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Phase 1 Status Report
Preliminary Results of Mapping Storm Tide Pathways on Martha's Vineyard: Aquinnah, Chilmark, Edgartown, Oak Bluffs, Tisbury, & West Tisbury

Prepared for the Martha's Vineyard Commission

Coastal Resilience Grant PROGRAM RFR ENV 21 CZM 02
Funded through the Massachusetts Office of Coastal Zone Management,
Executive Office of Energy and Environmental Affairs
and the Martha's Vineyard Commission

by
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Publication: 21-CL-07

Acknowledgements: We thank Adam Turner and Elizabeth Durkee at the Martha's Vineyard Commission and Stephen McKenna and Patricia Bowie at the Massachusetts Office of Coastal Zone Management.

Suggested citation:
Borrelli, M., Mague S.T., Legare, B.J., McCormack, B., McFarland, S.J., Solazzo, D., 2021. Mapping Martha's Vineyard Storm Tide Pathways: Aquinnah, Chilmark, Edgartown, Oak Bluffs, Tisbury, & West Tisbury. Tech. Rep. prepared for the Martha's Vineyard Commission: 21-CL-07, p.36.

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EXECUTIVE SUMMARY

Coastal tourism, recreational use and enjoyment of natural, coastal resources, and the ecosystem services these resources provide are large contributors to the State's economy. To sustain activities such as these, managers, first-responders, and public works professionals in low-lying coastal communities need information for real-time, and future planning purposes that is responsive to the threats posed by coastal hazards such storms and related flooding on a scale commensurate with local management priorities and responsibilities.

The mapping of storm tide pathways provides town staff and the public with contemporary information on the location of the potential pathways that, depending on the magnitude of a storm, convey coastal flood waters inland, enabling communities to respond to real time events and prevent future inundation. Storm tide pathways describe spatially how coastal waters can flow inland during a flooding event associated with storm surge, extreme high tides, or sea level rise.

Storm tide pathways for Martha's Vineyard were mapped in ½ foot increments starting at an elevation of 0.5 feet above mean higher high water up to a historical high-water elevation of 9.4' (2.87m) North American Vertical Datum of 1988 (NAVD88) for the 1938 Hurricane located off the Cliffs of Aquinnah. Approximately 8.5 feet were added to account for future sea level rise. For uniformity across the Island, initial mapping was conducted with all elevations referenced to NAVD88. Elevations were subsequently converted to Mean Lower Low Water for Vineyard Haven, the local tidal datum referenced by the with National Weather Service for its total water level projections.

Field work to verify and locate pathways accurately was conducted concurrently by two (2) field crews over four (4) days from March 15-18, 2021. A total of 793 pathways were identified in the initial desktop analysis. In the team laboratory analysis, approximately 174 desktop STPs were eliminated and 81 new STPs added for a total of 704 STPs identified for field evaluation. Upon completion of the field surveys, a total of 700 STPs were identified for the six Vineyard towns.

Presently, many low-lying coastal areas flood regularly during high water storm events, with some flooding occurring more frequently during so-called 'king tides. To illustrate the nature of the future threat facing low-lying communities this study has identified 54 pathways between 11.5 and 12.0 ft MLLW that have not flooded in decades and are approximately a foot above the historical high-water elevation, or project storm of record, used for this mapping effort.

Municipalities should be aware of the pathways that are just above the project storm of record and what resources would be affected by flooding in these areas and what steps should be taken. Further, for those 54 storm tide pathways more than 780 acres throughout the study area will be flooded that have yet to be flooded during a previous storm event. This represents a dramatic change in low-lying coastal areas the specifics of which may be unknown to many municipalities. Displaying these complex spatial datasets to the lay person is also a focus of this study.

In year 2 of this project these data will be further developed to be viewed in multiple locations. The first are digital, GIS-based data layers that can be used in a number of ways. Hardcopy maps can also be generated from the GIS data for training purposes, field use, or to have on hand in the event of power loss. Second, in collaboration with the Southern New England Weather Forecast Office of the National Weather Service (NWS), the incorporation of these data into the NWS Coastal Flood Threat and Inundation Mapping webpage (weather.gov/box/coastal) provides real-time total water level predictions to town staff and the public for approaching storm events. The GIS data generated from this project were reformatted to conform to NWS standards to display the data relative to NWS forecasts of 'Action Level', 'Minor', 'Moderate' and 'Major' flooding. These real-time NWS forecasts can be used with the webpage to aid in visualizing how an approaching storm and related flooding could impact an area.

The Center for Coastal Studies has developed a third way of viewing these data that combines the real-time water level forecasts of the NWS with the maps of storm tide pathways by building a standalone website (stormtides.org) that is easily updateable and maintained. These data can also be used offline by management entities and others. The mapping of storm tide pathways provides town staff and the public with critical information on the precise location of potential flooding that enables communities to address each individual pathway and prevent future inundation. These improved and easily accessible data will help communities to avoid, mitigate and prepare for increasingly severe flooding events. This Phase 1 report and associated data, while preliminary, provides a useful and usable series of maps for first responders, public works professionals, managers, and the public to help better understand impacts from coastal storms and sea level rise. It will be updated into a final report at the conclusion of the project to reflect the town-specific analyses, low lying roads inventory and storm tide app developed in Phase 2.

PROJECT BACKGROUND AND OVERVIEW

The low-lying communities of the Island of Martha's Vineyard have historically been vulnerable to inundation associated with coastal storms and flooding. As sea level rises, the threats associated with storm and nuisance tides are exacerbated particularly as the frequency and intensity of coastal storms appears to be increasing. Martha's Vineyard being an island further exacerbates the pressures of sea level rise and limits the viability of some long-term mitigation measures such as relocation. While contemporary historical high-water elevations for the Island appear to be associated largely with hurricanes, the impact of the Nor'easters of 2007, 2015 and 2018 to the Cape area highlights management challenges that 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.

Consensus among scientists indicates that sea levels are rising at an increasing rate. Therefore, much attention has been focused on efforts that enhance adaptation and increase resiliency related to climate change in coastal settings. As shown in Figure 1, current projections vary from a low of 0.6 feet to a high of 10.3 ft by the end of this century. However, such a broad range of projected sea level rise creates significant uncertainty for coastal managers faced with identifying potential hazards to and vulnerabilities of property and infrastructure, prioritizing response actions, and demonstrating to local governments the need to undertake actions despite the unavoidable uncertainties inherent in century-scale sea level rise projection scenarios. Annual or even decadal planning horizons are not easily defined or addressed within the context of sea level rise. Further, discussions and effective response actions, implementable at the local level, are difficult to identify.

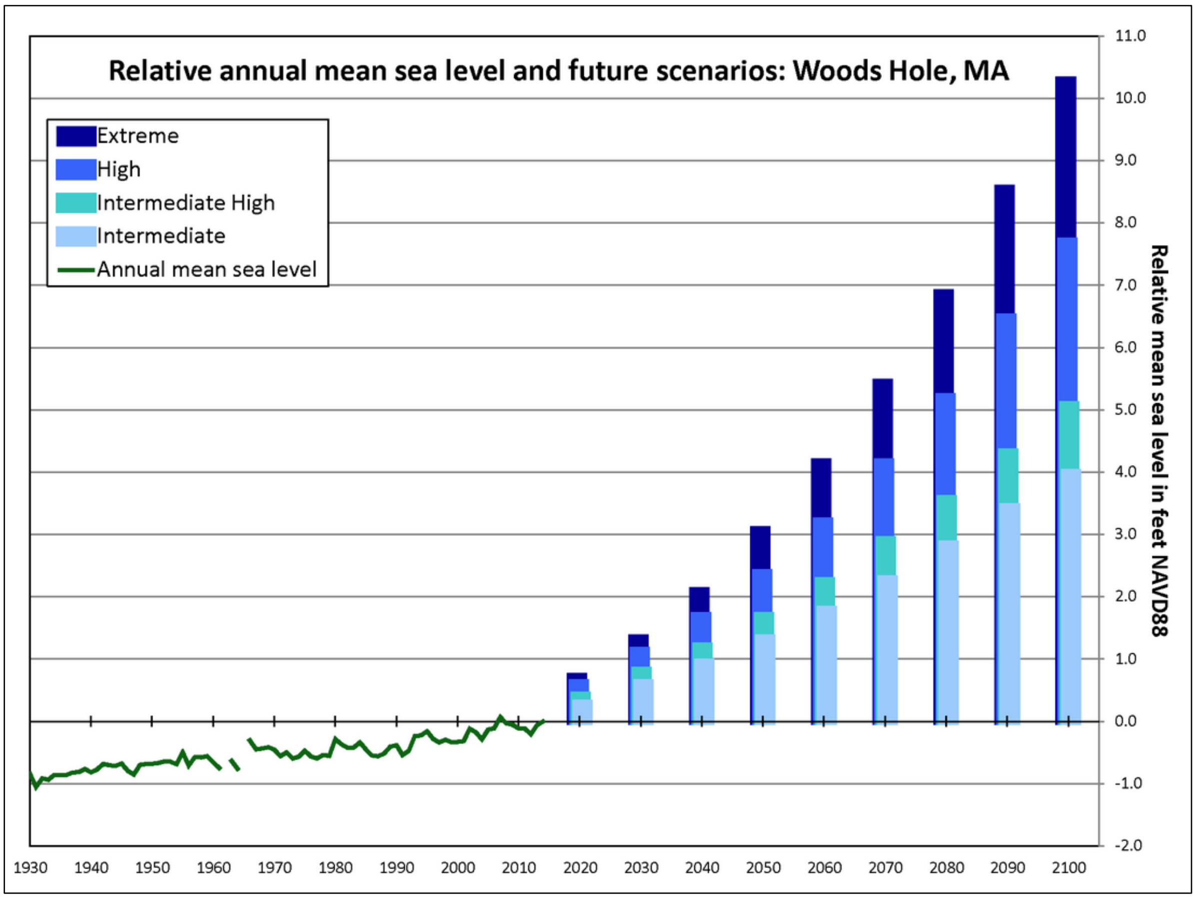

Figure 1. Relative sea level rise scenario estimates (in feet NAVD88) for Woods Hole, MA. Taken from https://resilientma.org/changes/sea-level-rise accessed on June 19th, 2021.

In addition to the issue of defining a suitable planning horizon to address sea level rise, the ability of coastal managers to identify potential vulnerabilities effectively and efficiently and to educate residents and community leaders about the threats associated with coastal inundation has been severely limited by the lack of accurate elevation data at a scale that is usable at the community level. For example, Flood Insurance Rate Maps (FIRMS), produced by the Federal Emergency

Management Agency (FEMA), have long been standard planning resources for coastal communities, however, these maps were intended to facilitate the determination of flood insurance rates and historically have lacked the topographic detail necessary for focused planning efforts. Until recently the accuracy of relatively low-cost elevation data has been appropriate only for general planning at regional scales and not appropriate for identifying inundation and flooding impacts over timeframes that meet the needs and budgets of most municipalities. Numerical modeling of storm surge, sea level rise, waves, or sediment transport (coastal erosion) can be effective for regional efforts to understand coastal evolution but can also be cost prohibitive. Further, vertical uncertainties associated with some of these models can be too coarsely scaled to inform site-specific decisions expected of local coastal managers.

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

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

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

While sea level rise projections are clearly critical for longer term planning considerations, particularly for large scale efforts, actual past, present, and future storm tide elevations provide another effective means of characterizing local coastal hazard vulnerabilities for community level planning actions. Figures 2a and 2b depict estimates of historical storm tide elevations for the Boston area (an east facing shore) and representative south facing shores, for various 17^{th} – 21^{st} century storms compiled from various sources. The current projections for the highest sea level rise scenario and the NOAA regression rate scenario are based on current tide gauge data obtained from the Boston tide gauge are shown through the year 2100.

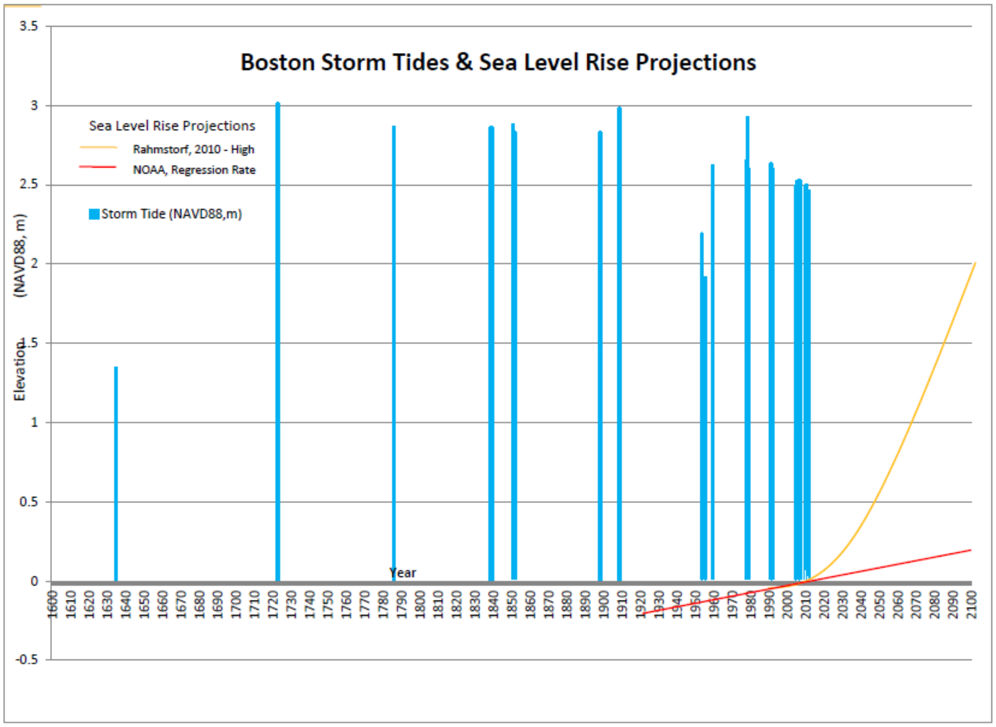

Figure 2a. Estimates of Historical Storm Tides for the Boston Area

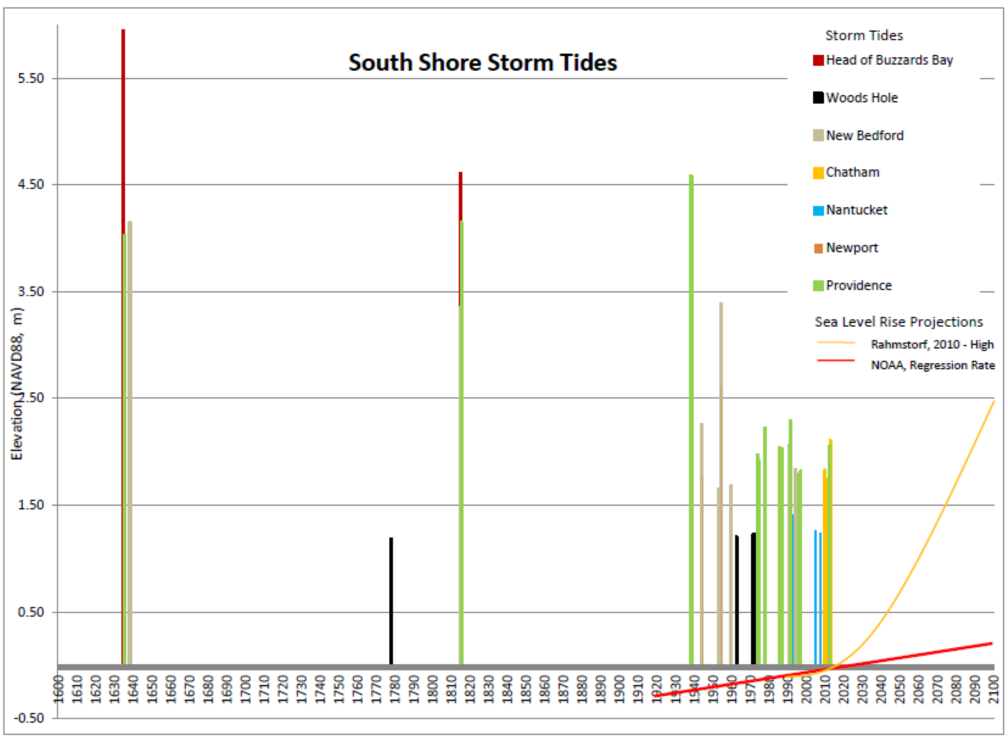

Figure 2b. Estimates of Historical Storm Tides for the South Shore.

Identifying potential future storm tide heights, coastal flooding extents, and areas of potential vulnerability using historical data provides several benefits to coastal communities. First, using actual historical storm tide data to identify coastal hazard vulnerabilities helps communicate a higher level of certainty by removing sea level rise and the disparity of projections (Figure 1) from the discussion of the most appropriate sea level rise elevation upon which to base short term planning strategies. Sea level rise notwithstanding, storm tides of significant magnitude have been experienced in the past and will continue to be experienced in the future. Second, contemporary storms of record provide an accurate, actual (i.e., indisputable) reference elevation that towns can plan for when history repeats or surpasses 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.

METHODS

Composite Storm Tide Profile for Mapping Martha's Vineyard STPs

Overview

The use of the historical record to supplement predicted storm and spring tide elevation data can provide valuable baseline information to Emergency Managers, Public Works Departments, Harbormasters and Coastal Resource Managers. Independent of long-term sea level rise projections, storm surge projections considered in the context of contemporary storms of record and accurate ground elevation data can be used to map the location of storm tide pathways with a high degree of certainty. As demonstrated in previous storm tide pathway mapping projects in Provincetown (Borrelli, et al., 2016b), Nantucket (Borrelli, et al., 2016b), Truro (Borrelli et al., 2017), Scituate and Cohasset (Borrelli, et al., 2020), funded by the Massachusetts Office of Coastal Zone Management Management's Coastal Resiliency Grant Program and the Municipal Vulnerability Preparedness (MVP) Program, when referenced to a common vertical datum that spans the land-sea interface, these data can be used by towns as the basis for short-term community planning decisions and real-time decisions necessary to respond to approaching coastal storms and related storm surge.

Characterizing Coastal Inundation

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

In addition to minor monthly inundation, many coastal communities are also experiencing severe flooding associated with relatively short duration, high intensity coastal storms. 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) or mean low water (MLW)). *Storm surge* refers to the increase in water level associated with the presence of a coastal storm. As the arithmetic difference between the actual level of the storm tide and the predicted tide height, *storm surges* are not referenced to a datum.

Storm surge magnitude and the time at which the maximum surge occurs relative to the stage of the astronomical tide are critical components of the maximum storm tide elevation experienced during any storm. The significance of this relationship is illustrated by the following example.

The highest observed tide for the Woods Hole tide gauge (#8447930, established on August 10, 1932) occurred at approximately midnight (12:00 AM) on September 21, 1938 (the Hurricane of '38) with a maximum storm tide elevation of 9.42 feet (2.87 meters) NAVD88[1]. As shown on Figure 3, this maximum water level occurred approximately a half hour before the predicted astronomical low tide of -1.52 feet (-0.46 m) NAVD88 at 12:28 AM. The corresponding storm surge (storm tide elevation – predicted tide) was, therefore, approximately 10.94 feet. Significantly, had this storm surge occurred at the time of the previous or next predicted high water, the maximum storm tide elevation could have been approximately 12.0' (3.7 m) NAVD88 or approximately 2.6 feet (0.8 m) higher.

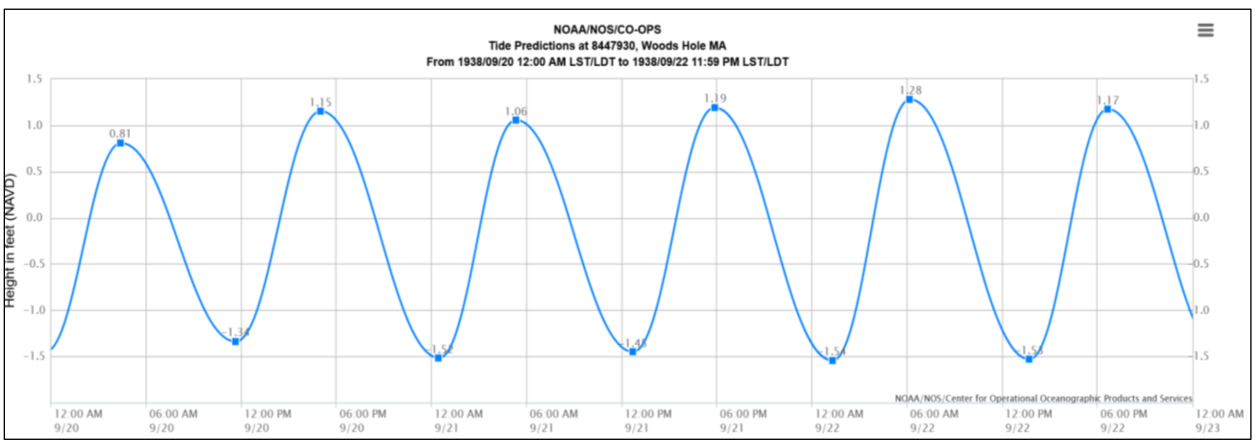

Figure 3. Predicted Tides, NOAA Tide Station 8447930, Woods Hole MA. The highest observed water level of 9.42' NAVD88 for the station occurred at midnight (12:00 AM) on September 21, 1938 during the Hurricane of '38. (Source: https://tidesandcurrents.noaa.gov/noaatidepredictions.html?id=8447930).

[1]https://tidesandcurrents.noaa.gov/datums.html?datum=NAVD88&units=0&epoch=0&id=8447930&name=Woods+Hole&state=MA

With average tide ranges on Vineyard and Nantucket Sounds ranging generally between 1.5 feet (0.45 m) and 4.0 feet (1.2 m) the timing of coastal storms for the immediate areas to the south of the Cape is perhaps less significant than for areas north of the of the Cape where tide ranges routinely exceed 9.5 feet (2.9 m). Notwithstanding differences in tide range, all storms on the Vineyard are possible of doing damage regardless of when they occur. For example, recognizing that coastal areas are generally low lying with low to moderate relief, an increase of 2.6 feet (0.8 m) to the storm tide elevation for example at the Woods Hole tide station could increase the height and inland extent of coastal storm tides sufficiently to result in severe damage to myriad properties depending on the nature of the adjacent topography.

Acknowledging the importance of not only the magnitude of the predicted storm surge but when it will occur relative to the stage of the tide, the National Weather Service (NWS) in Norton, MA maintains an informative website that depicts the relationship between predicted tidal cycles and estimates of storm surge and total water level at various Massachusetts locations (http://www.weather.gov/box/coastal)[2] as coastal storms approach New England. This project will provide information to the NWS Norton office with an additional data set of accurately mapped storm tide pathways that can be incorporated into its coastal storm surge website to reduce the uncertainty and improve the utility of storm tide inundation forecasts for the Vineyard Sound area.

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 to which a point's position on the earth's surface can be referenced (*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).[3] It is important to note that as local phenomena, the heights of tidal datums can vary significantly from one area 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).[4]

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

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[2] At the time of writing the NWS website was down for redesign. The web address may change after the redesign is completed.

[3] 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.

[4] 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.

tides of Massachusetts are semi-diurnal - *i.e.*, two high tides and two low tides each tidal day.[5] Although comparable in height, generally one daily tide is slightly higher than the other and, correspondingly, one low tide is lower than the other. Tidal heights vary throughout the month with the phases of the moon with the highest and lowest tides (referred to as spring tides) occurring at the new and full moons. Neap tides occur approximately halfway between the times of the new and full moons exhibiting tidal ranges 10 to 30 percent less than the mean tidal range (NOAA, 2000a) (Table 1).

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).

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

Tidal Datum	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 of the NTDE*

The Mapping of Storm Tide Pathways

Initial mapping of storm tide pathways begins with a computer-based analysis of the most representative lidar data. This analysis is then supplemented with field verification of the lidar data and conditions on the ground at the time of mapping. Typically, the latest lidar data set available will not represent the current conditions at the coast in every instance. The coastal environment is

[5] 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.

dynamic and constantly evolving and therefore the rigorous and time-consuming fieldwork of verifying the lidar and real-world conditions are important to this process.

Desktop Analysis

The ability to conduct accurate fieldwork is an important component of the STP verification process. First, though lidar data is the most accurate and cost-effective spatial data collected over broad areas, it only characterizes the topography of the mapped area for the actual date/time of the data acquisition. Due to the dynamic nature of the coast and its relationship to coastal flooding patterns, the location of many natural storm tide pathways is ephemeral with new pathways emerging in areas that have never flooded in the past. Second, the use of an RTK-GPS instrument provides the accuracy necessary for acquiring and verifying 3-dimensional positional data. In this way field data collected with the Center's GPS are used to corroborate or eliminate the presence of STPs identified in the desktop lidar analysis. Third, due to the dynamic nature of coastal environments, visual assessment of STPs in their geographic setting, often reveals changes in the landscape that are not evident in a desktop analysis of lidar data. Lastly, as noted above and also related to the ephemeral characteristics of the areas proximate to the shoreline, even the most current lidar is frequently out of date in these dynamic areas. Consequently, the GPS survey, coupled with field observation of each STP, provides the most current information regarding STPs that may have been modified due to changes in landform.

Martha's Vineyard has many public and private structures meant to protect infrastructure by controlling storm surge and the overland flow of sea water. Accurately mapping the pathways by which water flows inland necessitated the creation of an elevational dataset inclusive of all structures that influence the water's path, or those whose omission would otherwise misrepresent the reality on the ground. Specifically, we sought to map bridges, whose representation in lidar surfaces is often inaccurate, and seawalls, which impede overland flow, but would not typically be included in a digital terrain model (DTM), which by definition includes only bare-earth points. Our goal was to improve upon the standard bare-earth DTM by adding in bridges and walls to more accurately model storm tide pathways.

LIght-**D**etection **A**nd **R**anging, or lidar, is like radar and sonar but rather than using radio or sound waves it uses light. The lidar used for this study was from a 2016 overflight and was obtained from the NOAA Data Access Viewer (DAV) as 581 lidar files covering the area of Martha's Vineyard, and were downloaded in the NAD83 (2011) horizontal datum, NAVD88 vertical datum, and the UTM zone 19N projection. This raw point data of 11+ billion returns included all the points collected during lidar acquisition and came classified by the provider into 4 classes: unclassified, ground, noise, and water.

The ground classified points were the basis for the hybrid digital elevation model (DEM), as they are free of vegetation and man-made objects. No reclassification of this point class was necessary, and all the points were used. The water and noise classes were discarded because it was unlikely that they would contain the features on interest in mapping storm tide pathways. The features of interest were drawn from the points that were previously left unclassified by the lidar product provider. This class contained nearly 8 billion lidar returns, so it was necessary to separate out the points that were features of interest with regards to coastal flooding (e.g., bridges and walls) from those that were not of interest through a classification process.

The classification started by compiling shapefiles of known public and private structures, taken from the Massachusetts Ocean Resource Information System (MORIS) website created by the Massachusetts Office of Coastal Zone Management, then supplementing the files with additional hand-digitized walls and bridges. Once a shapefile existed that contained all the features of interest, it was used to classify the points that fell within the polygons into a new class. This class was then merged into the existing ground class to create a point cloud consisting of ground returns as well as returns representing low walls, high walls, and bridges. An added benefit of this work is related to the post-processing of lidar collected via aerial surveys that sometimes introduce uncertainties that exaggerate or diminish features in three-dimensional data and, as a result, can obscure or conflate the presence and scale of an inundation pathway. These effects have been shown to be associated with 'bare earth' models where elevations tend to be "pulled up" adjacent to areas where buildings have been removed (Figure 4) or "pulled down" in areas where bridges and roads cross streams or valleys, further emphasizing the value of field verification. A raster was generated at 1 m resolution from the classified point cloud.

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

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

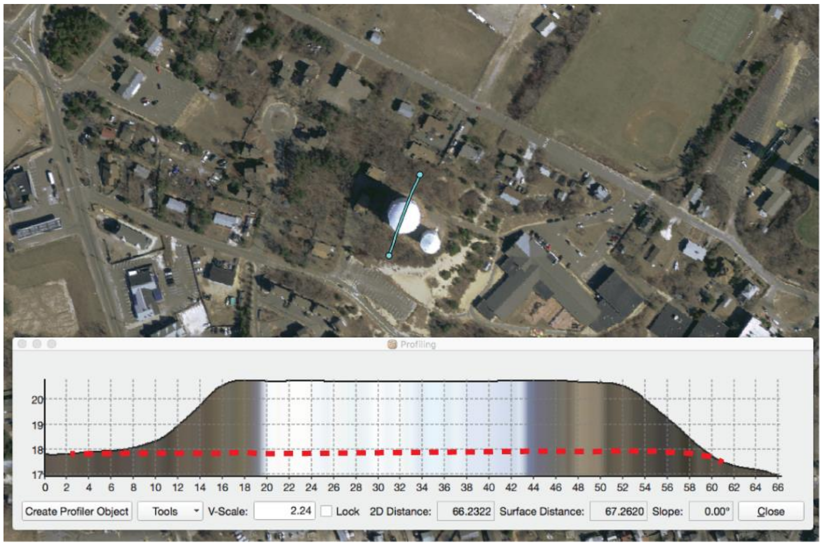

Figure 4. Example of ‘pull up’ near a water tower in Provincetown. Dotted red line is more representative of elevations at the water tower. Blue line in image is location in profile. Profile units = meters (Vert. NAVD88, Hor. NAD83), image taken from Borrelli, et al. 2017.

Another valuable feature of this data visualization software is the ability to drape 2-dimensional data, such as a vertical aerial photograph, over a 3D dataset (lidar). This allows the analyst to better document the STP location and to acquire information about the substrate on which the STP is located and its landscape setting. For example, an STP found on or near an ephemeral coastal feature such as a sandy beach or dune is characterized differently than one atop a concrete wall or other relatively static feature. In addition to providing managers with information on how to address an individual STP, these characterizations also inform the field team to more closely examine areas that are naturally evolving and to inspect the area for other to potential STPs that might not have appeared in the now dated lidar. The ability to drape aerial photographs proved extremely helpful for conducting the GPS field work, serving as a quick means of orientation, and placing the potential STP in its broader geographic context.

Field Work

Once a preliminary inventory of potential Martha’s Vineyard STPs was compiled in the desktop analysis and reviewed in a group setting by the project team, an extensive fieldwork assessment program was conducted to verify the presence or absence of the STP. When the presence of an STP was confirmed, the accurate horizontal and vertical location was obtained with the Center’s Trimble® R10 GNSS receiver utilizing Real-Time-Kinematic GPS (RTK-GPS). The Center subscribes to a proprietary Virtual Reference Station (VRS) network (KeyNetGPS) that provides virtual base stations via cellphone from Southern Maine to Virginia, including a station located on the roof of the Center’s laboratory building. This allows the Center to collect RTK-GPS without the need for a terrestrial base station or to post-process the GPS data, streamlining the field effort and increasing field work efficiency.

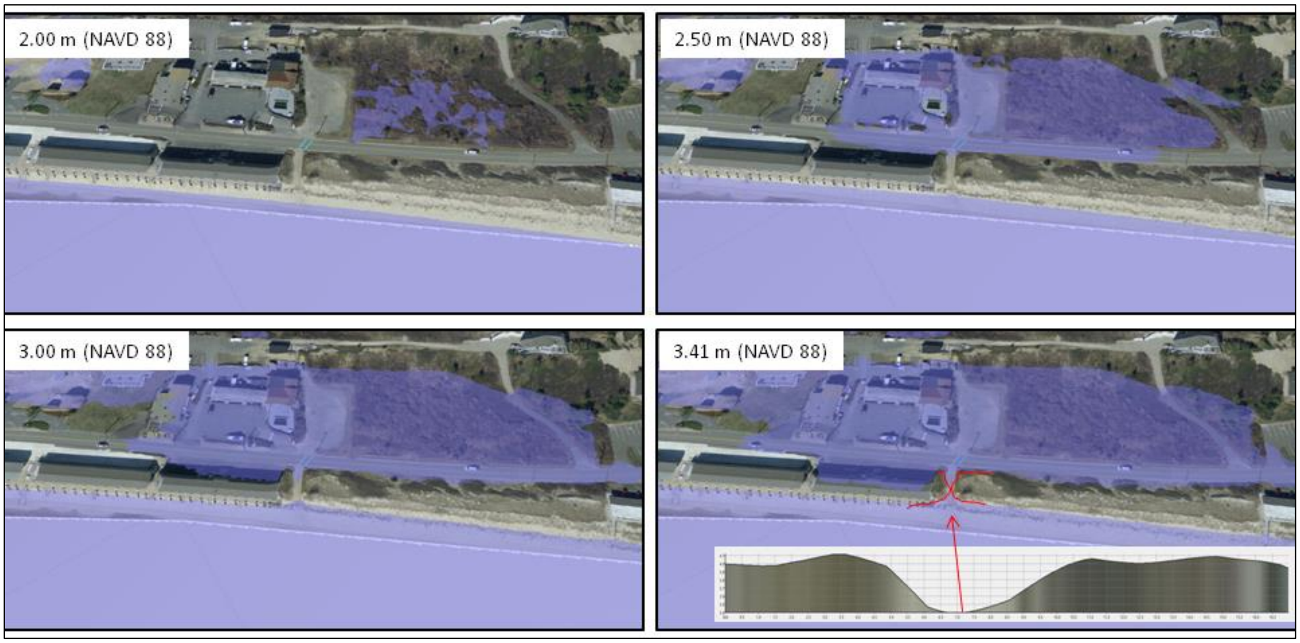

Figure 5. Draped aerial photograph over Lidar surface in North Truro. Blue areas are horizontal plane created in Fledermaus at increasing elevation. Lower right is example of a storm-tide pathway with accompanying profile. These images were generated before field work to identify potential STPs (image taken from Borrelli, et al. 2017).

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

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

In addition, prior to beginning STP field work, existing horizontal and vertical control established by the National Geodetic Survey and tidal benchmarks established by NOAA's Center for

Operational Oceanographic Products and Services (CO-OPS) were occupied to verify that GPS settings had not been altered and that the results would meet STP mapping objectives. Table 2 summarizes these results of these occupations and includes statistics confirming that field survey results meet objectives for mapping STPs.

At the completion of the desktop analysis, all potential STPs were compiled into a spatial database with x, y, z coordinates and uploaded into the Center's GPS. Using the "stakeout" function and aerial photographs to navigate to the precise location identified with the lidar, each potential STP location, and the adjacent area, was inspected by a 2-3-person team and occupied with the GPS mobile unit. This served four purposes, first to map the real-world location of the STP identified during the desktop analysis; second to increase the positional accuracy of the verified STP itself; third, to verify consistency with the current landscape setting; and lastly to confirm the positional accuracy of the lidar data.

	Reported Values			Unit 1 - CCS, R10			Unit 2 - Rental, R10			
Control	**Northing**	**Easting**	**Elevation**	**Northing**	**Easting**	**Elevation**	**Northing**	**Easting**	**Elevation**	**Comments**
AI 5592 (MVY A)	4,583,674.859	364,994.307	18.430	4,583,674.843	364,994.311	18.418	4,583,674.854	364,994.314	18.426	NGS (Primary) Airport
AI 5593 (MVY B)	4,584,073.283	365,793.997	17.240	4,584,073.280	365,793.980	17.245	4,584,073.270	365,793.994	17.253	NGS (Secondary) Airport
AI 5594 (MVY C)	4,582,709.396	364,559.067	15.670	4,582,709.415	364,559.076	15.681	4,582,709.387	364,559.071	15.675	NGS (Secondary) Airport
Edgartown NO 9 1960 (844 8558 TIDAL 9)	4,583,042.258	373,635.295	0.559	4,583,042.262	373,635.281	0.585	4,583,042.266	373,635.289	0.595	BBBJ75
Edgartown NO 11 1961 (844 8558 TIDAL 11)	4,583,064.658	373,615.034	0.941	4,583,064.660	373,615.057	0.950	4,583,064.638	373,615.040	0.917	OPUS BBDN12
Vineyard Haven VH 3 1995	4,590,746.674	366,114.810	11.324	4,590,746.689	366,114.806	11.323				OPUS BBDM85
Menemsha MEN 1 1994	4,579,615.742	352,184.152	1.732				4,579,615.760	352,184.166	1.740	OPUS BBDM82
SUM				-0.021	-0.001	-0.038	0.021	-0.022	-0.034	
Average				-0.004	0.000	-0.006	0.003	-0.004	-0.006	
Std Dev				0.013	0.015	0.013	0.014	0.007	0.020	
Count				6	6	6	6	6	6	
RMSE				**0.012**	**0.014**	**0.013**	**0.013**	**0.008**	**0.019**	
NSSDA (95%)				**0.021**	**0.024**	**0.026**	**0.023**	**0.013**	**0.037**	

Table 2. Martha's Vineyard STP Survey Control. Horizontal: NAD83 (2011), UTM 19N, meters; Vertical: NAVD88, meters.

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

After the field work was completed, the team returned to the laboratory to remove those points from the database determined not be STPs, incorporate newly identified STPs documented in the field, and provide all STPs with horizontal and vertical position information, substrate and geographic context labels, photograph links, and other pertinent information for inclusion into a comprehensive database. Once the information is quality controlled, the database is brought into the project GIS for use as an interactive archive of final STP 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 documented by the GPS observations and professional judgment to accurately represent the final STP location.

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

To increase the utility of the STP data and make visualizations more user friendly for local managers, inundation planes are also created. To visualize STPs and recognizing that floodplain mapping is not a goal of the project, the use of planes has been determined to be the clearest way of presenting the data in a useful manner while recognizing the uncertainty associated with the lidar. As discussed below, after reviewing the various scenarios, the lowest plane begins approximately one (1) foot above the elevation of a composite mean higher high water spring tide (MHHW) for the north side of the island. Planes are developed in 6-inch (half-foot) intervals to a maximum elevation of 18.04' NAVD88, the project storm of record of 9.4' NAVD88 plus 8.6 feet, and planes extracted for each range. In addition to providing an upper limit to project elevations, the project storm of record plus 8.6 feet provides a useful representation of potential future sea level rise scenarios that could have practical implications for local managers.

During the field work portion of the project, no data were collected on private property. If a point was inaccessible to the field team, it was labeled as an *unverified* STP, meaning the STP was identified as a potential STP in the desktop analysis, but due to circumstances it was inadvisable (e.g., private property) or impossible (e.g., beneath substantial tree cover and, therefore no GPS signal coverage)) for the field team to 'occupy' the potential STP. Due to the rapidly changing coastal landscape, STPs located on dynamic landforms such as coastal dunes were also labeled as unverified to not convey a sense of permanency to these locations. For this reason, unverified STPs located on rapidly changing natural landforms such as dunes or barrier beaches or in areas experiencing erosion should be viewed as a guide requiring periodic updating or verification.

Unverified STPs are not indicative of a lack of hazard, rather because it was chosen as a potential STP that warrants further investigation by the towns. The field team adjusts the STP location based on the real-world conditions if needed by selecting the lowest elevation point if the STP identified in the desktop analysis does not reflect the on-the-ground topography.

Low-Lying Roads and Infrastructure Vulnerability Assessment Methodology

To be completed in Year 2

RESULTS AND DISCUSSION

Creating a Composite Storm Tidal Profile for Mapping Martha's Vineyard STPs

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

- The landscape setting of the community (e.g., east facing v. south facing shores).
- The elevations of astronomical tides (e.g., the elevation of mean high water (MHW) in Boston Harbor is 4.31 feet NAVD88 v. an elevation of 0.56' NAVD88 for the mean high water in Woods Hole).
- General characteristics of astronomical tides (e.g., the average range (MHW minus MLW) of Boston Harbor tides is 9.49 feet while that of Woods Hole tides is only 1.79 feet).
- The topography (e.g., the elevation of the land relative to the community tidal profile) and 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 Islands); and
- The vertical relationship between 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 individual wharves but large-scale land making projects).

As discussed in the Methods section of this report, with such variation in physical characteristics, the initial step in the identification of storm tide pathways is the development of a datum-referenced tidal profile that characterizes average tidal heights, nuisance flooding, and storm tides for the area of interest. In addition to the more common tidal datums of mean high water springs (MHWS), mean higher high water (MHHW), mean high water (MHW), and mean sea level (MSL), to be useful this tidal profile considers the high-water lines of datum referenced historical storm tides including the elevation of the maximum contemporary storm tide experienced (i.e., the project storm of record) by the area.

In previous storm tide pathway mapping efforts, working storm tide profiles were developed based on data from one tide station covering the limited geography of the one- or two-town study area. In addition to NAVD88, final STP pathways were also reported in local MLLW to correlate with

National Weather Service storm advisories. For the Cape Cod Bay STP project (Borrelli, et al., 2021) this method was modified slightly, and a project-wide, composite storm tide pathway *mapping* profile was developed based on an average of MLLW tidal datum values (referenced to NAVD88) for several similar tide stations found along the Bay shoreline. At the conclusion of the mapping work, in addition to NAVD88, pathways were referenced to one of three MLLW zones. While the difference in elevation between MLLW zones was small (< 0.5'), this final step was performed to ensure compatibility with NWS reporting and correct visualization of STPs within GIS data planes.

Given its large geographic area, a similar process was followed for Martha's Vineyard and a composite tidal profile, referenced to NAVD88, was developed to facilitate STP mapping. This composite profile reflects the average of tidal datums for four short-term NOAA tide stations formerly located in: Menemsha Harbor (NOAA Sta #8448725); Vineyard Haven Harbor (NOAA Sta #8448157); Oak Bluffs Harbor (NOAA Sta #8448298); and Edgartown Harbor (NOAA Sta #8448558). The locations of these tide stations are shown in Figure 6.

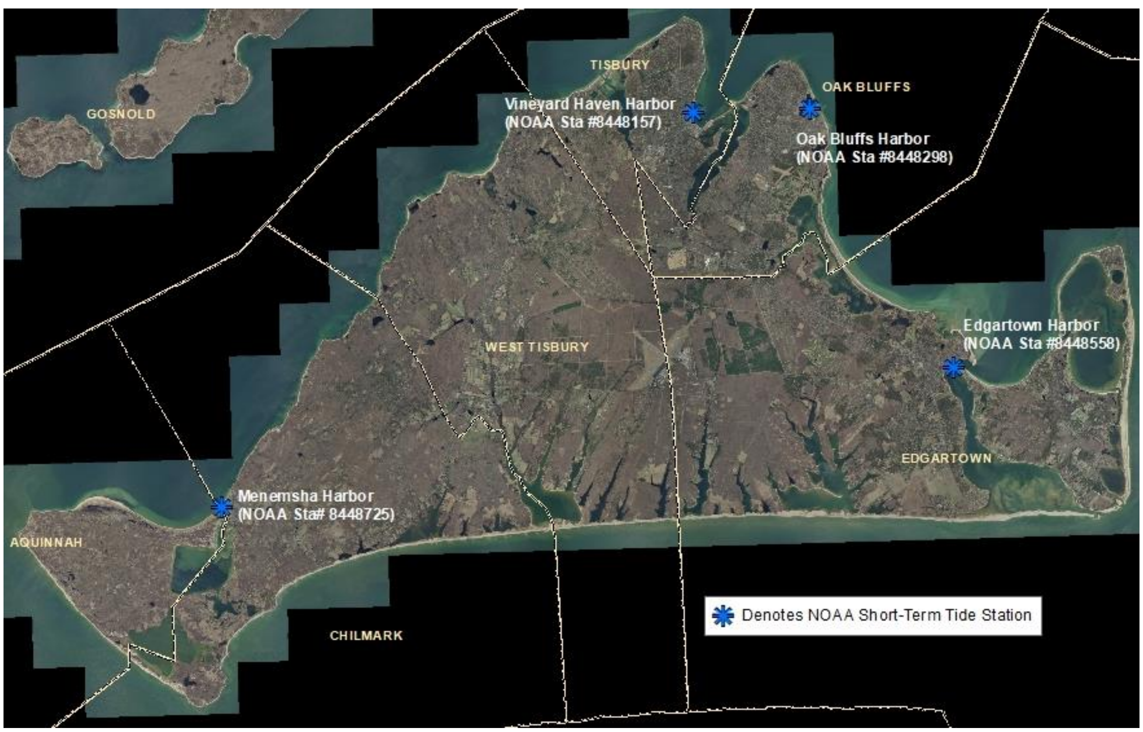

Figure 6. NOAA Tide Stations on Martha's Vineyard.

Menemsha Harbor tide station #8448725 was in operation off and on from June 1994 until September of 2013. Vineyard Haven tide station #8448157 was established in May 1994 and removed in September 1994 while the Edgartown Harbor tide station #8448558 was installed in August 2004 and removed in September of the same year. Tidal datums reported for these stations reflect values for the 1983-2001 National Tidal Datum epoch (NTDE). As summarized in Table

2, tidal benchmarks for these three stations were occupied prior to field survey work to verify the relationship of local tidal datums to NAVD88. Although no longer updated actively, information for Oak Bluffs tide station #8448208 for the 1960-1978 NTDE is available (https://tidesandcurrents.noaa.gov/benchmarks/benchmarks_old/8448208.html#DatumsPage) and estimates for mean values were developed for the 1983-2001 NTDE after recovering and occupying station tidal benchmarks.

Table 3 summarizes contemporary tidal datums for the Island and the relationship between mean lower low water (MLLW) and NAVD88 for the four, short-term NOAA tide stations. Values are in feet and are referenced in to NAVD88, the accepted vertical geodetic datum of the United States, to facilitate mapping and allow for comparisons around the Island. Values are also referenced to mean lower low water (MLLW), a local tidal datum used by the National Weather Service and the NOAA chart datum. Looking at the values for MLLW expressed in terms of NAVD88 reveals that while MLLW values do vary across the island, the maximum difference is only approximately 0.2 feet between Vineyard Haven and the Oak Bluffs and Menemsha stations.

DATUM	Edgartown 84485581		Vineyard Haven 84481571		Oak Bluffs [1] 8448208		Menemsha Harbor 84487251	
	NAVD88	MLLW	NAVD88	MLLW	NAVD88	MLLW	NAVD88	MLLW
MHHW	1.03	2.68	0.53	2.12	0.58	2.39	1.33	3.14
MHW	0.71	2.36	0.16	1.75	0.24	2.05	1.07	2.88
MSL	-0.22	1.43	-0.54	1.05			-0.44	1.37
MTL	-0.36	1.29	-0.64	0.95	-0.69	1.12	-0.31	1.50
MLW	-1.42	0.23	-1.44	0.15	-1.61	0.20	-1.69	0.12
MLLW	-1.65	0.00	-1.59	0.00	-1.81	0.00	-1.81	0.00
GT	2.68	2.68	2.12	2.12	2.39	2.39	3.14	3.14
MN	2.13	2.13	1.60	1.60	1.85	1.85	2.76	2.76
Highest Obs. Tide								
Elevation								
Date								
Time								

(1) Estimated Contemprary Tidal Datums based on field recovery and occupation of NOAA Tidal Benchmarks: 8208 B 1980 & 1/1928 (LW 0009)

Table 3. Contemporary Martha's Vineyard Tidal Datums (NTDE: 1983 – 01). Elevations in feet.

As the current plane of reference for NWS estimates of total predicted water level for the Island, STPs were referenced to the elevation of MLLW in Vineyard Haven (tide station #8448157). As described below, use of Vineyard Haven datum provides a direct relationship to NWS Action Stages. Since the planes developed for the final project GIS depict STPs organized into 0.5' ranges, the relatively small differences in MLLW elevation between stations did not overly complicate the visualization process allowing storm tide pathways and inundation planes to be displayed across the Island seamlessly. Since all tidal datums are referenced to NAVD88, if desired, the STP planes can be adjusted for the slight geographic differences in MLLW should NWS expand its advisories to additional Island harbors in the future.

Developing a Martha's Vineyard Composite Storm Tide Pathway Mapping Profile

As discussed above and shown in Table 2, comparisons of contemporary Vineyard MLLW tidal datums (with elevations referenced to NAVD88) vary slightly as one moves across the Island. As local tidal datums, variations in MLLW must be considered when integrating final storm tide pathway data with NWS total water level estimates since storm tide pathway analysis is conducted with all data referenced to NAVD88, a vertical, geodetic reference system allowing direct comparisons anywhere within the project area. 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), the storm tidal profile considers the high-water levels of datum referenced historical storm tides including the elevation of a maximum contemporary historical storm tide experienced off the Aquinnah Cliffs during the 1938 Hurricane and used as the "project storm of record" for this study. This elevation provides a baseline for establishing the upper boundary of the pathways analysis and is referred to as the *project storm of record* in order not to confer official storm of record status to any one event, a determination that is beyond the scope of this study.

In previous projects located north of the Cape, approximately four feet (1.25 meters) was added to the identified local, maximum observed storm tide elevation to acknowledge rising sea levels and the susceptibility of the east- and north-facing shores to nor'easters of increasing duration and intensity (Zervas, 2009). Applying this factor yielded a maximum STP mapping elevation of approximately 4.5 meters (14.75 feet) NAVD88 for these areas. Recognizing that areas south of the Cape, particularly south- and west-facing shores, are susceptible to potentially devastating storm surges associated with fast moving hurricanes, the maximum mapping elevation for the Island was increased to slightly more than 2.6 meters (8.6 feet) above the elevation of the identified project storm of record.

Table 4 summarizes the results of research conducted to identify reliable historical high-water elevations associated with notable Vineyard storm tides. To expand the historical record, historical high-water elevations for the south shore of the Cape from Woods Hole to Stage Harbor were also

Town	Location	Elevation (NAVD88, FT)	Elevation (NAVD88, M)	Storm	Date	Source	Comments
Chilmark	Mouth Menemsha Pond	7.8	2.38	Hurricane Carol	8/31/1954	COE Tidal Report, FIRM Report	
Chilmark	Old Hunt Pl.	7.0	2.13	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Aquinnah/Chilmark	Menemsha Pond	5.3	1.62	'38 Hurricane			
Aquinnah/Chilmark	Menemsha Pond	4.2	1.28	'44 Hurricane	9/ 14-15/1944	FIRM Report	
Aquinnah/Chilmark	Mouth Menemsha Pond	7.8	2.38	Hurricane Carol	8/31/1954	FIRM Report	
Aquinnah	Gay Head Cliffs	9.4	2.87	'38 Hurricane	9/21/1938	COE Tidal Report, FIRM Report	
Aquinnah	USC&GS Tide Gage	8.7	2.65	Hurricane Carol	8/3/1954	COE Tidal Profile	
Aquinnah/W Tisbury	Menemsha Pond	8.5	2.59	'38 Hurricane	9/21/1938	COE Tidal Profiles	8 reported HWMs, max ~ 8.5' NAVD88
West Tisbury	Runner Rd.	6.2	1.89	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Tisbury	USC&GS Tide Gage West Chop	6.4	1.95	'38 Hurricane	9/21/1938	COE Tidal Profiles	
Tisbury	USC&GS Tide Gage West Chop	5.7	1.74	'44 Hurriane	9/14-15/1944	COE Tidal Profiles	
Tisbury	Beach Road, Hancock & Sons Woodworkers	4.3	1.31	'38 Hurricane	9/21/1938	FIRM Report	
Tisbury	Beach Road, Hancock & Sons Woodworkers	5.6	1.71	'44 Hurricane	9/14-15/1944	FIRM Report	
Tisbury	Beach Road, Hancock & Sons Woodworkers	6.1	1.86	Hurricane Carol	8/31/1954	FIRM Report	
Tisbury	Beach Road Mobil Gas Co.	5.7	1.74	'44 Hurricane	9/14-15/1954	FIRM Report	
Tisbury	Beach Road Mobil Gas Co.	6.3	1.92	Hurricane Carol	8/31/1954	FIRM Report	
Tisbury	SSA, Union Street, Vineyard Haven Hrbr	6.3	1.92	Hurricane Carol	8/31/1954	FIRM Report	
Tisbury	Burt's Boatyard, Howard Avenue, Lagoon Pond	5.8	1.77	Hurricane Carol	8/31/1954	FIRM Report	
Tisbury	A&P Store, Water St.	6.3	1.92	Hurricane Carol	8/31/1954	FIRM Report	
Tisbury	Tilton Limber Co., Water St	6.3	1.92	Hurricane Carol	8/31/1954	FIRM Report	
Tisbury	Vineyard Haven Harbor	6.4	1.95	'38 Hurricane	9/21/1938	COE Tidal Profiles	14 reported HWMs, max ~ 6.4' NAVD88
Tisbury	Head of Pond Rd	3.8	1.16	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Tisbury	Owen Park Beach, Owen Park Way	5.0	1.52	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Oak Bluffs	East Chop	6.7	2.04	Hurricane Carol	8/31/1954	COE Tidal Profiles	2 reported HWMs, max ~ 6.7' NAVD88
Oak Bluffs		6.7	2.04	'44 Hurricane	9/14-15/1944	COE Tidal Profiles	7 reported HWMs, max ~ 6.8' NAVD88
Oak Bluffs	Our Market Store	5.7	1.74	Hurricane Carol	8/31/1954	FIRM Report	
Oak Bluffs	Greenleaf Ave	6.6	2.01	Hurricane Carol	8/31/1954	FIRM Report	
Oak Bluffs	East Chop Dr., Harbor	4.2	1.28	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Edgartown	USC&GS Tide Gage	6.1	1.86	'38 Hurricane	9/21/1938	FIRM Report	
Edgartown	USC&GS Tide Gage	6.5	1.98	'44 Hurricane	9/14-15/1944	FIRM Report	
Edgartown	Harborside Inn	6.9	2.10	Hurricane Carol	8/31/1954	FIRM Report	
Edgartown	Coulger's Garage	6.8	2.07	Hurricane Carol	8/31/1954	FIRM Report	
Edgartown	Felix Neck, Felix Neck Dr.	4.6	1.40	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Edgartown	Cook St. & South Water St.	3.8	1.16	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Edgartown	Bluefish Pt, Edgartown Rd.	5.8	1.77	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
Edgartown	South Beach State Park, Herring Creek Rd.	7.0	2.13	Sandy	10/28/2012	USGS Report	Generally Fair Confidence in Elevation
						USGS Report	Generally Fair Confidence in Elevation

Table 4. Martha's Vineyard Historical High-Water Elevations.

considered. Source material considered during the research can be found in the references section below.

As shown in Table 4, the maximum contemporary high-water elevation identified for the Martha's Vineyard mapping profile is associated with the Hurricane of 1938 and occurred off the Gay Head cliffs of Aquinnah. Based on a compilation of storm tide information provided by the Corps of Engineers in its 1988 *Tidal Flood Profiles New England Coastline* technical report and by FEMA in its Flood Insurance Study for Dukes Country (July 20, 2016), this elevation was estimated to 9.4 feet (2.87 m) NAVD88. The present storm of record for the Woods Hole tide gauge (#8447930, established on August 10, 1932) is also 9.4 feet NAVD88 and occurred during the Hurricane of '38. For comparison, the maximum storm tide elevation for Nantucket Harbor since 1965 is 5.8 feet (1.76 m) NAVD88, occurring during the Halloween Gale (a nor'easter) on October 30, 1991.

As the highest reliable, century-scale water level identified for Martha's Vineyard, the elevation of 9.4 feet (2.87 m) NAVD88 was used as the base line for the Island's STP analysis. Initially, 4 feet (~1.25 m) was added to this elevation to establish an upper limit for the STP analysis and to reflect rising sea levels. As discussed above, the final upper limit was increased by 8.6 feet (~2.5 m) to 18.04 feet (5.5 m) NAVD88 to reflect more intense coastal storms and to simplify conversions to MLLW, the STP range planes used in the GIS analysis. Table 5 summarizes the Composite Storm Tide Profile used to analyze and map STPs across the Island.

Martha's Vineyard STP Mapping Profile			
Station: 8445138			
	NAVD88 (FT)	**NAVD88 (m)**	**Comments**
Historical High Water Elevation 1938 Hurricane Plus 8.64 feet (2.63 meters)	18.04	5.50	Upper Limit of Storm Tide Pathway Mapping Analysis
Gay Head Cliffs Aquinnah	9.4	2.87	Historical High Water Elevation 1938 Hurricane
			Average: Edgartown (Sta 8448558), Vineyard Haven (Sta 8448157), Oak Bluffs (Sta 8448298), Menemsha Harbor (Sta 8448725)
MHHW	0.87	0.27	"
MHW	0.55	0.17	"
MSL	-0.40	-0.12	"
MTL	-0.50	-0.15	"
MLW	-1.54	-0.47	"
MLLW	-1.72	-0.52	"
GT	2.6	0.81	"
MN	2.1	0.64	"

Table 5. Composite Storm Tide Profile used for Mapping Martha's Vineyard STPs

Storm Tide Pathways and National Weather Service Storm Surge Predictions

For certain areas, the NWS correlates its total water level estimates with qualitative descriptions of the potential impacts likely associated with approaching storm tides. Related directly to the physical characteristics of a threatened area, the descriptions are organized by general elevation categories referenced to local MLLW and suggest action levels for coastal communities threatened by approaching coastal storms. The action levels are summarized as:

- *Action Stage*: The water level at which some type of mitigation action should be considered in preparation for an approaching coastal storm tide.
- *Minor Flooding Stage*: The water level at which some public threat, such as minor flooding of low-lying roads and infrastructure, may be anticipated although minimal or no property damage is expected.
- *Moderate Flooding Stage*: The water level at which some inundation of structures and roads and possibly some evacuation of people and/or transfer of property to higher elevations can be anticipated.
- *Major Flooding Stage*: The water level at which extensive inundation of structures, properties, and roads and significant evacuation of people to higher elevations is anticipated.

As an example, Table 6 summarizes the current NWS description of Action Levels frequently issued for Provincetown. In this example, NWS has divided its description of the Major Flooding Stage for Provincetown into three elevation-based levels that reflect the increased flooding threat associated with higher storm tide projections.

As an elevation-based system for describing the location and level at which storm tides begin to flow inland, storm tide pathways can be associated with NWS descriptive flood stages. For this reason, STPs comprising the final data set are referenced to MLLW in addition to NAVD88 and color coded to correspond to NWS's visualization of action levels. Over time, these descriptions can be expanded and supplemented with more detailed local information and knowledge based on the observations of municipal emergency managers, first responders and the public.

Elevation (MLLW FT.)	**Action Level**
17	Major life-threatening flooding occurs in Provincetown and Truro. Provincetown becomes isolated, with inundation along Routes 6 and 6A. Significant inundation occurs in the greater vicinity of Commercial Street and many adjacent side streets. Truro could become bisected with flooding along Route 6 and streets in the greater vicinity of the Pamet River and Little Pamet River marshes. Heed the advice of local officials and evacuate if asked to do so.
16	Major coastal flooding occurs in Provincetown and Truro, with Provincetown becoming isolated due to inundation of Routes 6 and 6A. Numerous roads in Provincetown are flooded, including but not limited to large stretches of Commercial Street, Routes 6 and 6A, as well as connecting side streets. Provincetown Airport is completely flooded. In Truro major flooding occurs in the greater vicinity of the Pamet River and Little Pamet River and associated marshland, with inundation along numerous nearby roads.

15	Major coastal flooding occurs in Provincetown and Truro. This includes flooding of Provincetown Airport, and inundation along stretches of numerous roads including Routes 6 and 6A, stretches of Commercial Street and nearby side streets. Provincetown may become isolated. In Truro portions of Route 6 and 6A are also flooded, with flooding of roadways including Dechampes Way, Great Hills and Salt Marsh Lanes, and Fisher, Old County, Castle, Great Hills, and Old Pamet Roads.
14	Expect moderate coastal flooding in the vicinity of Provincetown and Truro. In Provincetown, flooding occurs at Provincetown Municipal Airport, Race Point Road, Provincelands Road, and portions of Commercial Street and Route 6A. In Truro flooding occurs in the vicinity of the Pamet River and Parker Marsh, with flooding on several roads including Castle Road, Eagle Neck Road, Phats Valley Road and Mill Pond Road. Heed the advice of local officials, and evacuate if asked to do so
13	Expect minor coastal flooding of some low-lying roadways. Minor coastal flooding occurs in Provincetown, in the vicinity of Race Point Road and Provincetown Airport. In Truro backwater flooding occurs along the Pamet River.

Table 6. Provincetown NWS Action Levels (Source: https://water.weather.gov/ahps2/hydrograph.php?wfo=box&gage=pvhm3).

Presently, NWS does provide general elevation-based action levels with its projections of approaching storm tide for the Vineyard Haven Harbor area, however, lacking an active real-time tide station, heights have yet to be correlated specifically with corresponding landside threats and actions. Local observers can assist NWS with developing Action Level descriptions for areas not yet covered by detailed threat descriptions by archiving observations that correlate landside water levels with actual flooding events, elevations, and locations. Absent a real-time tide station, observations can be related to a datum-referenced tide staff installed prior to an approaching storm. Lacking a tide staff, maximum flooding extents can also be marked with paint, stakes, or even photographs that preserve a storm record for future field surveys.

Table 7 illustrates the present relationship between NWS Action Levels and the contemporary tidal datums for Vineyard Haven Harbor. STP data reflects the Vineyard Haven MLLW elevation to facilitate present use of the Action Levels. Since MLLW does not vary significantly across the Island, Action Levels can be further developed in the future and adjusted to reflect local observations with minimal modifications, if any, necessary to STP GIS range planes.

Storm Tide Pathways Across Martha's Vineyard

The desktop analysis of the lidar data yielded 793 potential STPs throughout 6 towns: Aquinnah, Chilmark, Edgartown, Oak Bluffs, Tisbury, and West Tisbury. The fieldwork, a total of eight (8) crew days, was completed over four (4) days from March 15 -18, 2021 using two survey crews to increase efficiency. As discussed above, the desktop analysis extended to potential STPs up to an elevation of approximately 5.5 m NAVD88. Each potential STP identified in the desktop analysis was inspected by the field team and the location was moved when observations by the field team determined that it was necessary to reflect contemporary topographic conditions.

Storm Tide Pathway Tide Profile / NWS Action Levels				
Based on Vineyard Haven Tide Station (NOAA Sta #8448157)				
	NAVD88 (FT)	NAVD88 (m)	MLLW (FT) Approx.	Comments
Historical High Water Elevation 1938 Hurricane Plus 8.64 feet (2.63 m)	18.04	5.50	19.74	Upper Limit of Storm Tide Pathway Analysis
Gay Head Cliffs Aquinnah	9.4	2.87	11.10	Historical High Water Elevation 1938 Hurricane
Major Flood Stage	6.9	2.10	8.5	National Weather Service Vineyard Haven
Moderate Flood Stage	4.9	1.49	6.5	National Weather Service Vineyard Haven
Minor Flood Stage	3.4	1.04	5.0	National Weather Service Vineyard Haven
MHHW	0.53	0.16	2.12	Based on Vineyard Haven (Sta 8448157)
MHW	0.16	0.05	1.75	"
MSL	-0.54	-0.16	1.05	"
MTL	-0.64	-0.20	0.95	"
MLW	-1.44	-0.44	0.15	"
MLLW	-1.59	-0.48	0.00	"
GT	2.12	0.65	2.1	"
MN	1.60	0.49	1.6	"

Table 7. National Weather Service Action Levels for Vineyard Haven Harbor.

Where possible, the field team occupied all 700 STPs identified in the desktop analysis. As discussed above, however, where STPs appeared to be on private property, or were located on dynamic natural landforms or otherwise inaccessible they were logged in the database attribute table as *unverified* for labeling in map documents, Of the 793 STPs identified in the desktop analysis, 174 were rejected during the team laboratory sessions process and removed from the database taken into the field. Conversely, the field team located and evaluated potential STPs in low-lying areas that were not captured by the lidar data during desktop analysis and, where warranted, added them as part of the fieldwork to better reflect the present-day topography and/or vulnerability, once again highlighting the need for field-based verification of each potential STP.

During the field work 176 pathways (25.1% of the total) were moved more than one (1) meter horizontally from their original position determined in the desktop analysis to better reflect current conditions. A total of 81 additional STPs were added to the final database as a result of the fieldwork, yielding a final set of 700 STPs throughout the 6 towns (Figure 7).

Types of Storm Tide Pathways

Several types of STPs are included in the final dataset: standard storm tide pathways (STPs) as discussed above; 'spillways' (STP-S); 'roadways' (STP-R); and unverified (STP-U). These sub-types were developed to reflect different on-the-ground morphologies and techniques needed to identify and/or describe potential inundation at these locations. It should be noted that 263 of the final 700 STPs were tidally restricted and cross over multiple types of STPs and therefore were not identified by the tidally restricted designation alone.

The 'standard' STP can be described as a relatively narrow low-lying area or pathway in which coastal flood waters could travel inland. Stopping flow through such an STP would prevent inundation up to a given elevation defined as a Pathway Activation Level (PAL), or the level at which water will begin to flow. For example, the PAL for the STP in Figure 4 is 3.41 m (NAVD 88) Therefore, when the water level reaches 3.41 m regardless of the driver (i.e., storm surge, waves, sea level rise) it will begin to flow inland. The PALs can be used by town staff to prioritize STPs for potential mitigation measures as efficiently and effectively as possible.

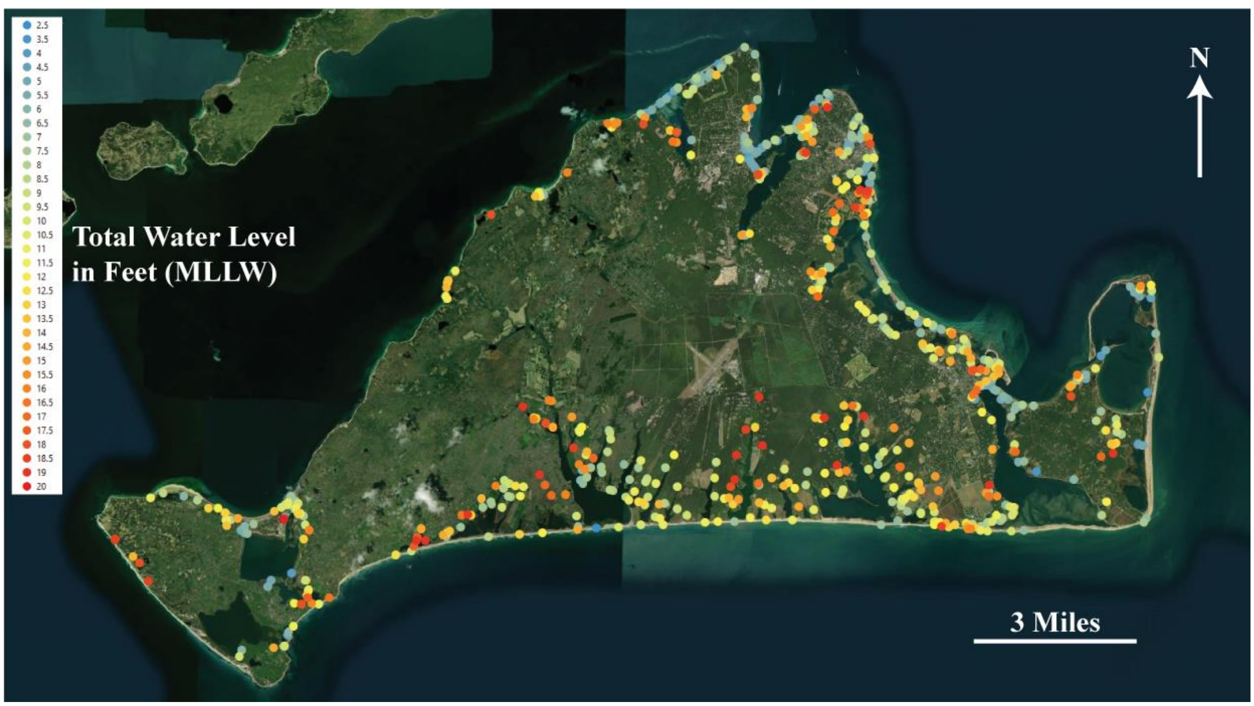

Figure 7. Location of the mapped storm tide pathways for the study area. STPs are color-coded by elevation.

The term 'spillway' was developed to reflect STPs located on areas of broad, low relief. The STP-Ss 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 conventional STPs (Figure 8). Actions planned to mitigate spillway STPs generally require design solutions 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 concern because of the lack of a well-defined pathway where flood waters can be controlled.

Finally, an unverified STP (STP-U) was defined to be an STP that was identified during the lidar analysis but was unable to be located or occupied by the field team for several reasons. As a ‘bare earth’ lidar data set, which is typical for these types of analyses. during processing vegetation, (trees, bushes, beach grass, salt marsh, etc.) and structures (houses, buildings, etc.) are removed from the data, hence the ‘bare earth’ name. Where this occurs, areas such as low spots found in the lidar analysis are not physically accessible, often located on private property, or merely artifacts of the bare-earth process. 333 STP-Us found in this study were located in low areas that will experience water flow, however, actual STP locations cannot be determined solely by the desktop analysis. This is frequently natural topographic changes (e.g., coastal dune migration) or human alterations (construction, development) since the lidar was collected.

For the former, future surveys can be supplemented by field teams using drones or when new lidar becomes available. For the latter, further field work will require permission to enter private property. All these STP-U’s are included in the final database as towns may want to pursue permission to locate critical STPs on private property or to monitor the changing positions of those located on dynamic landforms (e.g., with periodic and localized drone surveys). Table 8 summarizes the numbers of storm tide pathways by type for the entire island.

Storm Tide Pathways	**Standard (STP)**	**Spillway (STP-S)**	**Roadway (STP-R)**	**Unverified (STP-U)**
700	420	231	49	333

Table 8. Storm Tide Pathways for Martha’s Vineyard by type.

Figure 8. Example of topography consistent with a spillway STP. Almost 20% of the STPs mapped in the study were spillways. These areas will require a more extensive and concerted efforts to address.

These and other types of STP summary data can be used by towns to focus long-term planning and design efforts on threshold or priority elevations that highlight areas subject to inundation associated with sea level rise or with an increasing frequency of nuisance, or sunny day flooding. In addition, short-term summary information can be used to guide and develop storm preparation and proactive mitigation measures and strategies. The initial 2016 and 2017 STP pilot mapping projects have been used by Provincetown and Truro to prepare for approaching storms. For certain storms, town staff have monitored NWS real-time total water level predictions and implemented pre-storm mitigation measures successfully for affected STPs using sandbags, portable flood walls, and cordoning off potential hazardous roads for vehicles or pedestrians.

Island-wide STP Summary

Many low-lying coastal areas are experiencing inundation associated with nuisance, or sunny day flooding, storm surge and sea level rise. Based on data developed in this study, on average approximately 360 acres of land are inundated for every 6 inches of rise in total water level from 2.5 feet to 19.5 feet MLLW (Table 9, Figure 9). For the six (6) Vineyard towns, this ranges from an estimated low of 290 acres between 4.5 - 5.0 ft of TWL, to an estimated high of 484 acres between 8.5 – 9.0 ft TWL.

Table 9. Total storm tide pathways, cumulative area inundated and by Total Water Level (TWL). Datum is MLLW.

Plane (ft)	STPs	Range (ft)	Cumulative Acres	Acres by TWL
2.5	1	2.01-2.50	690.7	
3.0	1	2.51-3.00	1,074.1	383.4
3.5	3	3.01-3.50	1,488.7	414.7
4.0	9	3.51-4.00	1,792.3	303.6
4.5	22	4.01-4.50	2,117.9	325.6
5.0	34	4.51-5.00	2,407.9	290.0
5.5	35	5.01-5.50	2,763.1	355.3
6.0	32	5.51-6.00	3,134.3	371.2
6.5	33	6.01-6.50	3,535.2	400.8
7.0	31	6.51-7.00	3,864.0	328.8
7.5	35	7.01-7.50	4,185.7	321.8
8.0	29	7.51-8.00	4,482.1	296.3
8.5	31	8.01-8.50	4,838.2	356.1
9.0	24	8.51-9.00	5,323.1	484.9
9.5	33	9.01-9.50	5,618.5	295.4
10.0	28	9.51-10.00	6,048.0	429.5
10.5	24	10.01-10.50	6,389.7	341.7
11.0	19	10.51-11.00	6,872.5	482.8
11.5	27	11.01-11.50	7,333.7	461.2

12.0	27	11.51-12.00	7,653.9	320.2
12.5	14	12.01-12.50	8,097.1	443.2
13.0	24	12.51-13.00	8,425.1	327.9
13.5	20	13.01-13.50	8,766.7	341.6
14.0	19	13.51-14.00	9,122.0	355.3
14.5	17	14.01-14.50	9,460.9	338.9
15.0	11	14.51-15.00	9,806.1	345.1
15.5	16	15.01-15.50	10,192.6	386.5
16.0	15	15.51-16.00	10,530.8	338.2
16.5	10	16.01-16.50	10,883.5	352.7
17.0	11	16.51-17.00	11,239.7	356.2
17.5	8	17.01-17.50	11,563.3	323.7
18.0	11	17.51-18.00	11,888.8	325.4
18.5	9	18.01-18.50	12,190.3	301.6
19.0	11	18.51-19.00	12,560.2	369.9
19.5	5	19.01-19.50	12,969.7	409.4
	700			**12,279.0**

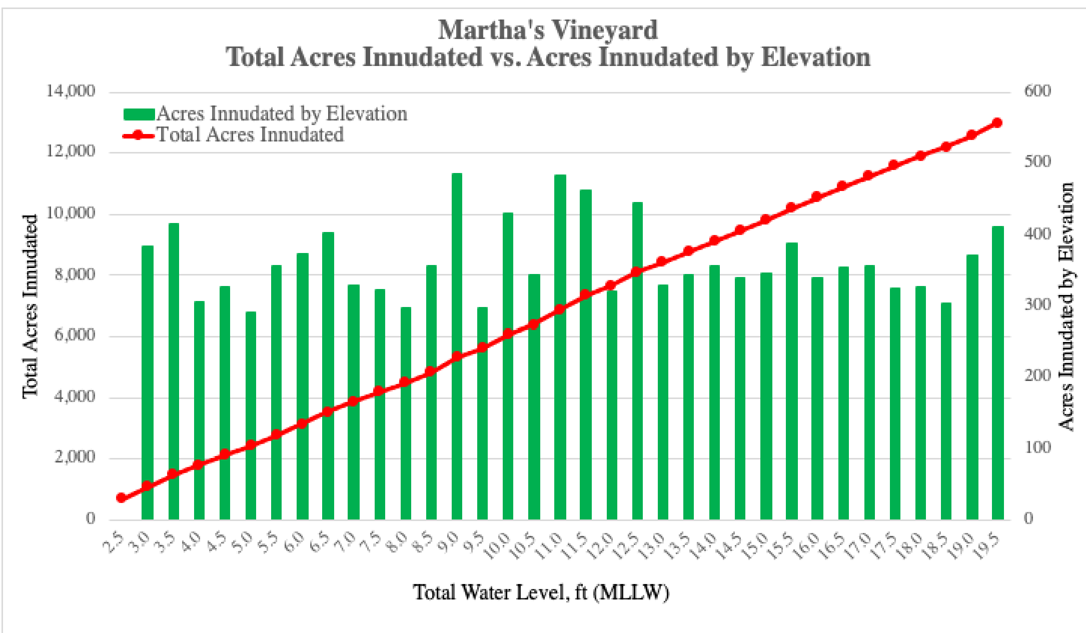

Figure 9. The red line represents the total cumulative area inundated with each 6-inch increase in total water level. The green bars represent the area inundated for each individual 6-inch increase in total water level. The average is approximately 360 acres per 6-inch increase in total water level.

Two of the highest values of inundation area for a 0.5-foot increase in total water level falls just at and above the project storm of record (11.10 MLLW) at 11.0 ft (482.8 acres) and 11.5 ft (461.2

acres). Peak storm surges from nor-easters or hurricanes, were they to coincide with a high astronomical tide, bringing total water levels just 6 inches above the project storm of record flooding could be seen in over 400 acres, that have not been significantly flooded since 1938. A storm with a total water level one foot higher than the project storm of record would yield an estimate of 780 inundated acres.

As illustrated by the preliminary database, many of the mapped STPs are located just above the elevation of the project storm of record used as the baseline for this analysis (11.10 MLLW). with mapping revealing that 54 STPs are less than 12 inches above this elevation (Figure 10). In other words, included in the STP mapping data are 54 locations throughout the study area that have not been flooded since before the 1938 hurricane, but would very likely be inundated with another 12 inches of total water level beyond that experienced during that storm.

Figure 10. Storm Tide pathways throughout the study area that are 1 foot above the project storm of record (n = 54).

The mapping of storm tide pathways in the manner developed by the Center for Coastal Studies has a diverse set of applications, ranging from short-term preparation for and response to approaching storms to medium-term planning for tourism and resource protection to long-term municipal planning and economic growth considerations with regards to rising sea level and development pressure. Although preliminary, these maps can be used by first-responders, planners, managers, and the general public to better understand the dynamic nature of the coast and the role storms and sea level rise will play in the future. They should be used with the understanding that the final version of these maps will be provided by the end of the project.

Storm Tide Pathways by Town

To be completed in Year 2.

Town of Aquinnah

Town of Chilmark

Town of Edgartown

Town of Oak Bluffs

Town of Tisbury

Town of West Tisbury

Coastal Flood Threat and Inundation Mapping webpage

To be completed in Year 2.

Stormtides.org

To be completed in Year 2.

Low-Lying Roads and Infrastructure Vulnerability Assessment

To be completed in Year 2.

REFERENCES:

Ashton, A.D, Donnelly, J.P., Evans, R.L. 2007. A discussion of the potential impacts of cimate change on the shorelines of Northeastern USA. Mitig Adapt Strat Glob Change. DOI 10.1007/s11027-007-9124-3. 25 p.

Bodnar, A.N. 1981. Estimating Accuracies of Tidal Datums From Short Term Observations. Technical Report NOS CO-OPS 0074. 40 p.

Boldt, K.V., Lane, P., Woodruff, J.D., Donnelly, J.P. 2010. Calibrating a sedimentary record of overwash from Southeastern New England using modeled historic hurricane surges. Marine Geology 275 (2010) 127-139. 13 p.

Borrelli, M., Mague, S.T., Smith, T.L., Legare, B., 2016a. A New Method for Mapping Inundation Pathways to Increase Coastal Resiliency, Provincetown Massachusetts. A report prepared for the Town of Provincetown, Massachusetts.

Borrelli, M., Mague, S.T., Smith, T.L., Legare, B., 2016b. Empowering Coastal Communities to Prepare for and Respond to Sea Level Rise and Storm-related Inundation: A Pilot Project for Nantucket Island. Tech. Report. p. 32.

Borrelli, M., Mague, S.T., Smith, T.L., Legare, B, 2017. Mapping Inundation Pathways to Provide Communities with Real-time Coastal Flood Forecasts: A Pilot Project with the National Weather Service. Center for Coastal Studies. p. 32

Borrelli, M., Mague S.T., Legare, B.J., McCormack, B., McFarland, S.J., Solazzo, D., 2021. Mapping Storm Tide Pathways in Cape Cod Bay. Tech. Rep. presented to the Cape Cod Cooperative Extension: 21-CL-05. p. 74.

Borrelli, M., McCormack, B., Mague, S.T., 2020. Mapping Storm Tide Pathways in Scituate and Cohasset: Assessing Coastal Vulnerability to Storms and Sea Level Rise.

Borrelli, M., Smith, T.L., Mague, S.T., in press. Vessel-Based, Shallow Water Mapping with A Phase-Measuring Sidescan Sonar. Estuaries and Coasts.

Cole, G. M. 1997. *Water Boundaries.* John Wiley & Sons. New York, NY. 193 p.

Cole, L.A. 1929. *Tidal Bench Marks State of Massachusetts.* Special Publication No. 155. Department of Commerce, U.S. Coast and Geodetic Survey. Washington. 1929. 39 p.

Crane, D.A. 1962. *Coastal Flooding in Barnstable County, Cape Cod Mass.* Massachusetts Water resources Commission. Charles I. Sterling, Director. December 1962. 63 p.

Donnelly, J.P, et al. 2001. 700 yr. sedimentary record of intense hurricane landfalls in southern New England. GAS Bulletin: June 2001; v.113; no. 6; p.714-727. 14 p.

Dunlop, T. 2014. They Never Really Hit the Vineyard, Right? Vineyard Gazette Magazine: History on the Water. September 2, 2014. Vineyard Gazette Archives. Accessed 4/1/21: https://mvmagazine.com/news/2014/09/02/they-never-really-hit-vineyard-right.

Flick, R. Murray, J. and Ewing, L 2003. *Trends in United States Tidal Datum Statistics and Tide Range.* Journal of Waterway, Port, Coastal and Ocean Engineering. ASCE. July/August 2003. p. 155–164.

Giese, G.S. 1978. *Effects of the Blizzard of 1978 on the Coastline of Cape Cod.* Provincetown Center for Coastal Studies. Chapter in “The Blizzard of 1978”, Effects of the Coastal Environments of Southeastern New England. Boston State College. 1978.

Gill S. K. and Schultz J. R. *Tidal Datums and Their Applications*. NOAA Special Publication, NOS CO-OPS 1. February 2001. 111 pp.

Kedzierski, J. 1992. *High Water Marks of the Halloween Coastal Storm, October 1991.* U.S. Army Corps of Engineers, Waltham MA. October 1992. 445 p.

Lin, N., Kopp, R.E., Horton, B.P., Donnelly, J.P. 2016. Hurricane Sandy’s flood frequency increasing form 1800 to 2100. PNAS Early Edition. Accessed 7/10/2020 at www.pnas.org/cgi/doi/10.173/pnas.1604386113. 5 p.

Marmer, H.A. 1927, revised, 1951. *Tidal Datum Planes.* Special Publication No. 135, U.S. Dept. of Commerce, U.S. Coast and Geodetic Survey.

Marmer, H. A. (1951). Changes in sea level determined from tide observations. *Coastal Engineering Proceedings*, *1*(2), 6.

Massachusetts Geodetic Survey. 1939. Storm Tide Hurricane of September 1938 in Massachusetts. Supplemented by High Water Data Floods of March 1936 and September 1938 in a separate volume herewith. Mass. WPA Project No. 16565, 100 Nashua Street, Boston, MA. Sponsored by Massachusetts Department of Public Works. 1939. 22 p. plus maps and tables.

Massachusetts Office of Coastal Zone Management. 2013. *Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning.* Executive Office of Energy and Environmental Affairs. December 2013. 22 p.

McCallum, B.E., et. al. 2013. *Monitoring Storm Tide and Flooding from Hurricane Sandy along the Atlantic Coast of the United States, October 2012.* Open-File Report 2013-1043. U.S. Department of the Interior. U.S. Geological Survey. 42 p.

Natural Disaster Survey Report. 1992. The Halloween Nor'easter of 1991. East Coast of the United states…Maine to Florida and Puerto Rico. October 28 to November 1, 1991. U.S. Department of Commerce. National Oceanic and Atmospheric Administration. National Weather Service. June 1992. 101 p.

NOAA, 2003. *Computational Techniques for Tidal Datums Handbook*. NOAA Special Publication NOS CO-OPS 2. National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services. Silver Spring, Maryland. September 2003. 113 p.

Renear, W.H. 1999. Martha's Vineyard's Ten Worst Storms 1625-1998. Accessed: 4/1/21: http://history.vineyard.net/dukes/storms.htm.

Richardson, W.S., Pore, N.A., and Feit, D.M. 1982. *A Tide Climatology for Boston, Massachusetts.* NOAA technical Memorandum NWS TDL 71. Techniques Development Laboratory, Silver Springs, MD. November 1982. 67 p.

Swanson, R. L. (1974). Variability of tidal datums and accuracy in determining datums from short series of observations (No. 64). National Ocean Survey.

Sweet, W., Park, J., Marra, J., Zervas, C., Gill, S. 2014. *Sea level Rise and Nuisance Flood Frequency Changes around the United States.* NOAA Technical Report NOS CO-OPS 073. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Serve, Center for Operational Oceanographic Products and Services. June 2014. 58 p.

U.S. Army Corps of Engineers. 1988. *Tidal Flood Profiles New England Coastline.* Prepared by the Hydraulics and Water Quality Section New England Division. September 1988. 29 p.

Weber, K.M., List, J.H., and Morgan, K.L.M. 2004. *An Operational Mean High Water datum for Determination of Shoreline Position from Topographic Lidar Data.* Open-File report 2004-xxx. U.S. Department of the Interior. U.S. Geological Survey. June 2004. 124 p.

Zervas, C. 2013. *Extreme Water Levels of the United States1893-2010.* NOAA Technical Report NOS CO-OPS 067. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Serve, Center for Operational Oceanographic Products and Services. September 2013. 200 p.

Zervas, 2009. *Sea Level Variations of the United States 1854-2006*. NOAA Technical Report NOS CO-OPS 053. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Serve, Center for Operational Oceanographic Products and Services. December 2009. 194 p.

Zervas, C. 2005. *Response of Extreme Storm Tide Levels to Long-term Sea Level Change.* NOAA/National Ocean Service Center for Operational Oceanographic Products and Services. 2005 IEEE. 6 p.

Flood Insurance Studies used for analysis in this study:

2016. *Flood Insurance Study, Dukes County, Massachusetts (All Jurisdictions).* Effective July 20, 2016. Federal Emergency Management Agency. Flood Insurance Study Number 25007CV000B. 65 p.

2010. *Flood Insurance Study, Dukes County, Massachusetts (All Jurisdictions).* Effective July 6, 2010. Federal Emergency Management Agency. Flood Insurance Study Number 25007CV000A. 66 p.

1997. *Flood Insurance Study, Town of Edgartown, Dukes County.* July 16, 1997. Federal Emergency Management Agency. Community Number 250069. 25 p.

1996. *Flood Insurance Study, Town of Gay Head [Aquinnah], Dukes County.* September 29, 1996. Federal Emergency Management Agency. Community Number 250070. 23 p.

1996. *Flood Insurance Study, Town of West Tisbury, Dukes County.* September 29, 1996. Federal Emergency Management Agency. Community Number 250074. 23 p.

1985. *Flood Insurance Study, Town of Chilmark, Dukes County.* October 15, 1985. Federal Emergency Management Agency. Community Number 250068. 37 p.

1984. *Flood Insurance Study, Town of Oak Bluffs, Dukes County.* September 18, 1984. Federal Emergency Management Agency. Community Number 250072. 30 p.

1983. *Flood Insurance Study, Town of Tisbury, Dukes County.* December 15, 1983. Federal Emergency Management Agency. Community Number 250073. 24 p.