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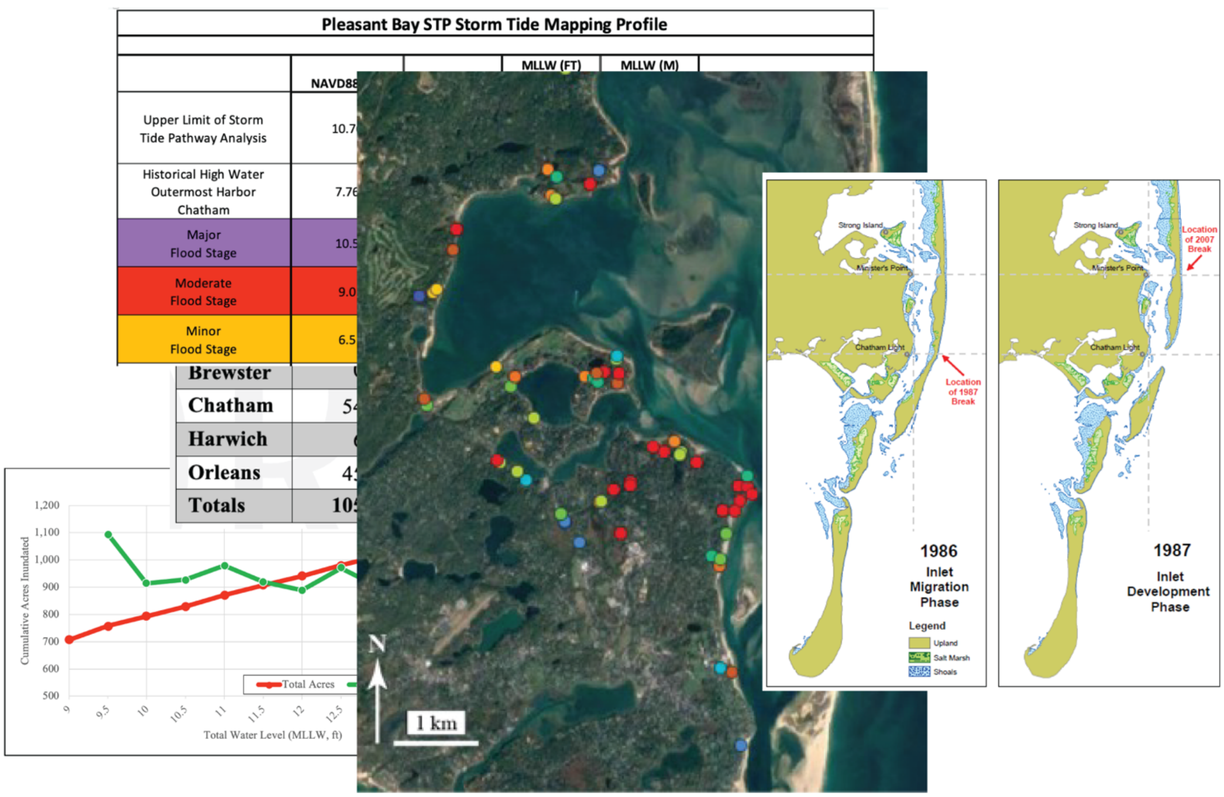
# *Mapping Storm Tide Pathways in Pleasant Bay, Cape Cod, Massachusetts*




*A report funded by and prepared for the Pleasant Bay Alliance*

*By*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*Publication: 23-CL-01*

**Acknowledgements**: We thank the Pleasant Bay Resource Management Alliance and Carole Ridley for the invitation to be part of the larger project and the Massachusetts Municipal Vulnerability Preparedness grant program for funding and Courtney Rocha for guidance and helpful feedback.

***Suggested citation:***
*Borrelli, M., Mague, S.T., Santos, P.P.G.M., 2023. Mapping Storm Tide Pathways in Pleasant Bay, Cape Cod, Massachusetts. Tech. Rep. presented to the Pleasant Bay Alliance: 23-CL-01. p. 40.*

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## *EXECUTIVE SUMMARY*

The mapping of storm tide pathways provides managers, town staff, and the public with contemporary information describing the location of potential pathways that can convey coastal flood waters inland during flooding events associated with storm surge, extreme high tides, or sea level rise. This information can also contribute to management decisions by communities that are responsive to real time events and address future inundation.

Storm tide pathways mapped along Pleasant Bay shorelines along Chatham, Harwich and Orleans (no pathways were found in Brewster) were visualized within the GIS in half-foot increments beginning at the elevation of the highest annual high tide up to a project storm of record (the January 4th 2018 storm) plus ~3 feet to account for increasing storm surges and future sea level rise. A total of 105 pathways were identified in the initial desktop analysis. After field work was conducted to verify, adjust, and locate pathways, 4 STPs were rejected from the desktop analysis, 9 were added in the field and 37 were moved more than 1 m from their initial position determined from the lidar in the desktop analysis. Based on this work, an average of approximately 39 acres of land are inundated with each half-foot rise in total water level along the mainland shores of Pleasant Bay. No STPs were mapped on the barriers or islands.

Increasingly, low-lying coastal areas that historically flooded primarily during discrete high water storm events are susceptible to more regular flooding during monthly spring tides. Significantly, this study identified 13 pathways between 10.5 – 11.5 ft (MLLW) that are approximately one foot above the project storm of record. While not the primary focus of this project, preliminary calculations indicate that an increase of one foot to the flooding associated with the January 2018 storm could result in an additional 78 acres of inundation throughout the study area. Since these areas have not flooded in recent history, coastal managers and other stakeholders may want to pay particular attention to potential impacts associated with sea level rise and increasing storm surges.

## *PROJECT BACKGROUND AND OVERVIEW*

Pleasant Bay has historically been vulnerable to inundation associated with coastal storms and flooding. These threats are further exacerbated by rising sea levels and flooding events that have increased in frequency and magnitude. Recent local storms such as the Nor'easters of 2015 and 2018, as well as Hurricane Sandy (2012), highlight 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.

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 in order 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) are 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 low-cost elevation data, while appropriate for regional scale planning efforts, did not support community scale efforts to identify the increasing threats associated with coastal storms over short-term timeframes. 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 area-specific decisions expected of local coastal managers.

Based on the long-range projections of sea level rise, and the catastrophic damage associated with large coastal storms, much attention is now focused on long term strategies to reverse current climate trends and slow, or reverse, the rate of sea level rise. Strategies to reduce greenhouse gas emissions to promote green energy, slow rising temperatures, and halt glacial ice melt, over the next hundreds of years are being discussed and debated at the international, national, and state levels. Clearly the policies and costs to confront these issues are long term, capital intensive, and more selectively implemented at the state or federal levels. 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 municipalities.

Recognizing the limited financial and technical resources of coastal communities, and their unique geography, often local responses and strategies to sea level rise and climate change can operate more effectively when considered 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

For short term, or local efforts, actual past and present storm tide elevations can provide an effective means of characterizing local coastal hazard vulnerabilities for community level planning actions. Figure 1 depicts estimates from several sources of historical storm tide elevations for the Boston area (an easterly facing shore) for various storms for the 17th - 21st centuries. The current projections for the highest sea level rise scenario and the NOAA regression rate scenario based on current tide gauge data obtained from the Boston tide gauge are shown through the year 2100.

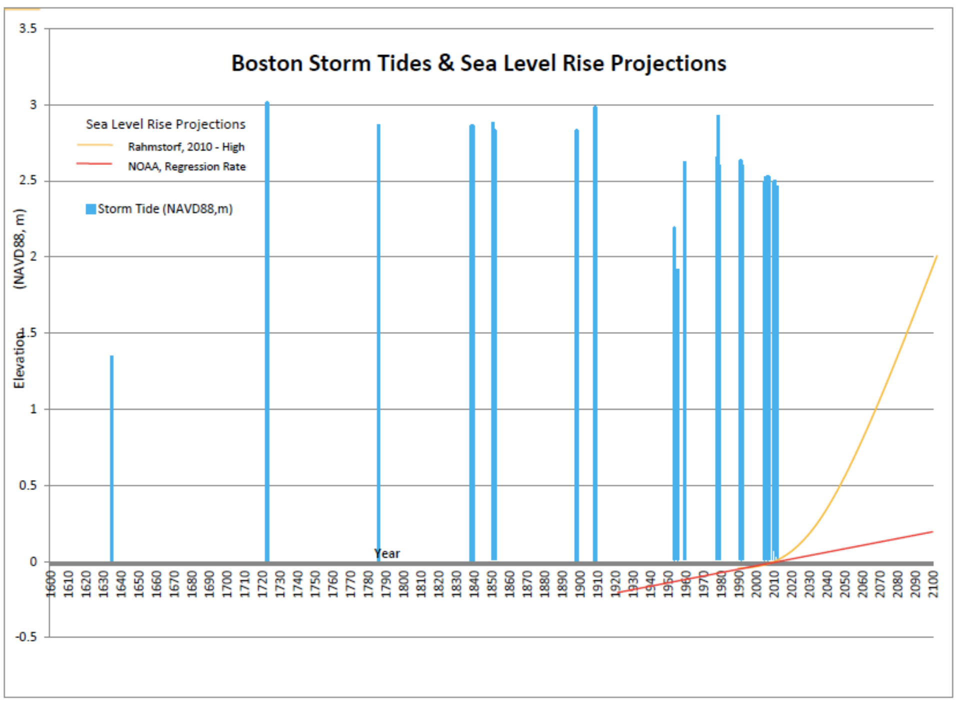


*Figure 1. Historical Storm tides and sea level rise.*

In recent history the “Blizzard of ‘78” had been the storm of record for Boston and most of Massachusetts. However, the January 4th, 2018 storm, approximately 9.66 ft NAVD88 (or 15.17 ft local MLLW) surpassed the total water level for the 1978 storm for much of the same area and is now the new storm of record for Boston as well as for Chatham at 7.76 ft NAVD88 (or 10.25 ft local MLLW). The 2.1 ft difference between the total water level elevation between Boston and Chatham for the same storm is related to the difference in tidal range between the two areas, 9.49 ft vs 4.64 ft, respectively and not uncommon. Storms can be very site specific and thus when doing these analyses the nearest storm-related TWLs are used.

Interestingly, the plot indicates that the storm tides and associated flooding for Boston reached an elevation of approximately 1 meter (~3 feet) above that of the highest sea level rise projection for the year 2100, illustrating the point that municipalities appear to be more susceptible to storm-related flooding now, and that preparing for these storm events can help communities prepare for future sea level rise. The plot further reveals that earlier estimates of storm tide heights have probably equaled or exceeded the 2018 maximum numerous times since the 17th century.

Identifying potential future storm tide heights, coastal flooding extents, and areas of potential vulnerability based on historical data provides several benefits to coastal communities. First, using actual historical storm tide data helps illustrate sea level rise scenarios without the need to select the most appropriate sea level rise elevation upon which to base short term planning strategies from the wide range of current projections. Sea level rise notwithstanding, storm tides of significant magnitude have been experienced in the past and will continue to be experienced again in the future. Second, contemporary storms of record provide an accurate and 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 pathways yields reliable information that can be used by coastal communities to plan for and implement ground level strategies in response to sea level rise and climate change.

*METHODS*

**Pleasant Bay STP Mapping Profile**

As discussed above 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 Massachusetts Office of Coastal Zone Management (CZM) Resiliency Grant projects with the towns of Provincetown, Nantucket, Scituate, Cohasset, and Truro; a Massachusetts Seaport Economic Council Grant with the Barnstable County Extension to complete mapping of Cape Cod Bay STPs; a grant with the Cape Cod Commission and the Barnstable County Extension, to map STPs along the Nantucket Sound shores of Barnstable, Yarmouth, Dennis, Harwich, and Chatham; and a project with the town to map the Little Beach area of Chatham; when referenced to a common vertical datum these data can be used by towns as the basis for near-term community planning decisions and real-time decisions necessary to respond to approaching coastal storms and related storm surge.

**Characterizing Storm Tide Inundation**

As relative sea level continues to rise, many coastal communities are experiencing minor flooding with the higher tides of the month (e.g., spring tides) or with changes in prevailing winds or currents. Often referred to as *nuisance* or *high tide flooding (HTF)* 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). Although site specific and varying with the tide range (Mn), minor HTF has been found generally to begin when coastal water levels exceed 1.75-2.5 ft (~0.5-0.8 m) above the mean higher high water (MHHW) level (Sweet, *et. al.,* 2021).

In addition to minor monthly inundation, many coastal communities are also experiencing periodic, 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. The maximum level of the storm tide is also referred to as the *total water level (TWL)* by the National Weather Service. Storm tides are referenced to datums, either to vertical 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.

In addition to the magnitude of the 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 this relationship is illustrated by the following example.

Prior to January 4, 2018, the storm of record for the Boston Tide Gauge (#8443970) occurred on February 7, 1978 (the Blizzard of ’78) with a maximum storm tide elevation of 9.59’ referenced to the North American Vertical Datum of 1988 (NAVD88). Occurring near the time of the predicted or astronomical high tide, the storm surge was approximately 3.5 feet. By comparison, the maximum storm tide elevation experienced during the blizzard of January 27, 2015 was 8.16’ NAVD88. Occurring shortly after the astronomical high tide, this elevation was the result of an astronomical tide height of 4.79’ NAVD88 and a storm surge of 3.37 feet. Significantly, the maximum storm surge for this event was 4.5 feet, however, because it occurred close to the time of low water, the corresponding storm tide elevation was only -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 9.2’ NAVD88, approximately 0.4 feet below the elevation of the storm of record.

Recognizing the significance 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 projects the timing of maximum storm surges and total water levels as coastal storms approach various Massachusetts locations. The current project for Pleasant Bay supplements information developed in a previous project for the Little Beach area of the town of Chatham and provide the NWS Norton office with an additional data set of accurately mapped storm tide pathways that can be incorporated into its *Coastal Flood Threat and Inundation Mapping* website (https://www.weather.gov/box/coastal?sid=BOX&zoomLevel=8&centerLat=42.17404&centerLng=-71.49837), expanding the geographic scope of reliable NWS forecasts for the east facing shoreline of Cape Cod.

## 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).[1] 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).[2]

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

Tidal heights also vary over longer periods of time due to the non-coincident orbital paths of the earth and moon about the sun. This variation in the path of the moon about the sun introduces

[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.

[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.

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 (Table 1) 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 | 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* |

### *The Mapping of Storm Tide Pathways*

Initial mapping of storm tide pathways begins with a computer-based analysis of the most representative lidar data available. Two datasets compiled by the U.S. Geological Survey were used: the 2013-2014 data set collected in the wake of Hurricane Sandy and the most recent lidar dataset from 2021. This analysis was then supplemented with field verification of the lidar data and conditions on the ground at the time of mapping. As the lidar metadata cautions, users need to be aware temporal changes may have occurred since the dataset was collected and that some parts of these data may no longer represent actual surface conditions. This can be particularly significant for coastal datasets where the latest available lidar data sets often do not represent current field conditions due to the dynamic and constantly evolving nature of coastal landforms or the presence of new development. Therefore, the rigorous and time-consuming fieldwork of verifying the lidar and real-world conditions are important components of the mapping process.

Desktop Analysis

The ability to conduct accurate fieldwork is a key component of the STP verification process. First, **LI**ght-**D**etection **A**nd **R**anging, or lidar data, is used to locate the preliminary set of STPs. Lidar data is the most accurate and cost-effective spatial data collected over broad areas. Of course, it only characterizes the topography of the mapped area for the actual date and time of the data acquisition. Lidar is similar to radar and sonar but rather than using radio or sound waves it uses light to collect elevation data. Due to the dynamic nature of the coast and its relationship to coastal flooding patterns, the location of natural storm tide pathways can be 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 revealed 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.

The lidar used for this study was collected via aerial surveys by the United States Geological Survey (USGS) along the coast of Cape Cod. The first in 2013-2014 as part of a post-Hurricane Sandy study. A small portion of inland areas were not covered by this lidar data. The second, in 2021. Respectively, metadata for the lidar accuracy reported that data was compiled to meet a horizontal accuracy of 0.36 and 0.11 meters (1.2 and 0.4 ft). Vertically, at the 95% confidence level the Vertical Accuracy, tested to meet vertical root mean square error (RMSEz) in open terrain tested at 0.052 and 0.037 meters (0.17 and 0.12 ft).

The post-processing of lidar collected via aerial surveys can introduce uncertainties that exaggerate or diminish features in three-dimensional data and, as a result, can obscure or conflate the presence and scale of an inundation pathway. These effects have been shown to be associated with 'bare earth' models where elevations tend to be "pulled up" adjacent to areas where buildings have been removed (Figure 2) or "pulled down" in areas where bridges and roads cross streams or valleys, further emphasizing the value of field verification.

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.

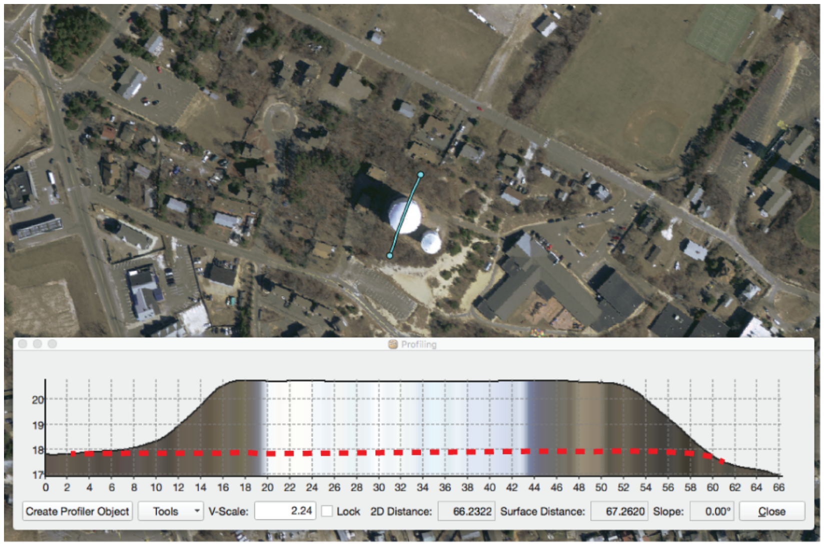


Figure 2. Example of 'pull up' near a water tower in Provincetown. Dotted red line is more representative of elevations at the water tower. Blue line in image is location in profile. Profile units = meters (Vert. NAVD88, Hor. NAD83), image taken from Borrelli, et al., 2017.

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

Another valuable feature of this data visualization software is the ability to drape 2-dimensional data, such as an aerial photograph, over a 3D dataset (lidar). This allows the analyst to better document the STP location and to acquire information about the landscape setting of the STP and the substrate on which it is located. 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 or permanent 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 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 means of orientation, and placing the potential STP in its broader geographic context.

## Field Work

Once a preliminary inventory of potential STPs along the Pleasant Bay shoreline 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 one of Center's survey grade Real-Time-Kinematic GPS (RTK-GPS) instruments. The Trimble® R10 GNSS receiver utilizes The Center's subscription 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 Hiebert Marine Lab in Provincetown. This allows the Center to collect RTK-GPS without the need for a terrestrial base station or to post-process the GPS data, streamlining the field effort and increasing field work efficiency.

The Center performed a rigorous analysis of this system to quantify the accuracy of this network see Borrelli, et al., (2021a) for details. 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).

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, is 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.

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 (i.e., relatively flat) and verifying the presence of an STP, 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 was quality controlled, the database was 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 was 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 inundation planes were created to make visualizations more user friendly for local managers. Recognizing that floodplain mapping is not a goal of the project, the use of planes to visualize STPs was determined to be the clearest way of presenting the data in a useful manner while recognizing the uncertainty associated with the lidar. After reviewing the various scenarios, the lowest plane was begun at the approximate elevation of a composite mean high water spring tide (MHWS) for the Pleasant Bay shoreline. Planes were developed in 6-inch intervals and extracted for each range to a maximum elevation represented by the project storm of record plus nine feet. In addition to providing an upper limit to project elevations, the project storm of record plus 3 feet (14.0 feet MLLW) provides a useful representation of potential near term future sea level rise scenarios or extreme storm events that would have practical implications for local managers. A 3-foot elevation above the storm of record was chosen as a good mix between the elevation of TWL that could be reached due to storm surge and sea level rise in the near future and the time after which the mapping of storm tide pathways would have to be remapped. If, for example, 6 feet was chosen, the changes that would take place during the time needed for 3 to 6 ft of sea level rise to occur would necessitate that low-lying coastal areas would likely have to be remapped due to natural and human-induced changes.

During the field work portion of the project, data was not collected on private property and considered inaccessible. Inaccessible points were 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., assumed to be private property) or impossible (e.g., beneath substantial tree cover and, therefore no GPS signal coverage) for the field team to occupy it. Due to the rapidly changing coastal landscape, STPs located on dynamic landforms such as coastal dunes were also labeled as unverified to reflect the lack of permanency of these locations. For this reason, unverified STPs located on rapidly changing natural landforms such as dunes, barrier beaches or in areas experiencing erosion should be viewed as a guide requiring periodic updating or verification. An unverified STP should not be considered as indicative of a low hazard level. Rather because it was identified as a potential STP, it may warrant further investigation on a case-by-case basis.

Mapping storm tide pathways, as with any mapping effort, is a balance between reflecting on the ground conditions and providing clear and useful information. To assist the user with STP interpretation, planes showing the extent of potential flooding at half-foot intervals are provided with the GIS data. Based solely on lidar, the range planes are not intended to be used as an accurate source of floodplain boundaries but as a way to visualize how storm tides of increasing heights can make their way inland. For this reason, it is important to view STPs with the planes to help evaluate the level of threat posed by an approaching coastal storm and to develop potential mitigation strategies, particularly in flat areas where inundation is not controlled by discrete STPs but exhibits sheet flow across broad areas with no easily identifiable points that can be used to halt or control the inland flow of water.

For example, along flat sections of road where there are multiple, closely spaced low spots, identifying multiple STPs provides little value to the user. In these situations, typically information on the lowest STP has been provided to characterize a threshold level at which the road will begin to experience inundation. Areas with STPs potentially triggered by an approaching storm should then be viewed in the context of the appropriate range plane to assess potential responses. This is particularly true in areas where the inland progression of storm related flooding occurs more as sheet flow rather than along definable pathways. As always, the STP should be viewed in conjunction with the range planes to assess potential inland response measures related to estimated storm surge heights. In many areas, culverts, bridges, etc. provide a significant continuous hydraulic connection that could carry tide water inland. Since hydraulic analyses of these types of structures is beyond the scope of this project, coastal flooding is assumed to be able to be carried inland unrestricted and therefore, STP information is provided on the more inland parallel roads to help guide potential mitigation efforts.

## RESULTS AND DISCUSSION

### STP Mapping Reference Framework

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

- The landscape setting of the community (e.g., open ocean vs protected shores).

- The elevations of astronomical tides (e.g., a mean high water (MHW) elevation for Boston Harbor of 4.31 feet (1.31 m) NAVD88 v. 2.31 ft. (0.74 m) NAVD88 for Chatham Fish Pier).
- Typical characteristics of astronomical tides (e.g., the mean range (Mn) - MHW minus MLW - of Boston Harbor tides is 9.49 feet (2.89 m) while that for Stage Harbor is 4.60 feet (1.40 m)).
- The topography (e.g., the elevation of the land and community development history relative to the 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 minor changes in water levels);
- The nature of coastal landforms (e.g., the rock shorelines of the North shore v. the dynamic sandy shorelines of Cape Cod); and
- The vertical relationship between historical development patterns and adjacent water levels (e.g., development in Boston began in the early 17$^{th}$ 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, 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), the tidal profile should consider the approximate high water record of datum referenced historical storm tides and the elevation of the maximum contemporary storm tide experienced (termed the project storm of record) in the area. As sea levels continue to rise, an estimate of future storm tides is provided by adding three feet to this localized storm of record (Zervas, 2009). As discussed below, the dynamic nature of Pleasant Bay presents an interesting challenge for developing a tidal profile for mapping STPs.

**The Pleasant Bay Storm Tide Mapping Profile**

Pleasant Bay is an estuarine system that is constantly evolving in response to rising sea levels and coastal storms. As the system responds to these long- and short-term environmental stressors, the configuration and location of its barrier beach and inlet(s) change influencing the volume, current strength, and tidal range of water entering and leaving the Bay. (PBRMA, 2018, revised 2020). These changes, in turn, result in a dynamic tidal profile that varies through time in response not only to sea level rise but the location of the Chatham tidal inlet (Giese, G.S. & B. Legare, 2021;and Borrelli, et. al., 2019). Recent trends in Bay tidal dynamics have been monitored and assessed by CCS and illustrate the effects of inlet location on tide ranges within the Bay, including a general decrease in magnitude in northern areas of the Bay as the inlet migrates south (Giese, *et al* 2021;

Giese *et al* 2019; Borrelli, *et al,* 2019; Legare and Giese, 2017; Legare, 2016; and Giese *et al,* 2009.).

Table 2 summarizes annual tide ranges reported for Pleasant Bay from 1887 to 2022. Tide ranges before 2012 were obtained from various publications of the U.S. Coast & Geodetic Survey and its successor agencies. Yearly tide ranges from 2012 to 2022 are based on the results of the CCS tide monitoring program sponsored by the Pleasant Bay Resource Management Alliance (PBRMA).

Table 2. Historical Tide Ranges (Mn): Tide ranges refer to the general area of Chatham Light/Chatham Fish Pier.

| Year | Mn (Feet) * See Note | Source |
|---|---|---|
| 1886 | 6.7 | Henry Marindin, U.S.C.& G.S. |
| 1887 | 6.0 | H-1817, U.S.C.& G.S. Annual Reports |
| 1955 | 3.6 | H-8348, U.S.C.& G.S. Descriptive Report |
| 1956 | 3.9 | H-8349, U.S.C.& G.S. Descriptive Report |
| 1978 | 3.3 | NOAA, NOS Tide Tables |
| 1987 | 3.1 | NOAA, NOS Tide Tables |
| 2007 | 5.0 | NOAA CO-Ops (83-01 NTDE) |
| 2012 | 5.7 | CCS |
| 2013 | 5.8 | CCS |
| 2014 | 5.6 | CCS |
| 2015 | 5.4 | CCS |
| 2016 | 4.9 | CCS |
| 2017 | 4.6 | CCS |
| 2018 | 5.2 | CCS |
| 2019 | 5.2 | CCS |
| 2020 | 4.6 | NOAA CO-Ops (83-01 NTDE) |
| 2021 | 4.6 | CCS |
| 2022 | 4.6 | CCS |

When looked at together, tide ranges can be seen to have fluctuated by almost 3.5 feet over the period of 140-150 year inlet migration cycle (Giese *et al,* 2009; Borrelli, *et al, 2019a and 2019b).* Figure 3 illustrates the dynamic nature of estuary landforms, showing various configurations of Pleasant Bay, including the location of the inlet(s) for the period 1886 – 2009 (Giese *et al,* 2009).

The effects of inlet location on tide range are illustrated with the new inlet created off Chatham Light in 1987 that resulted in an increase in the tide range within the Bay by almost 2-feet over the 20 year period from 1987 to 2007. Most recently, based on CCS's ongoing monitoring of Bay

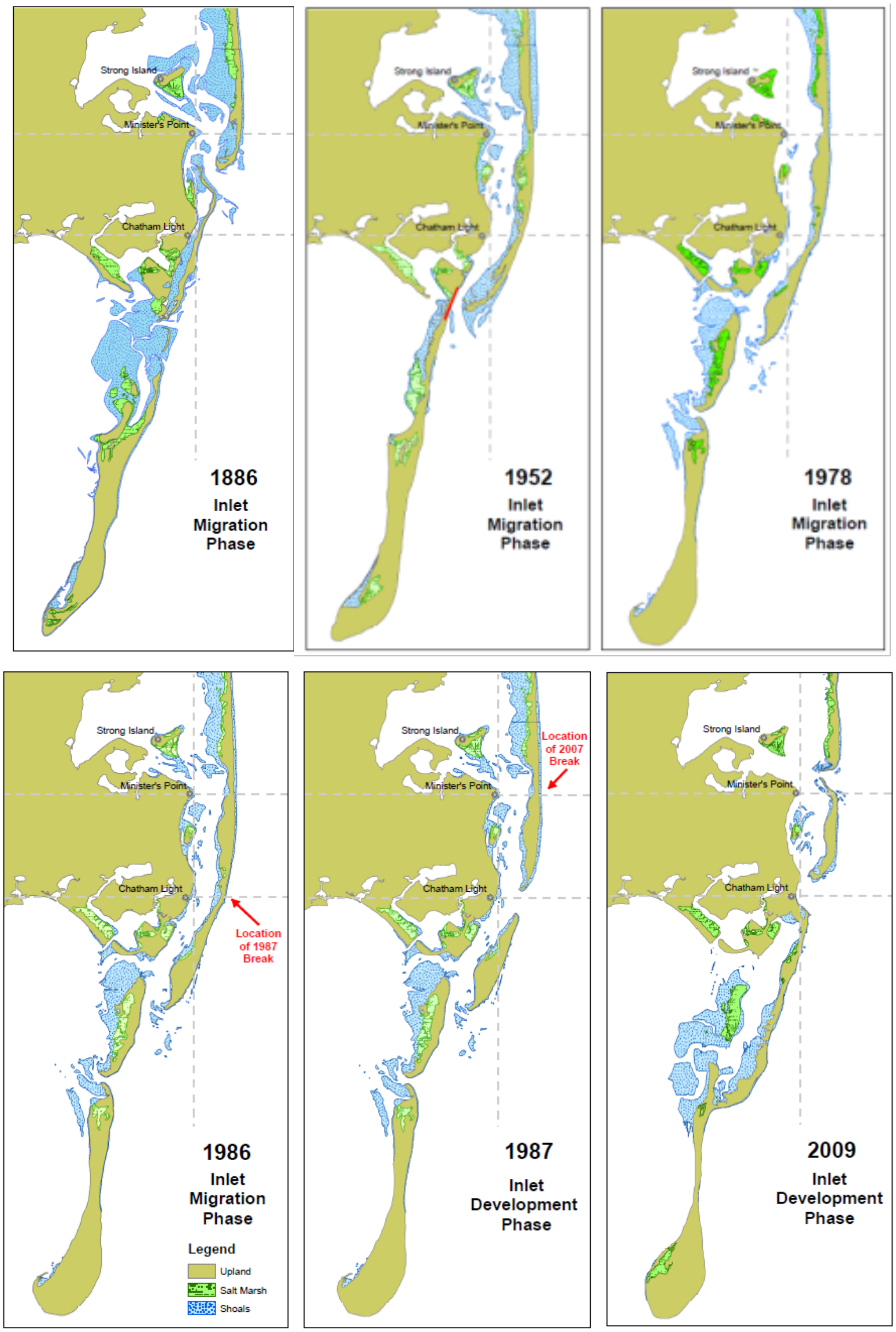


Figure 3 Changing configurations of the Nauset Beach/Pleasant Bay/Chatham Harbor barrier beach system (Giese *et al,* 2009).

tides, this range has been observed to vary by as much as 0.6 feet per year over the period of 2012 to 2022 in response to the formation of an additional inlet off Minister's Point to the north of the 1987 location. Clearly, although the tide ranges and corresponding MLLW elevations vary geographically only slightly within Pleasant Bay over short time frames, there can be significant variation over longer periods in response to changing physical conditions in the Bay, and in particular the location of the inlet(s). The changing Pleasant Bay tides present a new challenge for developing a tidal profile that minimizes the uncertainty associated with communicating the potential threats associated with approaching coastal storms.

Where possible, CCS tidal profiles for projects covering limited geographic areas have been developed based on data from one, real time contemporary tide station. Since tidal datums vary locally, however, several of the completed STP projects have required the use of a composite tidal profile based on limited information associated with former tide stations. These composite tidal profiles are termed *storm tide mapping profiles* and were developed to facilitate the mapping of STPs covering broad geographic areas with varying local tidal datums. Although relatively limited in geographic scope, the development of an STP mapping profile for Pleasant Bay must consider the temporal effects of continuously changing landforms on the complex coastal processes responsible for local tide ranges and datums.

In March of 2017, the Center for Coastal Studies installed a HOBO™ U20 water level logger in Outermost Harbor anticipating a potential new inlet formation through South Beach, on the outer barrier beach in Chatham. On April 1, 2017 (the April Fool's Day nor'easter), a new inlet formed across from Outermost Harbor approximately 2 miles to the south of the Fish Pier in Chatham Harbor (Borrelli *et al, 2018).* This tide data was used in conjunction with data from NOAA's real-time tide station Chatham (STA # 8447435, Aunt Lydia's Cove) located on the Chatham Fish Pier to develop an appropriate, contemporary project storm tide mapping profile to complete STP mapping in Pleasant Bay. Table 3 shows 1983-2001 National Tidal Datum Epoch (NTDE) values for tidal datums at both stations. Datums are referenced to NAVD88 for comparative purposes and illustrate the closeness profile values. Interestingly, 1983- 2001 NTDE tidal datum values for Station 8447435 were updated from previously reported 2007 values in 2020, presumably to reflect the effect of the new 2017 inlet on local tidal dynamics.

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. To integrate final storm tide pathway data with NWS total water level estimates, however, tidal datums must also be referenced to MLLW. Table 3 illustrates that while MLLW values do vary, within the project area the current difference is only 0.12 feet between the datum referenced values for the Chatham Fish Pier and Outermost Harbor. Based on this close agreement, the tidal profile used to map Pleasant

Bay STPs was referenced to the elevation of MLLW at Chatham (Station 8447435). Significantly, this is the current plane of reference for NWS estimates of total predicted storm water levels for the east coast of the Cape, providing a direct relationship to NWS Action Stages. Based on this assessment, the following relationship between local MLLW and NAVD88 at the Chatham Fish Pier was used for Pleasant Bay:

$$\textbf{Elevation}_{\textbf{MLLW}} \textbf{ - 2.49 feet = Elevation}_{\textbf{NAVD88}}.$$

Table 3. Tidal Datum Profiles for the Chatham Fish Pier and Outermost Harbor. MSL has not been calculated for the Outermost Harbor data set.

| | | **NOAA Sta: 8447435 Chatham NTDE: 1983-2001 Accepted: May 14, 2020** | **CCS Tide Station Outermost Harbor NTDE: 1983-2001 January 1-31, 2018** |
|---|---|---|---|
| **Tidal Datum** | **Description** | **NAVD88 (FT)** | **NAVD88 (FT)** |
| **MHHW** | Mean Higher High Water | 2.68 | 2.80 |
| **MHW** | Mean High Water | 2.31 | 2.28 |
| **MSL** | Mean Sea Level | 0.06 | N/A |
| **MTL** | Mean Tide Level | -0.01 | 0.11 |
| **MLW** | Mean Low Water | -2.33 | -2.06 |
| **MLLW** | Mean Lower Low Water | -2.49 | -2.66 |
| **GT** | Great Diurnal Range | 5.18 | 5.46 |
| **Mn** | Mean Tide Range | 4.64 | 4.34 |
| **HWI** | Greenwich High Water Interval (Hours) | 4.87 | 4.48 |
| **LWI** | Greenwich High Water Interval (Hours) | 11.77 | 11.58 |

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 tide mapping profile considers the high water levels of datum referefnced historical storm tides. Table 4 summarizes the results of research conducted to identify reliable historical high water elevations within Pleasant Bay. Source material considered during the research can be found in the references contained at the end of the section.

Table 4. Pleasant Bay Historical High Water Elevations.

| Town | Location | Elevation (NAVD88, FT) | Elevation (NAVD88, m) | Storm | Date | Source |
|---|---|---|---|---|---|---|
| Chatham | Outermost Harbor | 7.76 | 2.37 | Nor'Easter | 1/4/2018 | CCS Tide Gauge |
| Chatham | Chatham Fish Pier | 7.20 | 2.20 | | 2/9/2013 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 6.96 | 2.12 | Nor'Easter | 1/3/2014 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 6.88 | 2.10 | Nor'Easter | 2/9/2013 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Harbor Clafflin Landing Rd. | 6.60 | 2.01 | Sandy | 10/28/2012 | January 2016 Nor'Easter |
| Chatham | Chatham Harbor End Cowyard Road | 6.60 | 2.01 | Halloween Storm | 10/31/1991 | COE Report Halloween Storm HWMs |
| Chatham | Chatham Fish Pier | 6.32 | 1.93 | | 1/30/2018 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.31 | 1.92 | | 3/8/2013 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.29 | 1.92 | | 2/26/2010 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.29 | 1.92 | | 3/7/2013 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.28 | 1.91 | | 1/2/2010 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.26 | 1.91 | | 3/1/2010 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.24 | 1.90 | | 12/27/2010 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.14 | 1.87 | | 2/8/2016 | NWS Historic Crest Data |
| Chatham | Chatham Fish Pier | 6.00 | 1.83 | Nor'Easter | 1/30/2018 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.99 | 1.83 | | 2/26/2010 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.99 | 1.83 | | 3/7/2013 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.96 | 1.82 | | 1/2/2010 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.94 | 1.81 | | 3/1/2010 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.92 | 1.80 | | 12/27/2010 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.82 | 1.77 | | 2/8/2016 | NOAA Tide Gauge # 8447435 |
| Chatham | Chatham Fish Pier | 5.28 | 1.61 | Nor'Easter | 1/24/2016 | NOAA Report |
| Chatham | Harbor Coves | 5.00 | 1.52 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Orleans | Meetinghouse Pond at Barley Neck Rd. | 4.90 | 1.49 | Sandy | 10/28/2012 | USGS Report |
| Chatham | Ryder's Cove | 4.30 | 1.31 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Chatham | Strong Island Rd. Parking Area | 4.30 | 1.31 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Chatham | Scatteree Rd. Landing | 4.20 | 1.28 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Chatham | Aunt Lydia's Cove | 4.10 | 1.25 | '38 Hurricane | 9/21/1938 | FIRM Report |
| Chatham | Route 28 at Muddy Creek | 4.10 | 1.25 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Chatham | Aunt Lydia's Cove | 4.10 | 1.25 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Chatham | Frost Fish Creek, East of Rte 28 | 3.80 | 1.16 | Blizzard of '78 | 2/7/1978 | FIRM Report |
| Chatham | Head of Muddy Creek | 2.90 | 0.88 | Blizzard of '78 | 2/7/1978 | FIRM Report |

As shown in Table 4, the maximum contemporary high water elevation identified for the Pleasant Bay mapping profile is 7.76 feet NAVD88 reported by the Center for Coastal Studies tidal data at Outermost Harbor for the January 4, 2018, nor'easter. The NOAA tide gauge records identify the maximum observed water level for this area as 6.96 feet NAVD88 occurring on January 3, 2014. The NOAA gauge, however, was not operating during the 2018 storm and, for this reason, the elevation of the January 4, 2018, recorded by CCS was used as the "reference or project storm of record" for this study and used as the baseline for establishing the upper boundary of the storm tide pathways analysis.

Table 5 Pleasant Bay STP Storm Tide Mapping Profile (National Weather Service Action Stations in color)

| Pleasant Bay STP Storm Tide Mapping Profile | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | NAVD88 (FT) | NAVD88 (m) | MLLW (FT) Approx. | MLLW (M) Approx. | Comments |
| Upper Limit of Storm Tide Pathway Analysis | 10.76 | 3.28 | 13.25 | 4.04 | January 4, 2018 Nor'easter High Water Elevation Plus 3 feet (0.91 m) |
| Historical High Water Outermost Harbor Chatham | 7.76 | 2.37 | 10.25 | 3.13 | CCS Tide Gauge Historical High Water Elevation January 4, 2018 Nor'Easter |
| Major Flood Stage | 10.5 | 3.20 | 13.0 | 3.96 | National Weather Service Chatham East Coast (Station # 8447435) |
| Moderate Flood Stage | 9.0 | 2.75 | 11.5 | 3.51 | National Weather Service Chatham East Coast (Station # 8447435) |
| Minor Flood Stage | 6.5 | 1.98 | 9.0 | 2.74 | National Weather Service Chatham East Coast (Station # 8447435) |
| High Tide Flooding Level (HTF) | 4.4 | 1.30 | 6.9 | 2.10 | Estimated |
| MHWS | 2.05 | 0.63 | 4.54 | 1.38 | Estimated |
| MHHW | 2.68 | 0.82 | 5.17 | 1.58 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| MHW | 2.31 | 0.70 | 4.80 | 1.46 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| MSL | 0.06 | 0.02 | 2.55 | 0.78 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| MTL | -0.01 | 0.00 | 2.48 | 0.76 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| MLW | -2.33 | -0.71 | 0.16 | 0.05 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| MLLW | -2.49 | -0.76 | 0.00 | 0.00 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| | | | | | |
| GT | 5.18 | 1.58 | 5.2 | 1.58 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |
| MN | 4.64 | 1.41 | 4.6 | 1.41 | Chatham Harbor (NOAA Sta 8447435) Updated: May 20, 2020 |

Table 5 summarizes the Storm Tide Mapping Profile used to analyze and map STPs. This table also includes the approximate elevation of Pleasant Bay *nuisance tides* or *high tide flooding*, calculated as 1.75 feet (0.5m) above MHHW (Sweet *et. al.,* 2021) and illustrates the relationship of National Weather Service Action Stages to Chatham (Station # 8447435) tidal datums. A factor of three (3) feet (~ 1 meter) was added to the project storm of record to recognize near-term rising sea levels and increasing storm intensities resulting in an upper vertical mapping boundary of 10.76 feet NAVD88 (13.25 feet MLLW). Final datum values were adjusted slightly to simplify conversions from NAVD88 to MLLW and accommodate the 0.5 feet range planes used in the GIS analysis and integration with NWS Action Levels discussed in more detail below.

**Storm Tide Pathways and National Weather Service Storm Surge Predictions**

For certain areas, the NWS provides a qualitative description of the impacts likely to be associated with its estimates for potential total water levels associated with approaching storm tides. Related directly to the physical characteristics of a threatened area, the descriptions correspond to the following general categories and suggest action levels for coastal communities threatened by approaching coastal storms. The action levels are summarized below.

- *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 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 have been color coded to correspond to NWS's characterization of action levels. As shown in Table 6, NWS descriptions of action levels for Chatham Station 8447435 (Aunt Lydia's Cove), are currently incomplete and general.

Table 6. Aunt Lydia's Cove NWS Action Levels

| Elevation (MLLW FT.) | Action Level |
|---|---|
| 13 | Significant flooding of low lying coastal areas is expected from Chatham northward along the east shore of the Cape. Immediate coastal roads will be flooded for a time near high tide and |

| | |
|---|---|
| | significant beach erosion is likely. Localized evacuations of the most vulnerable coastal areas may be required. |
| **11.5** | No description at this time |
| **9** | Flooding of lowest lying coastal areas is likely. Some immediate coastal roads may be flooded nearest the time of high tide. Large swells may also produce some localized beach erosion. |

Over time, these descriptions can be expanded and supplemented with more detailed information corresponding to individual STPs based on the observations of municipal emergency managers and responders. Similarly, descriptions of Action Levels for areas not covered by NWS descriptions could be developed by archiving observations that correlate water levels with actual flooding events, elevations, and locations. As an example, Table 7 summarizes the current NWS description of Action Levels for Provincetown.
(Source: https://water.weather.gov/ahps2/hydrograph.php?wfo=box&gage=pvhm3).

Table 7 Provincetown NWS Action Levels

| 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 8 illustrates the relationship between NWS Action Levels and contemporary tidal datums for Provincetown, Chatham-East Coast, Chatham-South Side, and Nantucket. Action levels for Boston have been provided for a comparison of various action levels based on geographic location.

Table 8. Contemporary Tidal Datums.

Contemporary Tidal Datums    Units: FEET    NTDE: 1983 - 2001

| | Boston Harbor 8443970 | | Provincetown Harbor 8446121 | | Chatham - East Coast 8447435 | | Chatham - South Side 8447505 | | Nantucket Harbor 8449130 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NAVD88 | MLLW | NAVD88 | MLLW | NAVD88 | MLLW | NAVD88 | MLLW | NAVD88 | MLLW |
| | | | | | | | | | | |
| NWS Action Levels | | | | | | | | | | |
| Major | 10.5 | 16.0 | 9.5 | 15.0 | 10.5 | 13.0 | 8.8 | 11.5 | 5.9 | 8.0 |
| Moderate | 9.0 | 14.5 | 8.5 | 14.0 | 9.0 | 11.5 | 7.8 | 10.5 | 4.4 | 6.5 |
| Minor | 7.0 | 12.5 | 7.5 | 13.0 | 6.5 | 9.0 | 6.3 | 9.0 | 2.9 | 5.0 |
| Action | 6.0 | 11.5 | 6.5 | 12.0 | 5.5 | 8.0 | --- | --- | --- | --- |
| | | | | | | | | | | |
| Tidal Datums | | | | | | | | | | |
| MHHW | 4.77 | 10.28 | 4.62 | 10.08 | 2.68 | 5.17 | 1.89 | 4.58 | 1.49 | 3.58 |
| MHW | 4.33 | 9.84 | 4.16 | 9.62 | 2.31 | 4.80 | 1.52 | 4.21 | 1.15 | 3.24 |
| MSL | -0.30 | 5.21 | -0.43 | 5.03 | 0.06 | 2.55 | -0.35 | 2.34 | -0.32 | 1.77 |
| MTL | -0.42 | 5.09 | -0.48 | 4.98 | -0.01 | 2.48 | -0.45 | 2.24 | -0.37 | 1.72 |
| MLW | -5.16 | 0.35 | -5.13 | 0.33 | -2.33 | 0.16 | -2.43 | 0.26 | -1.89 | 0.20 |
| MLLW | -5.51 | 0.00 | -5.46 | 0.00 | -2.49 | 0.00 | -2.69 | 0.00 | -2.09 | 0.00 |
| | | | | | | | | | | |
| GT | 10.28 | 10.28 | 10.08 | 10.08 | 5.17 | 5.17 | 4.58 | 4.58 | 3.58 | 3.58 |
| MN | 9.49 | 9.49 | 9.29 | 9.29 | 4.64 | 4.64 | 3.95 | 3.95 | 3.04 | 3.04 |
| | | | | | | | | | | |
| Highest Obs. Tide | | | | | | | | | | |
| Elevation | 9.66 | 15.17 | 9.77 | 15.23 | 7.76 | 10.25 | --- | --- | 5.78 | 7.87 |
| Date | 1/4/2018 | 1/4/2018 | 1/4/2018 | 1/4/2018 | 1/4/2018 | 1/4/2018 | --- | --- | 10/30/1991 | 10/30/1991 |
| Time | 17:42 | 17:42 | 12:45 | 12:45 | | | | | --- | --- |

## Storm Tide Pathways along the Pleasant Bay Shoreline

The desktop analysis of the lidar data yielded 105 potential STPs. The analysis was conducted along all of the mainland of Pleasant Bay. The barriers were not mapped. STPs were found in, Chatham, Harwich, and Orleans, none were found in Brewster. However, flooding that occurs through STPs found on the other three towns may effect areas within Brewster. Two days of field work were needed to complete the mapping of Storm Tide Pathways. The surveys were conducted in the spring of 2023. As discussed above, the desktop analysis extended the STP analysis up to an elevation of approximately 3.3 m NAVD88. Each potential STP identified in the desktop analysis was inspected and assessed in the field and the location moved when observations determined that it was necessary to reflect contemporary topographic conditions.

Where possible, the field team occupied all STPs identified in the desktop analysis. As discussed above, however, where STPs appeared to be located on private property, on dynamic natural landforms, or otherwise inaccessible they were logged in the database attribute table as unverified for labeling in map documents, Of the 105 STPs identified in the desktop analysis, 12 were rejected during the team laboratory sessions and removed from the database taken into the field. A total of 9 additional STPs located in low-lying areas that were not captured during the desktop analysis of the lidar data were added to the final database as a result of the fieldwork, yielding a final set of 105 STPs throughout the 3 towns (Figure 4).

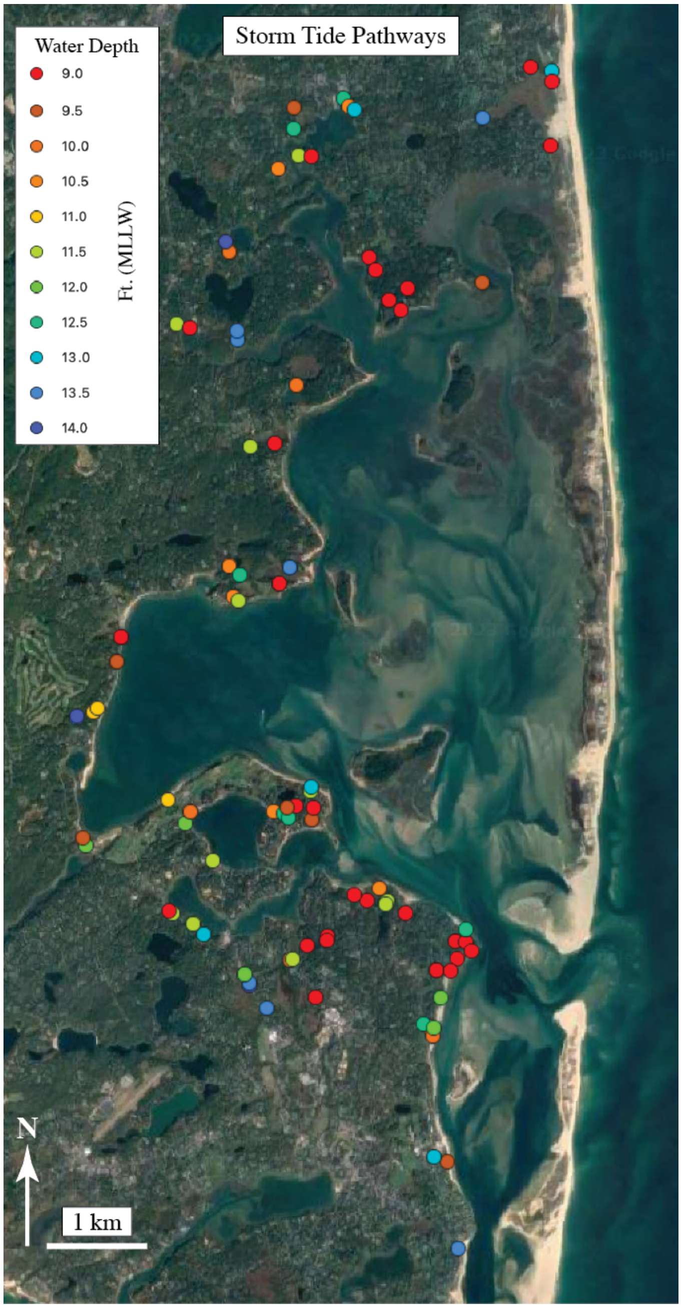

Figure 4. Location of the 100 mapped Storm Tide Pathways for the study area. STPs are color-coded by elevation.

During the field work 37 pathways (35.2% 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. Despite the reliability of the lidar, the removal, addition, and movement of STPs in the field highlight the need for field-based verification of each potential STP.

Types of Storm Tide Pathways

Based on field observations during this study and past work, many types of STPs exist and when viewing the data several things should be kept in mind. For example, there are Primary, Secondary, Dependent and Roadway STPs. A Primary STP is the first place where water will flow into an area from the body of water in question (i.e., open ocean, bay, pond, etc.). A Secondary STP is an STP whose likeliest source of inundation will be through the corresponding Primary STP. A Secondary STP must be of higher or equal elevation than the Primary STP. Therefore, all Secondary STPs must have a Primary STP associated with it and the Primary STP must be lower in elevation. A Dependent STP is an STP whose likeliest source of inundation will be through a corresponding Primary STP of higher or equal elevation. Therefore, the moment the Primary STP is inundated the Dependent STP, will, by definition, have deeper water depths than the Primary STP. Care should be taken when addressing STPs or Primary STPs with Dependent STPs associated with them. These relationships are apparent when viewed in conjunction with the visualization planes. A Roadway STP is a pathway that only crosses a road, no other resources public or private are impacted. Other STPs can cross over roads, but STP-Rs only cross over roads.

Another STP distinction is that of Verified vs. Unverified. A Verified STP is one that the survey teams were able to occupy and collect high quality GPS data at the location. An Unverified STP is defined as a likely STP that was identified during the lidar analysis but was unable to be occupied by the field team for reasons, such as in being located on private property or on a very dynamic natural setting. For example, if an STP was located in a dune from lidar that was even only a year old, it is likely that the area has changed. This STP is kept in the dataset indicating that the area may be susceptible to low-lying pathways. In this study there were 35 Unverified STPs and 70 Verified STPs (Table 10). No survey teams entered onto private property or along roads marked 'Private Property', 'No Trespassing', etc., unless given explicit consent by the owners.

In naturally dynamic areas, future site-specific surveys can be supplemented by field teams using drones or as new lidar becomes available. To verify inaccessible data located on private property, approvals from owners may be warranted to assess potentially important STPs. All unverified STPs (STP-Us) are included in the final database. The full range of Unverified sub-classifications in the GIS data are as follows:

- *I = Inaccessible (dynamic areas, beaches, dunes, hazardous areas, etc.)*
- *NV = No Vertical GPS data was able to be collected, though lat/lon data were collected.*
- *P = Private Property*
- *S = No GPS Signal (under trees, next to walls, buildings, etc.)*

No Vertical GPS data (NV) typically occurred in areas of poor reception, but unlike the 'S' sub-classification, where no signal was available, an NV-STP had a 'weak' signal, so an accurate latitude and longitude was achievable, but not a vertical elevation. Based on the location of the STP, additional non-GPS field work may be warranted to collect vertical data, which is of particular importance in flat areas (Figure 5).

Figure 5. Example of Road STP located along an area of little relief. Water will flow from the salt marsh over the road and back into the salt marsh on the other side of the road. This image was captured in Scituate, MA (taken from Borrelli, et al., 2020).

Monitoring dynamic STPs may also be critical for areas along natural shorelines where locations can quickly and drastically in response to storms. These STPs are difficult to identify, and change is ongoing, but attention should be paid, particularly after a storm event as the evolution of these features can make low-lying areas behind them, or in close proximity, more vulnerable.

**Project-wide STP Summary**

STPs are described as relatively narrow, low-lying areas or pathways that based on their elevation are likely to convey coastal flood waters inland. Often, stopping flow at the elevation at which the STP would be overtopped could prevent inundation of significant inland areas. In addition to storm events, low-lying coastal areas are often experiencing inundation associated with nuisance, or 'sunny day' flooding, storm surge and sea level rise. The elevations at which coastal waters will begin to flow through a STP and the nature of the impacted areas can be used by town staff to evaluate and prioritize mitigation responses.

Table 9 and Figure 6 summarize the extent of flooding by elevation in 0.5 foot increments for the study area. Based on this data, on average approximately 39 acres of land are inundated for every 6 inches of rise in total water level from 9.0 feet to 14.0 feet MLLW. This ranges from a low of 33.4 (11.50 – 11.99 ft, MLLW) to a high 50.1 acres (9.00 – 9.49 ft, MLLW).

Table 9. Storm tide pathways totals, area and cumulative area inundated by Total Water Level (TWL). Vertical Datum is MLLW. Green highlighted elevations denote inundation that will occur when TWL is 1ft above the Project Storm of Record.

| ***Plane (ft)*** | ***STPs*** | ***Range (ft)*** | ***Total Acres*** | ***Δ Acres*** |
|---|---|---|---|---|
| ***9.0*** | 35 | 9.00 - 9.49 | 706.68 | --.- |
| ***9.5*** | 9 | 9.50 - 9.99 | 757.62 | 50.9 |
| ***10.0*** | 5 | 10.00 - 10.49 | 793.12 | 35.5 |
| ***10.5*** | 9 | 10.50 - 10.99 | 829.75 | 36.6 |
| ***11.0*** | 4 | 11.00 - 11.49 | 870.82 | 41.1 |
| ***11.5*** | 12 | 11.50 - 11.99 | 906.73 | 35.9 |
| ***12.0*** | 6 | 12.00 - 12.49 | 940.09 | 33.4 |
| ***12.5*** | 7 | 12.50 - 12.99 | 980.41 | 40.3 |
| ***13.0*** | 6 | 13.00 - 13.49 | 1,014.61 | 34.2 |
| ***13.5*** | 9 | 13.50 - 13.99 | 1,048.55 | 33.9 |
| ***14.0*** | 3 | 14.00 - 14.49 | 1,097.69 | 49.1 |
| ***TOTALS*** | ***105*** | ***9.00 – 14.49*** | ***Δ = 391.01*** | ***Avg = 39.1*** |

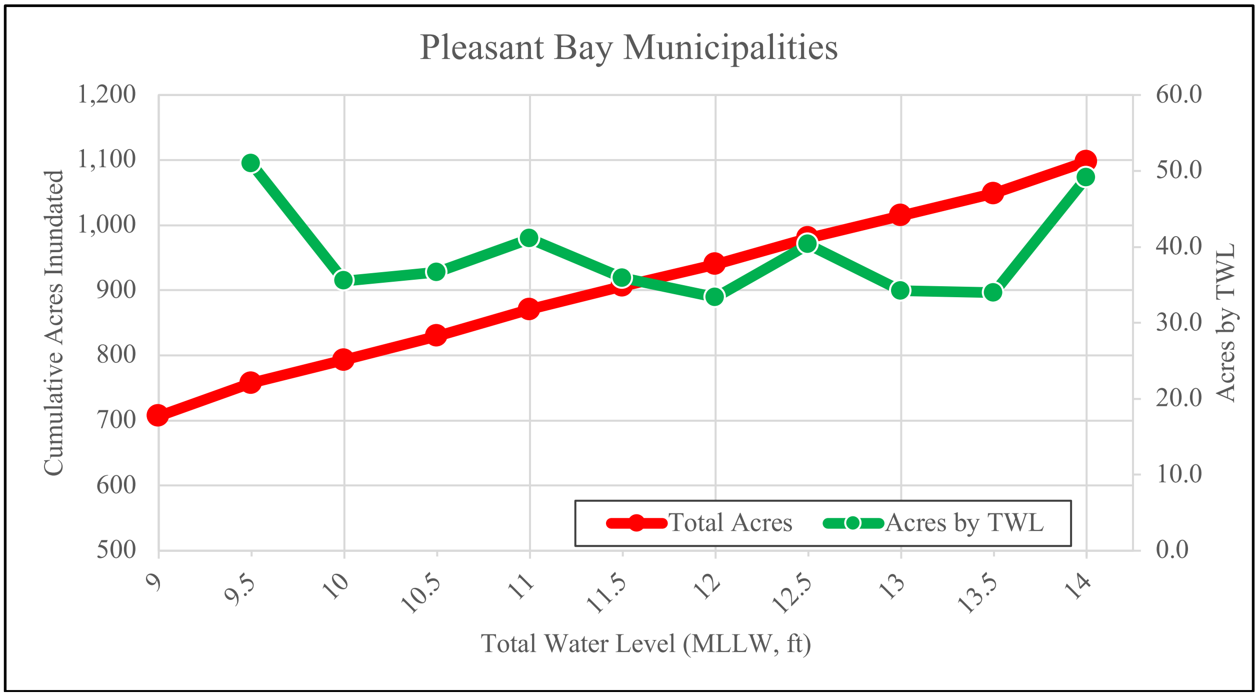


Figure 6. The red line represents the total cumulative area inundated with each 6-inch increase in total water level. The green bars represent the area inundated for each individual 6-inch increase in total water level. The average is approximately 450 acres per 6-inch increase in total water level.

The highest value of inundation area for a 0.5-foot increase in total water level is the lowest water elevation mapped at 50.9 acres between 9.0 and 9.5 ft (MLLW) which falls below the project storm of record (10.25 ft, MLLW). Just below that value, 49.1 acres will become inundated between 14.0 – 14.5 MLLW, which is the highest water elevation mapped for this study. Were peak storm surges from a nor-easter or hurricane to coincide with a high astronomical tide that raised total water levels 6 inches beyond the previous storm of record (10.5 – 11.0 ft, MLLW) over 36.6 acres would flood that have not flooded in recorded history. A storm with a total water level one foot higher than the project storm of record would yield an estimated 77.7 acres of inundation in areas not previously flooded (10.5 – 11.5 ft, MLLW). Sea level has risen approximately 8-10 inches regionally over the last century, increasing the likelihood of future flooding in the study area above the project storm of record.

As illustrated by the 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. The mapping of storm tide pathways reveals that 13 STPs are less than 12 inches above this elevation (Figure 7). In other words, included in the STP mapping data are 13 locations throughout the study area that have not flooded in recorded history but would very likely be inundated with another 12 inches of total water level beyond that experienced during the January 4th, 2018 storm.

## Storm Tide Pathways by Town

The sections below provide a brief summary for each town developed from the GIS data. All elevations presented in the tables are referenced to MLLW. As the plane of reference for soundings on NOAA navigation charts and tide tables, MLLW is often referred to as “chart datum” and used for many local coastal management applications. As discussed above, MLLW is used by the National Weather Service (NWS) for its estimates of total water level (TWL) (astronomical tide height plus storm surge) associated with approaching coastal storms. For this reason, all TWLs are presented in MLLW. Recognizing that MLLW varies locally, elevation references to NAVD88 are included within the project GIS database to facilitate regional comparisons.

Of the 105 storm tide pathways mapped 35, or 33.3%, were unverified (Table 10). There were no STPs (verified or unverified) mapped in Brewster. Chatham has 12 unverified STPs, Harwich has 1, Orleans has 22. It is recommended that each town evaluate its unverified STPs and based on local knowledge assess whether further action is required.

*Table 10. Verified vs. Unverified Storm Tide Pathways by town.*

| Town | Total | Verified | Unverified | % Unverified |
|---|---|---|---|---|
| **Brewster** | 0 | 0 | 0 | 0.0% |
| **Chatham** | 54 | 42 | 12 | 22.2% |
| **Harwich** | 6 | 5 | 1 | 16.7% |
| **Orleans** | 45 | 23 | 22 | 48.9% |
| **Totals** | **105** | **70** | **35** | **33.3%** |

Based on the Lidar used for the project, the summary tables accompanying each section illustrate the distribution of town STPs by NWS action stage. It should be noted that the NWS flooding categories are not binned in equal increments which Table 8 reflects. Care should be taken to closely analyze where STPs are located relative to critical infrastructure and to evaluate the elevation of individual STPs relative to surrounding topography before identifying and prioritizing appropriate mitigation measures.

Town of Chatham

Based on the desktop analysis and the field verification, a total of 54 storm tide pathways were identified in the town of Chatham (Figure 7). For the reasons discussed above, 12 STPs were unverified and may warrant further investigation based on local knowledge. Notably, the rise in acres inundated with 6-inch increases in total water level is very linear (Figure 8). For every 6-inch increase in total water level an average of 18.9 acres gets flooded, with a low of 14.9 acres (10.00 – 10.49 ft, MLLW) and a high of 32.4 acres (12.00 – 12.49 ft, MLLW).


Figure 7. All 54 Storm Tide Pathways in Chatham along the Pleasant Bay Shoreline. The image shows the southern extent of areas mapped in Chatham. Southern Harwich is included as flooding through these STPs may affect Chatham.

The project storm of record used for Chatham is the January 4th, 2018 storm. This study has identified 6 pathways in Chatham that are only 12 inches above the water level seen during that storm. Such a 1-foot increase in total water level is likely to flood approximately 208.8 acres of land from 10.50 to 11.49 ft (MLLW). These likely represent new areas of flooding that the town may want to consider in future planning efforts.

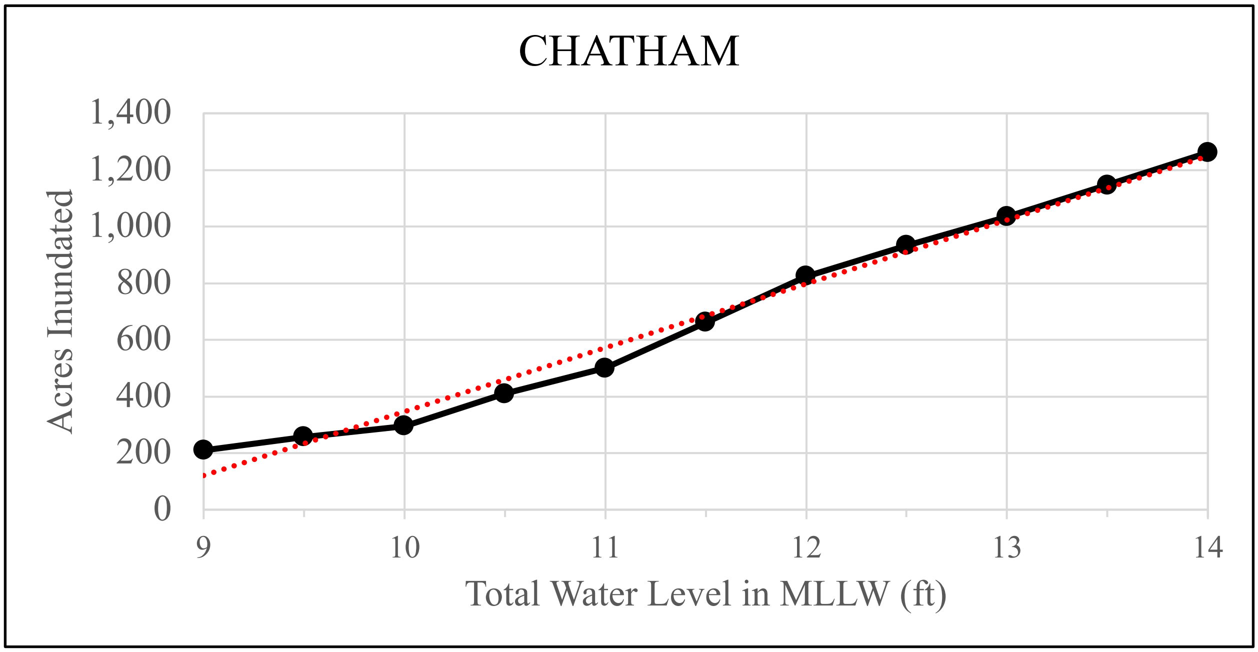


Figure 8. Town of Chatham. Total area inundated with ½ ft increases in total water level (ft. MLLW). Dotted red line is trendline. Note the linear trend.

Town of Harwich

Based on the desktop analysis and the field verification, a total of 45 storm tide pathways were identified in the town of Harwich (Figure 9). For the reasons discussed above, 22 STPs were unverified and may warrant further investigation based on local knowledge. Notably, the rise in acres inundated with 6-inch increases in total water level is very linear (Figure 10). For every 6-inch increase in total water level an average of 3.54 acres gets flooded, with a low of 1.16 acres (12.50 – 12.99 ft, MLLW) and a high of 17.9 acres (14.00 – 14.49 ft, MLLW).


*Figure 9. All 128 Storm Tide Pathways in Harwich. Adjacent towns are included as flooding through these STPs may affect Harwich.*

The project storm of record used for Harwich is the January 4th, 2018 storm. This study has identified 2 pathways in Harwich that are only 12 inches above the water level seen during that storm. Such a 1-foot increase in total water level is likely to flood approximately 7.0 acres of land from 10.50 to 11.49 ft (MLLW). These likely represent new areas of flooding that the town may want to consider in future planning efforts.

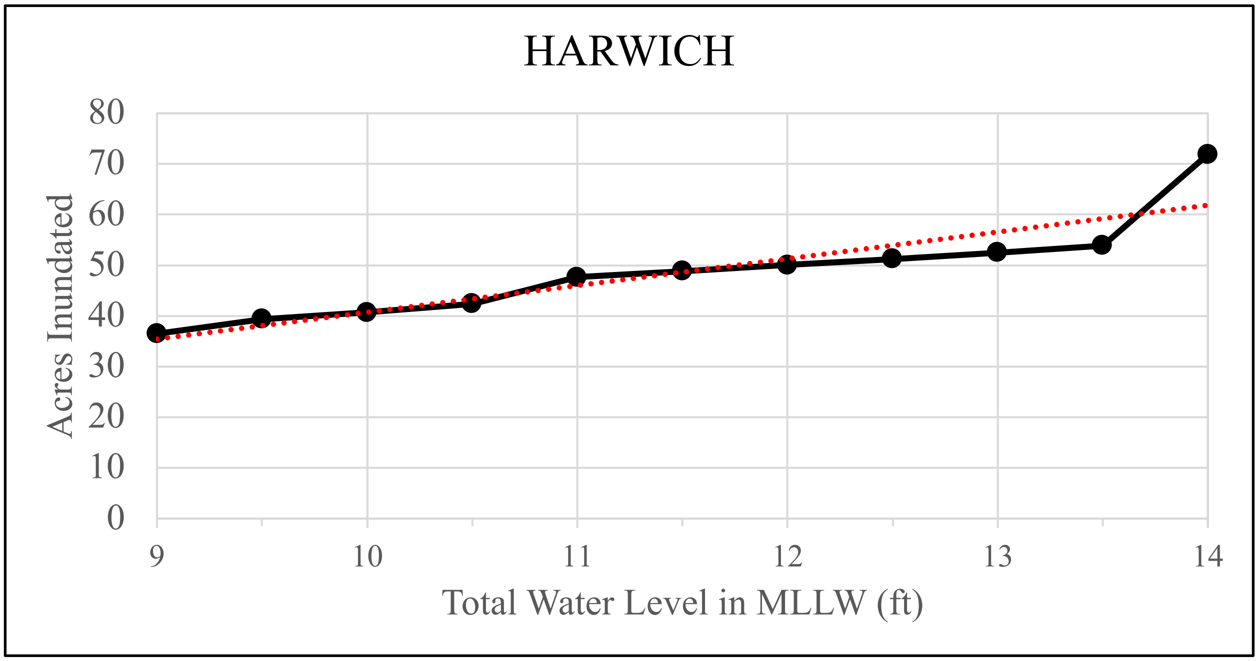

Figure 10. Town of Harwich. Total area inundated with ½ ft increases in total water level (ft. MLLW). Dotted red line is trendline. Note the linear trend.

Town of Orleans

Based on the desktop analysis and the field verification, a total of 45 storm tide pathways were identified in the town of Orleans (Figure 11). For the reasons discussed above, 22 STPs were unverified and may warrant further investigation based on local knowledge. Notably, the rise in acres inundated with 6-inch increases in total water level is very linear (Figure 12). For every 6-inch increase in total water level an average of 16.7 acres gets flooded, with a low of 13.75 acres (13.00 – 13.49 ft, MLLW) and a high of 20.8 acres (12.50 – 12.99 ft, MLLW).

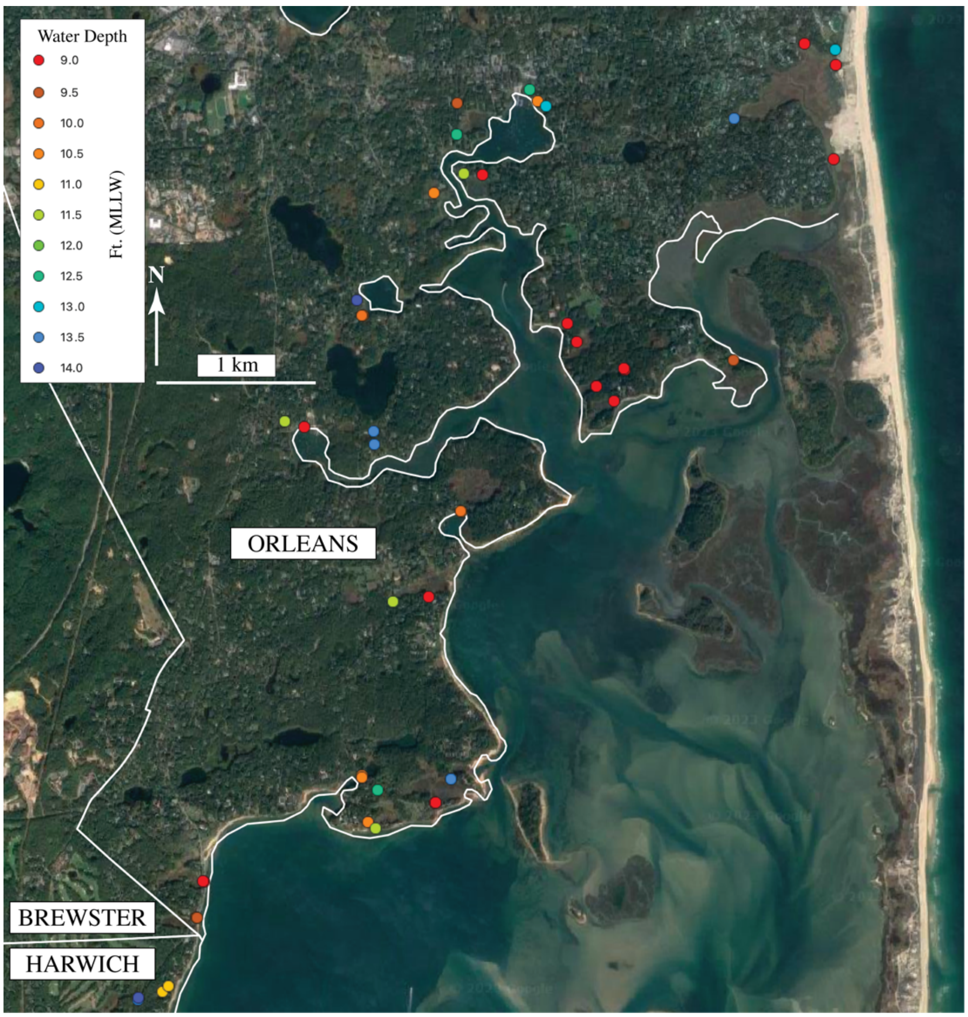


Figure 11. All 332 Storm Tide Pathways in Orleans. Adjacent towns are included as flooding through these STPs may affect Orleans.

The project storm of record used for Orleans is the January 4th, 2018 storm. This study has identified 5 pathways in Harwich that are only 12 inches above the water level seen during that storm. Such a 1-foot increase in total water level is likely to flood approximately 35.1 acres of land from 10.50 to 11.49 ft (MLLW). These likely represent new areas of flooding that the town may want to consider in future planning efforts.

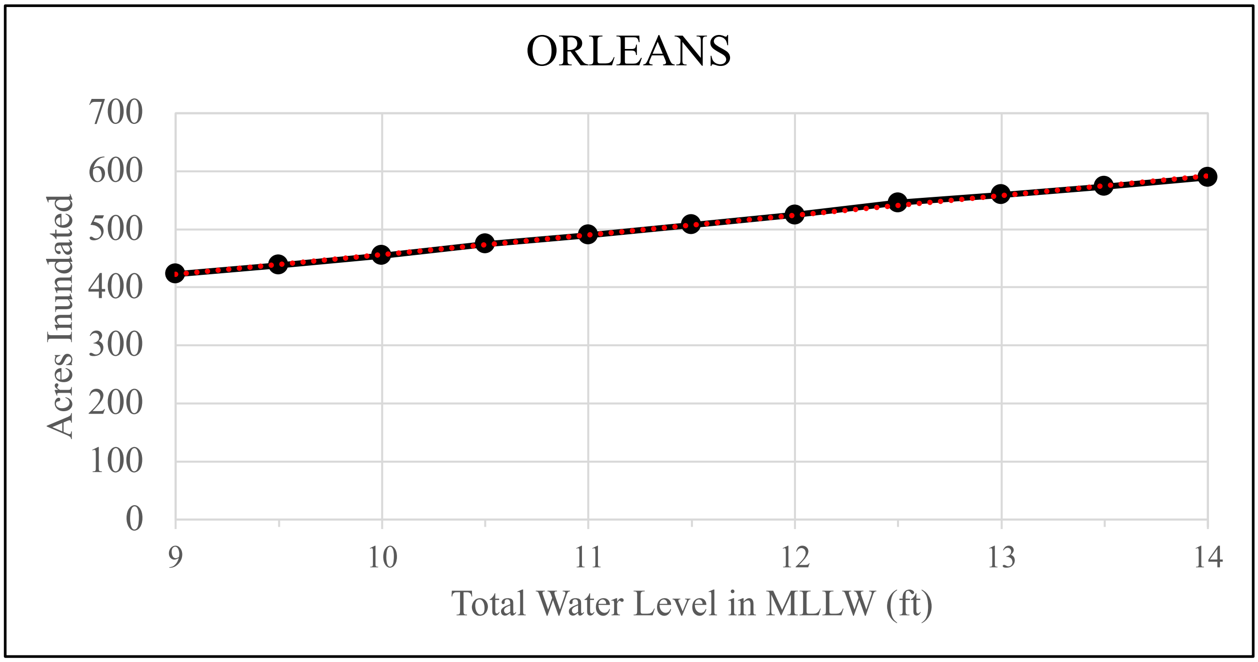


Figure 12. Town of Orleans. Total area inundated with ½ ft increases in total water level (ft. MLLW). Dotted red line is trendline. Note the linear trend.

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