it occurred close to the time of the predicted low water, the corresponding storm tide elevation was only 1.0' MLLW (-1.1' 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 approximately 7.7' MLLW (5.6' NAVD88), approaching the elevation of the storm of record. 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 Southern New England Weather Forecast Office of the National Weather Service (SNEWFO-NWS) has been working on an experimental website (accessible at http://www.weather.gov/box/coastal) that estimates storm surge and total water level for various locations as coastal storms approach New England.

The effects of storm tides on coastal communities are dependent on many factors. These include:

- The shoreline orientation of the community (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 4.31 feet NAVD88 v. the elevation of mean high water for Woods Hole is 0.56' NAVD88);
- general characteristics of astronomical tides (e.g., the average range (MHW-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 rocky 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 landmaking efforts).

With such variation in physical characteristics, the initial step in the identification of inundation pathways for a community is the development of a datum-referenced tidal profile.

The Nantucket Island tide station (#8449130) was first installed by the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS) on October 4, 1963. This station, located on Steamship Wharf, was replaced with the present station on September 18, 1990. As an island, the ability to connect tidal information by traditional survey methods with former geodetic datums such as the National Geodetic Vertical Datum of 1929 (NGVD29) presented certain problems. For this reason, until recently, station #8449130 was referenced to the station and local tidal datums. Benchmarks established at various locations near the waterfront as early as 1934 served to memorialize the relationship between gauge readings and these local datums (Table 1).

Primary Benchmark Stamping	**Designation**	**Year First Established**
TBM[1] NO 25 1968	844 9130 Tidal 25	1968
TBM NO 22 1934	844 9130 Tidal 22	1934
TBM NO 23 1934	844 9130 Tidal 23	1934
9130 G 1976	844 9130 G	1976
9130 H 1976	844 9130 K	1976

Table 1. Tidal Benchmarks on Nantucket Island

In June of 2012, NOS established elevations, referenced to the North American Vertical Datum on 1988 (NAVD88) on an existing National Geodetic Survey control point. Referred to as Tidal Bench Mark 8449130 K (NGS PID AJ 4032), this benchmark is located across the Harbor on the grounds of the U.S. Coast Guard Base Brant Point. As a primary benchmark for Tidal Station #8449130, the center for Coastal Studies (CCS) occupied this point with its RTK GPS and found close agreement with the reported horizontal (NAD83) and vertical (NAVD88) values. In addition, CCS recovered and occupied the following benchmarks established for tidal station #8449130. The results of the survey agreed closely and were used to develop the following relationship between local MLLW and NAVD88.

$$\text{Elevation}_{\text{MLLW}} + 2.09 \text{ feet } (0.68\text{m}) = \text{Elevation}_{\text{NAVD88}}$$

$$\text{Elevation}_{\text{STATION DATUM}} - 3.00 \text{ feet } (-0.91 \text{ m}) = \text{Elevation}_{\text{MLLW}}$$

This relationship between MLLW and NAVD88 is shown graphically on Figure 3**.** The tidal datums represent average tidal elevations computed for the 1983 to 2001 National Tidal Datum Epoch (NTDE). Recognizing that tidal heights vary with location around the Island, on the strength of the historical tide information, the published tidal datums for the Harbor were converted from the station datum to NAVD88 and used as the reference throughout the project area and for direct comparison with the tidal profiles of other areas. Information for NOAA tide station #8449130 can be found at http://tidesandcurrents.noaa.gov/stationhome.html?id=8449130#info providing a real-time source of 6-minute water level observations for Nantucket Harbor and the Sound.

Table 2 depicts the highest tide and storm surge for each year from 1965 to 2015 referenced to NAVD88 and MLLW. The maximum storm surge and the maximum storm tide rarely occur on the same day. Figure 3 shows a plot of the maximum annual values of Table 2. While data points are widely dispersed, it is interesting to note that the trendlines for both data sets indicate an increase in the maximum annual storm tide and storm surge over the past 50 years.

Maximum Tide Elevation (Feet) *				Maximum Storm Surge (Feet)	
Year	**Date**	**NAVD88**	**MLLW**	**Date**	**Feet**
1965	07/01/65	2.33	4.42	2/25/65	1.29
1966	12/29/66	3.01	5.10	1/23/66	2.02
1967	04/29/67	3.51	5.60	5/28/67	3.38
1968	11/22/68	3.41	5.50	11/10/68	2.69
1969	02/10/69	3.31	5.40	2/10/68	2.20
1970	01/08/70	3.11	5.20	12/26/70	2.32
1971	01/01/71	2.80	4.89	3/28/71	1.91
1972	01/02/72	3.51	5.60	2/19/72	2.99
1973	03/23/73	3.54	5.63	3/22/73	3.03
1974	08/18/74	2.90	4.99	12/2/74	1.85
1975	12/22/75	2.63	4.72	11/25/75	2.06
1976	03/17/76	3.12	5.21	1/22/76	1.54
1977	10/14/77	2.81	4.90	1/7/77	2.47
1978	02/07/78	4.04	6.13	2/6/78	2.92
1979	01/25/79	3.70	5.79	1/25/79	2.23
1980	03/22/80	2.81	4.90	3/22/80	2.18
1981	11/16/81	2.91	5.00	12/6/81	1.98
1982	10/09/82	3.17	5.26	4/6/81	2.55
1983	11/25/83	3.20	5.29	2/12/83	2.32
1984	03/29/84	3.05	5.14	3/29/84	3.30
1985	01/05/85	3.03	5.12	3/12/85	1.89
1986	12/31/86	3.22	5.31	11/19/86	2.40
1987	01/02/87	4.25	6.34	11/12/87	2.67
1988	01/26/88	2.59	4.68	4/11/88	1.44
1989	01/07/89	2.76	4.85	2/24/89	1.75
1990	12/04/90	3.08	5.17	10/27/90	2.15
1991	10/30/1991**	5.78	7.87	10/30/1991**	4.60
1992	12/12/92	4.60	6.69	12/12/92	3.29
1993	12/16/93	3.61	5.70	3/13/93	3.16
1994	03/04/94	2.80	4.89	12/23/94	2.46
1995	12/20/95	3.72	5.81	12/20/95	2.10
1996	01/08/96	3.31	5.40	1/8/96	2.98
1997	01/10/97	3.65	5.74	4/19/97	3.36
1998	01/29/98	3.53	5.62	2/6/98	2.56
1999	12/01/99	2.93	5.02	12/1/99	2.68
2000	12/12/00	2.82	4.91	1/25/00	2.10
2001	03/07/01	4.03	6.12	3/7/01	3.22
2002	11/06/02	3.66	5.75	12/26/02	2.59
2003	01/04/03	3.62	5.71	12/7/03	3.00
2004	11/13/04	2.91	5.00	12/26/04	2.35
2005	01/23/05	4.12	6.21	1/23/05	3.20
2006	01/31/06	3.60	5.69	2/12/06	2.60
2007	11/03/07	4.03	6.12	11/3/07	3.11
2008	01/28/08	3.25	5.34	1/28/08	2.37
2009	06/22/09	3.55	5.64	12/20/09	2.81
2010	01/02/10	3.80	5.89	12/26/10	2.94
2011	09/30/11	2.78	4.87	10/30/11	2.72
2012	10/29/12	3.89	5.98	10/29/12	3.90
2013	02/09/13	4.80	6.89	2/9/13	4.39
2014	01/03/14	4.51	6.60	1/3/14	3.50
2015	01/27/15	5.18	7.27	1/27/15	4.56

* Elevations before 1996 based on hourly readings estimated to be within 0.5' of maximum elevation

** Storm of Record - Note: Maximum water elevation did not occur at time of maximum storm surge.

Table 2 Maximum Annual Storm Tides and Storm Surges recorded at the Nantucket Harbor Tide Station. (#8449130) since 1965

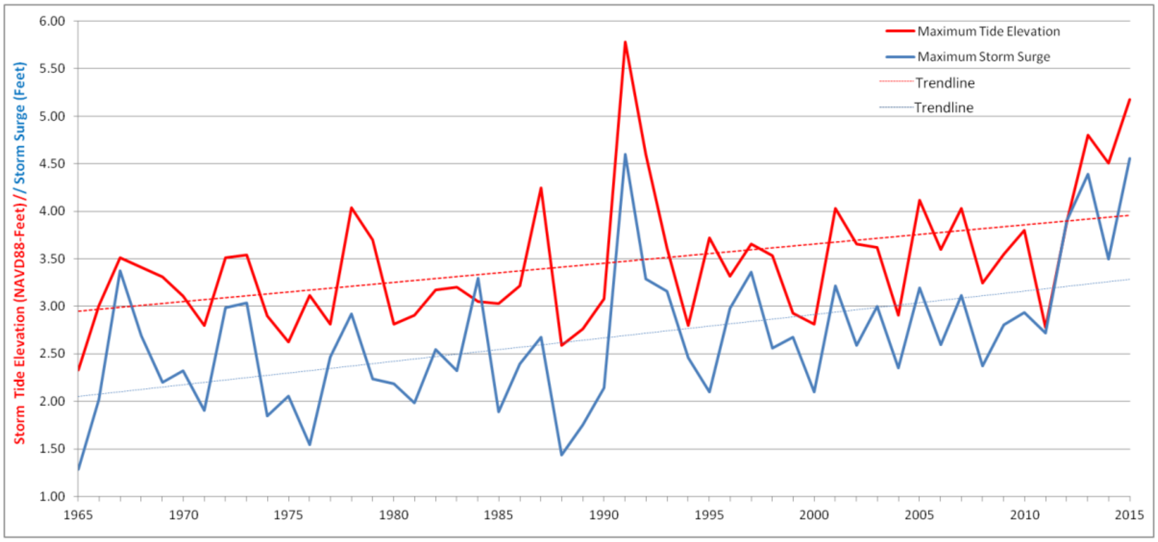

Figure 3 Plot of Maximum Annual Storm Tides and Storm Surges recorded at the Nantucket Harbor Tide Station. (#8449130) since 1965. Note upward trendlines.

Based on historical research, Table 3 ranks the top twenty storm tides experienced in Nantucket Harbor since 1963. Referenced to NAVD88 and MLLW, the increase in elevation between the top 5 tides is approximately a 1 foot; between the top ten tides approximately a foot and a half; and between the top twenty tides approximately 2 feet. The relative closeness of these rankings further illustrates the importance of the not only the magnitude of storm surge but when it occurs relative to the time of high tide.

Nantucket Harbor (Station 8449130)
Highest Recorded Water Levels

Rank	Date	NAVD88 (Ft.)	MLLW (Ft.)
1	10/30/1991	5.78	7.87
2	1/27/2015	5.18	7.27
3	2/9/2013	4.80	6.89
4	12/12/1992	4.60	6.69
5	1/3/2014	4.51	6.60
6	1/2/1987	4.25	6.34
7	1/23/2005	4.12	6.21
8	2/7/1978	4.04	6.13
9	3/7/2001	4.03	6.12
10	11/3/2007	4.03	6.12
11	10/29/2012	3.89	5.98
12	1/2/2010	3.80	5.89
13	12/20/1995	3.72	5.81
14	1/25/1979	3.70	5.79
15	11/6/2002	3.66	5.75
16	1/10/1997	3.65	5.74
17	1/4/2003	3.62	5.71
18	12/16/1993	3.61	5.70
19	1/31/2006	3.60	5.69
20	6/22/2009	3.55	5.64

Table 3. Top 20 historical storm-tides recorded at the Nantucket Harbor Tide Station. (#8449130) since 1965

Using this information and historical resources, Table 3 represents the tidal profile used to screen IPs for Nantucket Harbor and the surrounding areas. APPENDIX A includes a list of references considered in developing this profile. As shown by the table, the maximum storm tide elevation considered in this analysis was the storm tide of record plus 6 feet (13.78' NAVD88). A review of the NOAA tide charts for Nantucket Harbor indicated that the maximum astronomical high water predicted for 2015 was 2.21' NAVD88. To evaluate potential nuisance flooding associated with more frequent non-storm tidal events, this elevation was used as the beginning level for the IP analysis.

Nantucket Harbor Tidal Profile Station: 8449130			
	NAVD88 (FT)	MLLW (FT)	Comments
Storm of Record plus 6 Feet	11.78	13.87	Upper Limit of Storm Tide Pathway Analysis
Significant Flooding	7.91	10.00	SNEWFO-NWS Significant Flooding low lying areas, road closures, evacuations, high erosion
Major Flooding	5.91	8.00	SNEWFO-NWS
Halloween Storm (Oct. 30, 1991) Storm of Record	5.78	7.87	Storm of Record Based on 50 Year record NOAA Tide Station 8449130
Blizzard of 2015	5.13	7.22	NOAA Tide Station #8449130
Moderate Flooding	3.91	6.00	SNEWFO-NWS Flooding low lying areas, Harbor, & Atlantic Ave. Some evacuations expected
Minor Flooding	2.91	5.00	SNEWFO-NWS (Moderate flooding in Harbor & some low lying roads)
Action Stage 2	2.41	4.50	SNEWFO-NWS (Minor flooding on Easy St)
Maximum 2015 Predicted High	2.21	4.30	From 2015 NOAA Tide Predictions
Action Stage	1.91	4.00	SNEWFO-NWS
MHWS	1.75	3.84	NOAA Tide Station #8449130
MHHW	1.49	3.58	NOAA Tide Station #8449130
MHW	1.15	3.24	NOAA Tide Station #8449130
MSL	-0.32	1.77	NOAA Tide Station #8449130
MTL	-0.37	1.72	NOAA Tide Station #8449130
MLW	-1.89	0.20	NOAA Tide Station #8449130
MLLW	-2.09	0.00	NOAA Tide Station #8449130

* Denotes Storm Tide Action Level from Southern New England Weather Forecast Office of the National Weather Service experimental Coastal Flood Threat and Inundation Mappingwebpage (http://www.weather.gov/box/coastal)

Table 4. The Nantucket Tidal Profile.

For reference purposes, Table 4 also includes coastal flood stages established by the Southern New England Weather Forecast Office of the National Weather Service (SNEWFO-NWS) as part of its experimental *Coastal Flood Threat and Inundation Mapping* webpage. Original levels referenced to local MLLW have been converted to NAVD88 for comparative purposes. The flood stages and corresponding action alerts can be summarized generally as follows:

- **Action Stage**: NWS or a partner/user needs to take some type of mitigation action in preparation for possible significant storm related impacts.
- **Minor flooding:** minimal or no property damage is anticipated but there may be some public threat associated with a possible storm.
- **Moderate Flooding:** some inundation of structures and roads and some evacuation of people and/or transfer of property to higher elevations are anticipated.
- **Major Flooding:** extensive inundation of structures and roads and significant evacuation of people and/or transfer of property to higher elevation are anticipated.

Due to the low relief (flatness) of waterfront areas, such as the downtown harbor region, where a slight vertical rise in water level can affect large horizontal areas, it is clear why the elevations defining the lower stages are so close.

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 most coastal residents know, 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 high tide, correspondingly, one low tide is lower than the other (Table 5). 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).

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

[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.

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.

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 5. Common Tidal Datums (Source: NOAA, 2000b).

As an island and presumably because of its distance offshore connecting Nantucket to a geodetic, mainland vertical datum does not lend itself to traditional surveying methods and NGVD29 was never formally adopted for the Island. As a result, Island datums, based on local tidal information and memorialized by benchmarks, were adopted for work requiring a tidal connection. Probably the most widely used, the *Half-tide Level of 1934*, was based on tidal readings of the 1930s and was used for among other things as the vertical plane of reference for the initial series of Flood Insurance Rate Maps (FIRMs). An example of another tidal datum encountered on the island is the Mean Low Water datum of 1992 (MLW of 1992), which presumably was derived based on tidal observations in the early 1990s.

NAVD88, is a fixed vertical reference system, similar in nature to NGVD29, 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.

Based on field work conducted by CCS using RTK-GPS, relationships between the various island vertical planes were developed. While not the objective of this study Figure 4 shows the relationship between the various vertical datums encountered during this project and is included here for informative purposes. Care should be exercised when converting from one datum to another and the results verified depending on the purpose of the work.

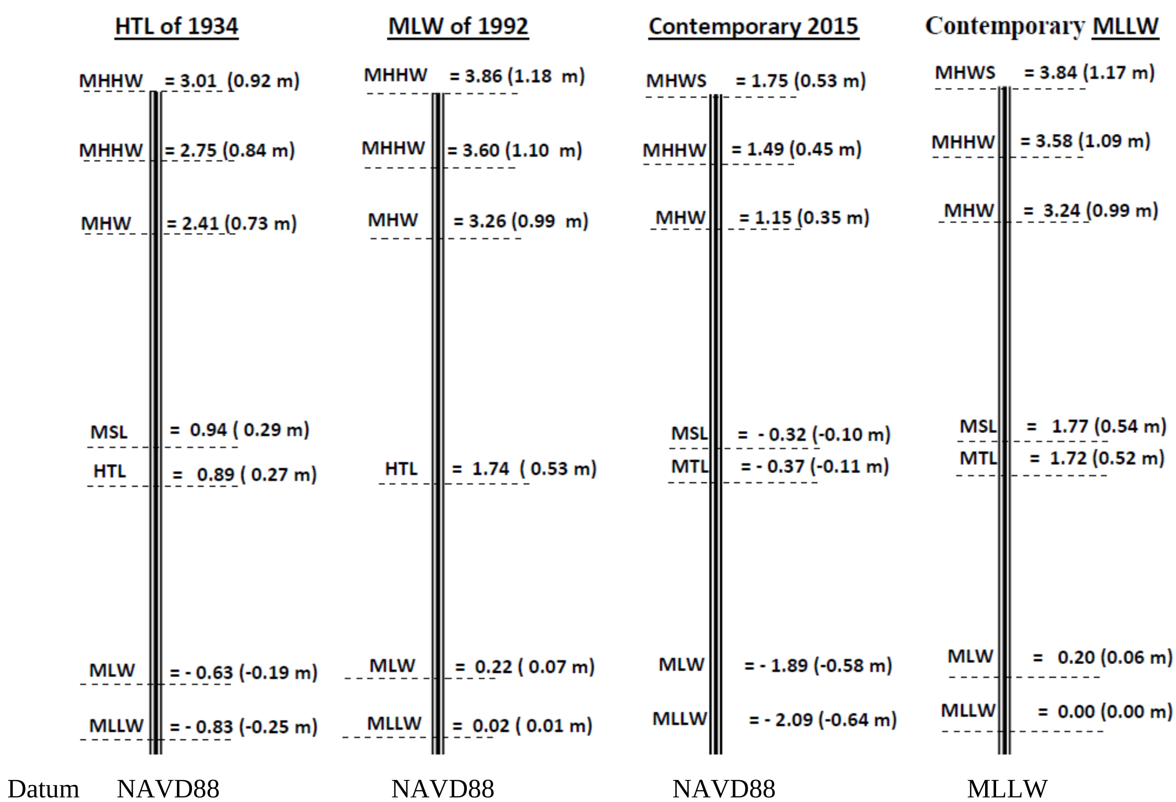

Figure 4 Contemporary & Historical Datum Relationships for Nantucket Harbor. Contemporary data based on 1983 – 2001 NTDE and a Mean Range (Mn) = 3.04 feet.

PROJECT RESULTS

The Storm Tide Pathway Final Dataset

The desktop analysis of the lidar data yielded 129 potential STPs throughout the study area (Figure 5). Each STP was inspected by the 3-person team in the field and the collected RTK-GPS data downloaded to the laptop where it was compared against the lidar. Frequently, based on these observations, the potential STP was moved when the team determined the 2010

Figure 5. Top: initial set of STPs identified in desktop analysis of lidar (n = 129). Middle: Final, color-coded Storm Tide Pathways (n = 76). Bottom: final STPs underlain by initial set of STPs (white).

lidar was not representative of the 2015 real-world terrain. All field adjusted STPs were located accurately by RTK-GPS for later incorporation into the comprehensive database.

The final dataset contains 76 storm-tide pathways with the areas around Madaket and downtown Nantucket Harbors containing the greatest densities of STPs (Figure 5). A comparison of the preliminary and final datasets demonstrates the value of the fieldwork, where 53 (47%) of the potential STPs identified during the desktop analysis were eliminated. Finally, approximately 7 potential STPs were either removed or not able to be verified (discussed below) along the south shore and Siasconset beaches where field inspection revealed that points: were found to be higher than represented on the lidar or the maximum study elevation (storm of record plus 6 feet); had moved since the lidar was acquired in 2010: did not provide an inundation pathway that threatened natural or human resources (e.g. the pathway lead to a hollow between primary and secondary dunes); and/or could not accessed.

As an erosion dominated shoreline (see CZM Shoreline Change Project, http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/shoreline-change/, accessed 6/21/16) this area of the Island is subject to significant wave action that contributes to frequently shifting landforms and topography and periodic overwashes in the vicinity of the Great Ponds. As a dynamic environment, the south shore is an example of the type of shoreline for which the use of lidar to identify potential STPs is less useful since it can be quickly out of date. Further, relying on field locations of actual STPs can also be misleading as the shoreline continues to evolve daily.

Recognizing the ephemeral nature of some STPs along an active coast, a more viable management approach may require a more contemporary reference framework than that provided by lidar or archived GPS locations of STPs. Further, for these areas other factors such as wave heights and general topographic information may provide more effective information upon which to base real-time emergency management decisions.

As discussed earlier, PALs and IRs were developed for each STP, with the excpetion of those classified as unverified (discussed below). Initially, the Individual Ranges (IR) were initially developed at 1-foot intervals, however, due to the low relief (i.e., little change in elevation for an extended distance) of Nantucket coastal areas, IRs were developed at ½ ft range intervals to provide more effective management information. In addition to the need for tighter

IR range intervals, the low relief along areas of the island, also highlights the vulnerability of these areas to relatively small increases in sea level.

Types of Storm Pathways included in the Database

There are several types of STPs included in this dataset: the standard Storm Tide Pathway (STP) as discussed above, the 'spillway' (STP-S); the 'roadway' (STP-R); and the unverified (STP-U) (Table 6). The sub-types were developed to reflect different on-the-ground morphologies and techniques used to characterize potential inundation at these locations.

Table 6. Breakdown of Storm Tide Pathways

Pathways	Standard (STP)	Spillway (STP-S)	Roadway (STP-R)	Unverified (STP-U)
76	21	5	23	27

The 'standard' STP is described as a relatively narrow low-lying area where flowing water is conveyed inland by the natural topography (Figure 6). The term "spillway" is a term developed to reflect the low relief of the area. An STP-S is 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 STPs. Actions planned to mitigate spillway STPs 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 are of interest precisely because the characteristic that makes them function like a spillway (i.e., a broad flat area of inundation with no clear, narrow pathway for floodwaters to enter), often makes it difficult to modify in ways that will control inundation. The downtown area has several spillway STPs, including walls, natural and man-made berms, and a dike. Not restricted to a discrete point or conveyance, these types of STPs (i.e., STP-S) most likely will require more comprehensive, area-wide approaches to mitigate inland inundation than that required for conventional STPs.

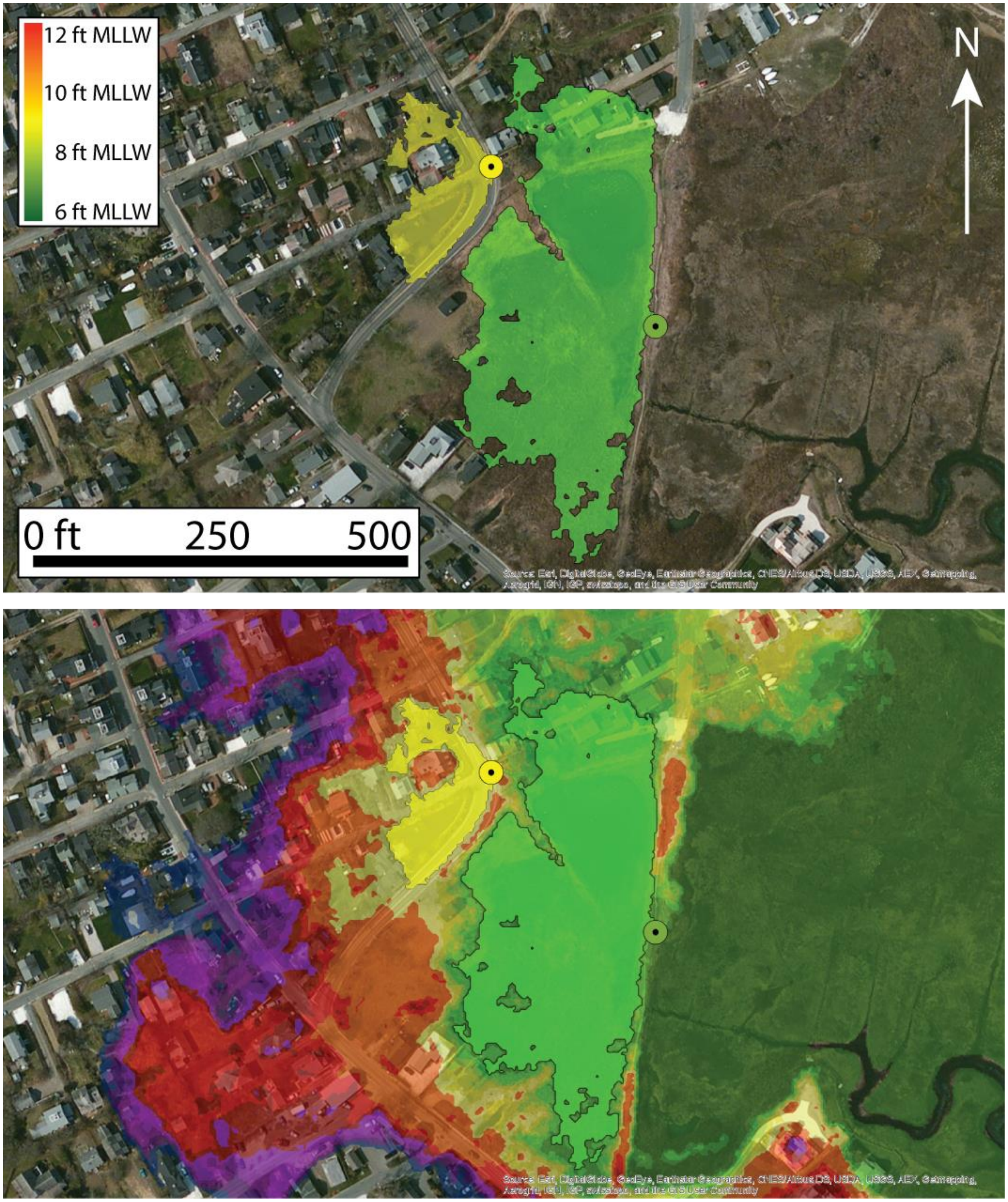

Figure 6. South of downtown Nantucket. Top: two STPs with corresponding Pathway Activation Levels.Bottom

Roadway STPs (termed STP-R) were delineated as they are associated with inundation that only effects roadways. Based on the fieldwork, 23 STP-Rs were documented along central and eastern sections of Polpis Rd and the western end of Madaket Rd. Since this study does not calculate the probability of flooding events nor perform an engineering analysis of the open-channel flow, the STP-R reflects only the location of an inundation pathway and the potential area affected based on lidar elevations and the GPS survey data since access along these roads may be impacted. Another way to think of STP-Rs is that the primary hazard associated with them is the water flowing over the road. If water crosses a road and continues inland to inundate more areas, the point at which the water crossed the road was characterized as an STP and not an STP-R. (Therefore, an STP could flood a road, but an STP-R 'only' floods a road).

Finally, unverified STPs (STP-Us) were defined to be potential STPs identified during the desktop analysis that could not be occupied by the field team. As discussed above, the lidar used for this study is a "bare earth lidar data set (typical for these types of analyses) from which vegetation, (trees, bushes, beach grass, salt marsh, etc.) and structures (houses, buildings, etc.) were removed from during processing (hence the 'bare earth" designation). As a result, certain low spots found in the lidar analysis could not be accessed or were otherwise inaccessible (e.g. private property) (Figure 7).

Figure 7. Example of an STP-U. This was characterized as an unverified STP due to its locationon private residential property.

Many of the 27 STP-Us compiled in this study are located in low areas that will experience inundation but, due to the above fieldwork limitations, the precise location of the STP could not be documented through GPS occupation. To provide for a complete database, the potential location of these STPs was retained in the database and cited accordingly so that they can be located should occupation be possible.

The data layers developed for this study were also used to prioritize the present and future projects the town has identified within its 2014 Coastal Management Plan (http://www.nantucket-ma.gov/281/Coastal-Management-Plan-Work-Group). The 2013-14 USGS lidar was used to map the Individual Ranges (extent of inundation) for the entire island from the highest spring tide of the year to the Storm of Record + 6ft. This was done to help prioritize the projects within the CMP regardless of the presence or absence of an STP. Though ground-truthing the extent of this inundation was beyond the scope of this study, this analysis and mapping was undertaken to provide the town with the best possible data set going forward and in fact this island wide mapping, was not in the project proposal. The 22 locations noted within the CMP for current and potential projects were overlain onto the IRs and the locations relative to the STPs and other potential hazards were documented (Figure 8). Center staff worked with Town staff to convey the impact these new data will have on project design and implementation.

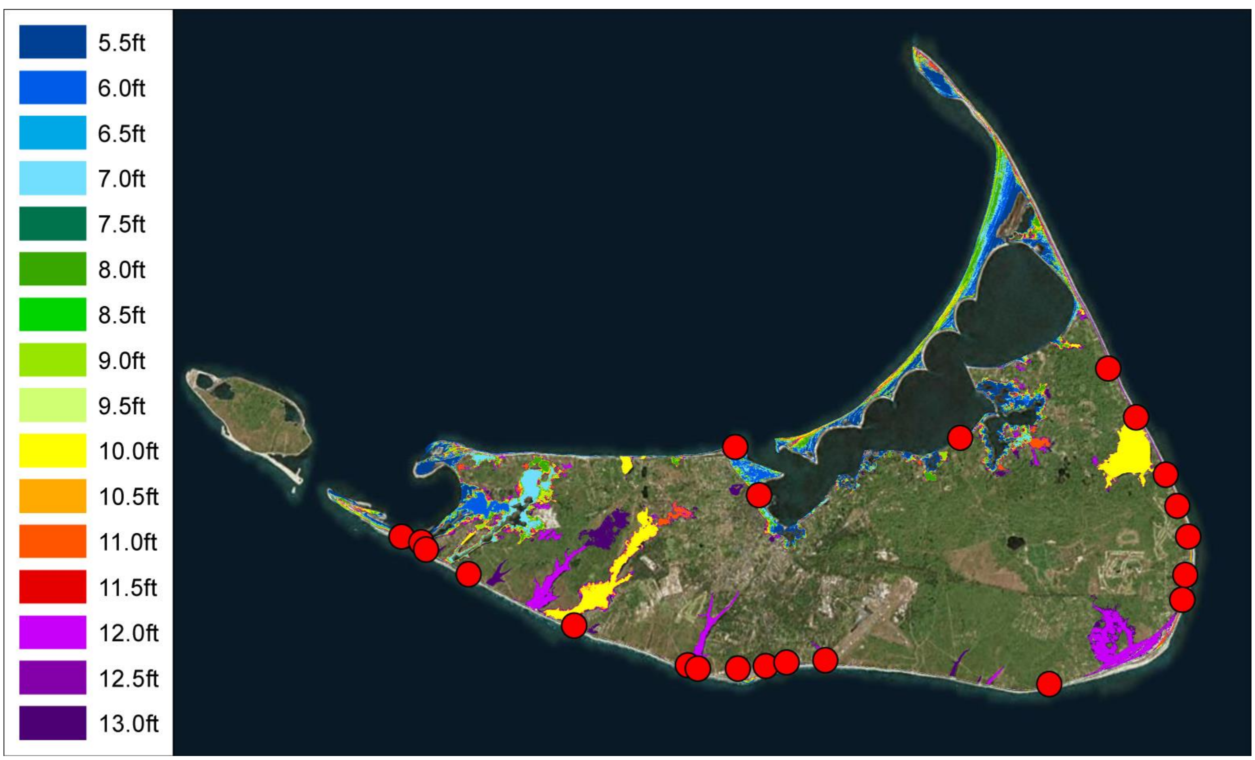

Figure 8. Extent of inundation based on 2013-14 USGS lidar for the entire island. Elevations are in MLLW ft. based on NOAA's Nantucket Tide Gauge. Red dots are locations of projects within the town's 2014 Coastal Management Plan.

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 storm tide pathways.

Appendix A

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

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