A Summary of High Tide Flooding Recorded by the Hampton, New Hampshire Tide Gauge: 2013-2020

December 2021

NEW HAMPSHIRE DEPARTMENT OF Environmental Services

R-WD-21-15

A Summary of High Tide Flooding Recorded by the Hampton, New Hampshire Tide Gauge: 2013-2020

Prepared for:
New Hampshire Department of Environmental Services Coastal Program

Prepared by:

Tiffany Chin,
Coastal Management Specialist,
New Hampshire Department of Environmental Services Coastal Program

Kirsten Howard,
Resilience Program Coordinator,
New Hampshire Department of Environmental Services Coastal Program

Portsmouth Regional Office
Pease International Tradeport
222 International Drive, Suite 175
Portsmouth, NH 03801
(603) 559-1500 | www.des.nh.gov

Robert R. Scott, Commissioner
Mark Sanborn, Assistant Commissioner

December 2021

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. EXECUTIVE SUMMARY

The town of Hampton, New Hampshire (NH), is vulnerable to flooding both from high tides and from storm surges. The Hampton Beach Village District, located on a highly developed barrier island between the Atlantic Ocean and the marshes of the Hampton-Seabrook Estuary, currently experiences road inundation and property flooding during extra high tides. In the low-lying areas of Hampton, floodwaters approach roadways and begin to impact landowners when water levels reach 10 feet above Mean lower low water (MLLW). These conditions are exacerbated by storm surges and the presence of large, battering waves, particularly during the Nor'easter storms that are characteristic to the Northeastern United States in the winter and early spring. Climate change projections indicate that coastal New Hampshire should plan for sea levels to rise by 1.3 to 2.3 feet above 2000 levels by 2050, and extreme weather is predicted to increase in frequency and severity (NH Coastal Flood Risk Technical Advisory Panel, 2020). Given these predicted changes in the near future, it is important that the residents, visitors, and the community of Hampton, NH, and the surrounding areas understand current flood conditions and prepare for future impacts.

Since 2013, a tide gauge located in Hampton Harbor, NH, has been measuring water levels at 6-minute intervals on a near-continuous basis. In this report, the New Hampshire Department of Environmental Services Coastal Program, along with partners at the National Oceanic and Atmospheric Administration (NOAA) and the Northeast Regional Association of Coastal and Ocean Observing Systems (NERACOOS), analyzed the Hampton Harbor tide gauge data record to understand and summarize the frequency of high tide flooding in Hampton, NH.

Key findings from this analysis include:

- At least one high tide over 10 feet MLLW was recorded on 30% to 40% of days each year between 2013 and 2020.
- High tide flooding occurs approximately 3 times more frequently on an annual basis than the NOAA tide charts predict, in part due to the influence of weather and storm surges.
- Sea level rise will dramatically increase the frequency and severity of flooding in coastal areas of Hampton, NH. Under a 2-foot sea level rise scenario, 95% of high tides annually will exceed 10 feet.
- Under a 2-foot sea level rise scenario, the average number of days per year with a major flood (over 13 feet) would increase to 27 days. Only one major flood was recorded during the entire time series of 2013-2020.

These findings confirm that residents, local decision-makers and emergency management officials should refer to the Hampton Harbor tide gauge 3-day forecast and real-time information in addition to the more commonly used NOAA tide prediction tables (sometimes referred to as tide charts) to ensure a better understanding of coastal flood risk and appropriate responses. The tide gauge dataset acts as a climatology that supports real-time forecasts and storm warnings issued for the protection of life and property. The report findings underscore the need for advanced planning and action to mitigate sea-level rise and increasing flooding in Hampton and coastal New Hampshire. The report findings also support the need for continued investments in monitoring water levels and tidal inundation throughout the region.

2. INTRODUCTION

Purpose of the Report

The purpose of this report is to summarize the frequency of high tide flooding in Hampton, NH, determined through an analysis of high frequency tide gauge data from Hampton Harbor, and to communicate the implications of these findings for the community and residents of Hampton and the surrounding region. A high tide of 10 feet referenced to Mean lower low water[1] (MLLW) is considered the "Action" level for flooding in Hampton by the National Weather Service (National Weather Service Atlantic Coast at Hampton hydrograph). At the Action stage, road inundation and property flooding approach Hampton's most low-lying neighborhoods (National Weather Service Atlantic Coast at Hampton hydrograph; SLR Consulting, 2021b; Town of Hampton Code Section 805-9(M)(1)). This report can inform floodplain management decisions and planning for future sea level rise and tide conditions in the Town of Hampton and the surrounding region.

Acknowledgements

This report was funded, in part, by the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management under the Coastal Zone Management Act in conjunction with the New Hampshire Department of Environmental Services Coastal Program (NHCP).

An advisory team provided insight and technical assistance throughout the creation of this report, including advising on data analysis methodology, conducting quality assurance, and providing information about maintenance of the tide gauge.

The advisory team includes:

- John Cannon, National Weather Service
- Jamie Carter, NOAA
- Steve Couture, NHCP
- Nathalie DiGeronimo, NHCP
- Rayann Dionne, Seabrook Hamptons Estuary Alliance
- Jake Kritzer, NERACOOS
- Kevin Lucey, NHCP
- Jackie Motyka, NERACOOS
- Francesco Peri, Charybdis Group LLC
- Tom Shyka, NERACOOS
- Ben Sweeney, NHCP
- David Wolcott, NOAA CO-OPS
- Chris Zervas, NOAA CO-OPS

Site Background and Context

Hampton, NH, a coastal town located in Rockingham County, is vulnerable to flooding from both storm surges and high tides. The town of Hampton has a long history of flood events, documented as far back as 1723 (SLR Consulting, 2021b), but flooding has been increasing in frequency and severity and is

[1] Mean Lower Low Water (MLLW) is the average height of the lowest tide each day.

expected to get worse as sea level rise accelerates (SLR Consulting, 2021a). The riverine and coastal flood hazard risk in Hampton is ranked as severe by the Hampton Hazard Mitigation Plan (Hampton Hazard Mitigation Plan, 2016; SHEA, 2019), and critical facilities in Hampton, including the fire station and wastewater treatment plant, are at risk of flooding with present-day storm surges and under future sea level rise projections (SLR Consulting, 2021b).

Figure 1. A low-lying neighborhood in Hampton Beach is flooded at high tide and standing water covers the street. "High Tide November 16, 2020 on the Marsh side of Hampton Beach" Credit: Marie Sapienza

Hampton Beach, which is a barrier island village district within the Town of Hampton, is home to approximately 2,685 permanent residents (US Census Bureau, 2019) and hosts many seasonal summer residents along with high numbers of tourist visitors. Hampton Beach is highly developed, and residents are particularly vulnerable to flooding from both the Atlantic Ocean and the salt marshes of the Hampton-Seabrook Estuary (Figure 1). High tide flooding typically occurs in the low-lying areas west of Route 1A adjacent to the marshes of the Hampton-Seabrook Estuary (Figures 2 and 3). Due to the risk of property damage from coastal flooding, the town of Hampton has taken steps to strengthen its floodplain regulations in recent years, requiring new and substantially improved buildings near the tidal shoreline to follow more protective requirements than those in the 2015 International Building Code enforced by the State of NH (Office of Strategic Initiatives, NH Floodplain Management Program, 2021a; NH Department of Safety, 2021). Additionally, the town has implemented a parking program for residents who are impacted by flooding when tides are over 10 feet or during storm surges, allowing them to park their cars for free in municipal lots at higher elevations (Town of Hampton Code Section 805-9(M)(1)). Despite these mitigation measures, the Town of Hampton continues to experience disproportionate property damage due to flooding when compared to the rest of the State of New

Hampshire. As of May 24, 2021, Hampton buildings comprise 24% of all National Flood Insurance Program policies in the State of New Hampshire and 11% of all NH repetitive loss properties are located in Hampton (Office of Strategic Initiatives, NH Floodplain Management Program, 2021b). Paid flood insurance claims to Hampton property owners have totaled $6.23 million, which is 12% of NH paid claims (Office of Strategic Initiatives, NH Floodplain Management Program, 2021b).

New coastal flood hazard analyses show that the coastal high hazard area (VE Zone on FEMA Flood Insurance Rate Maps) has expanded in Hampton (Hampton Beach Area Commission, 2021) and predicted sea level rise and sea-level-rise-induced groundwater rise indicate that coastal flooding will continue to worsen over time in Hampton (Wake et al., 2019). The impacts to infrastructure and critical facilities from sea level rise could range broadly depending on the magnitude of sea level rise. For example, under a scenario of low sea level rise (1.7 feet), 3.4 miles of roadways in Hampton would be impacted by flooding (RPC, 2015). This increases to 13.2 miles under a 4 feet SLR scenario and 20.6 miles under a 6.3 feet SLR scenario (RPC, 2015). These values becoming increasingly concerning when storm surge is considered. The low SLR scenario (1.7 feet) plus storm surge leads to 20.7 miles of roadways impacted, nearly the same amount as the high SLR scenario (6.3 feet) considering astronomical tides alone (RPC, 2015).

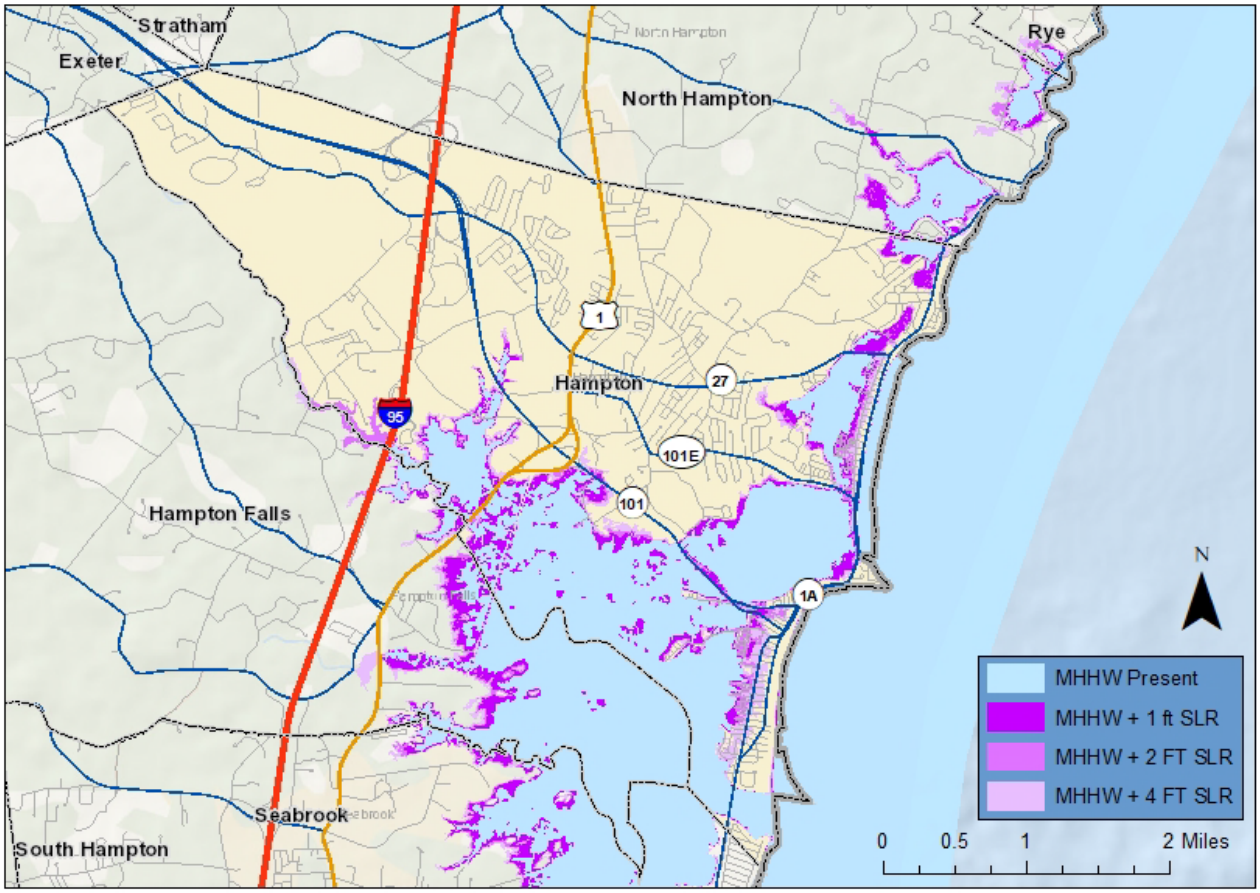

Figure 2. Map of the Town of Hampton (in yellow), and surrounding areas, depicting the current extent of inundation at Mean Higher High Water (MHHW) and the increase in flood extent under different sea level rise (SLR) scenarios.

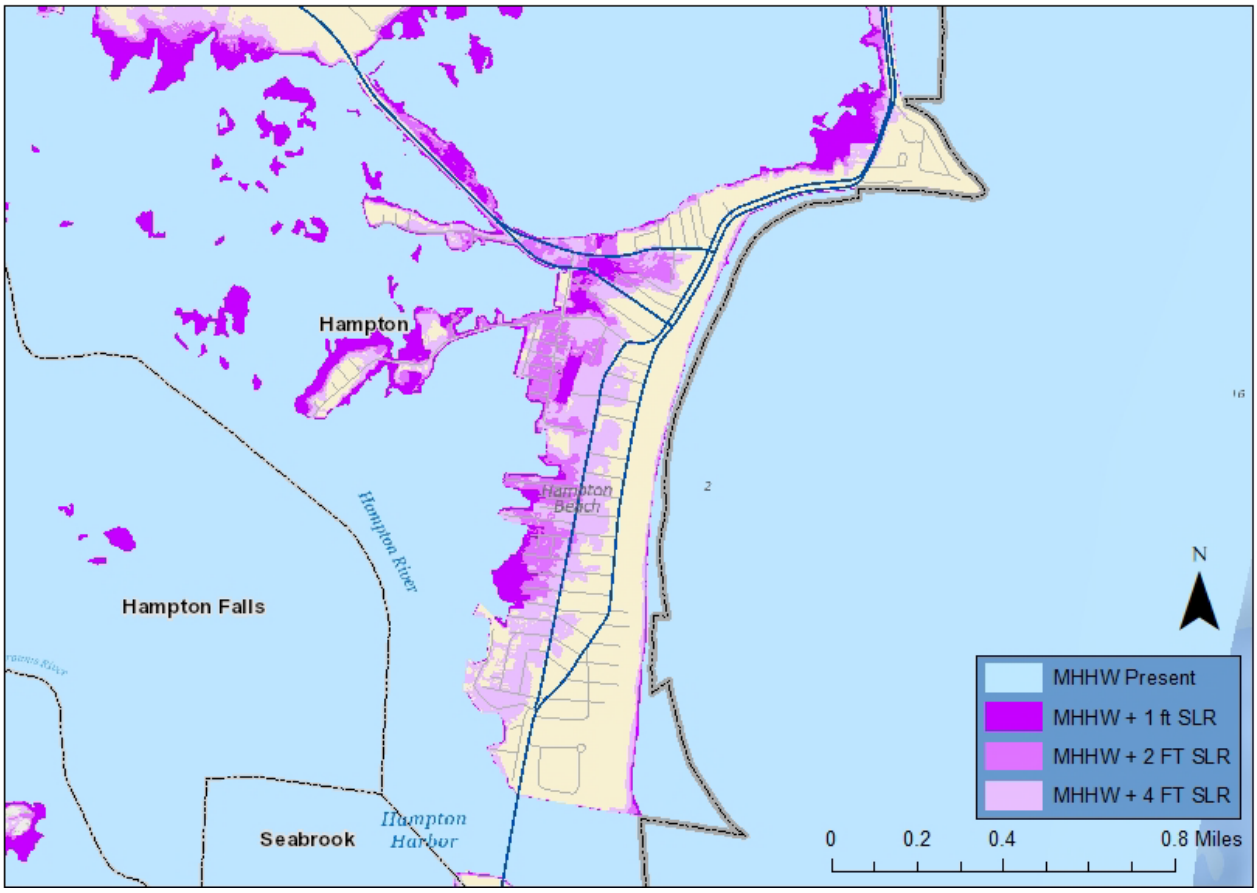

Figure 3. Map of Hampton Beach depicting the current extent of inundation at Mean Higher High Water (MHHW) and the increase in flood extent under different sea level rise (SLR) scenarios.

Hampton Harbor Tide Gauge

In order to better understand the potential impacts of future flood projections, an understanding of the current flood conditions is needed. A tide gauge that measures water levels at 6-minute intervals is located in Hampton Harbor, northwest of the Hampton Harbor State Pier (Figure 4). The tide gauge was installed in December 11, 2012, with funds provided by the Piscataqua Region Estuaries Partnership (PREP) and has been collecting data on a near-continuous basis since February 2013. The gauge is currently maintained with support from NERACOOS. Due to gauge maintenance issues or malfunctions, there are occasional short gaps in the data and two longer (> 1 month) gaps in 2016 and 2019. Data were accessed by direct request to tide gauge administrators at Charybdis Group, LLC. Real time tide gauge height observations and forecasts are available from the National Weather Service , and historical monthly data are available from NOAA Tides and Currents . For more information about the Hampton Harbor tide gauge instrument, see the Methods section of this report.

Figure 4. The tide gauge is located at the Hampton Fire Department pier in Hampton Harbor. The location is marked here by a red circle.

The water level data captured by the tide gauge are used to determine daily high and low tide levels, including tide levels during storm events. The heights recorded by this tide gauge differ from the values available from NOAA tide chart predictions because they capture, in real time, the influence of weather and wind action on water height, whereas the NOAA tide charts are astronomical predictions. The National Weather Service (NWS) has provided thresholds of Minor, Moderate and Major flood severity for Hampton (Figure 5). At Minor flood stage (11 feet), flooding of low-lying, vulnerable waterfront locations is expected and up to one foot of inundation can occur. During a Moderate flood, widespread flooding of waterfront areas, damage to vulnerable structures, and 1 to 3 feet of inundation can be expected, while a Major flood is expected to bring over three feet of inundation, destruction of the most vulnerable properties, severe flooding of roadways, and risks to the life of anyone remaining in the area (Thompson, 2011). Measured tide heights are referenced to Mean Lower Low Water (MLLW), which is the average height of the lower of two low tides each day (NOAA Tides and Currents). In this report, we use eight years of tide data (2013-2020) collected by the Hampton Harbor tide gauge and categorize high tides according to the NWS categories to understand flood frequency and severity in Hampton, NH.

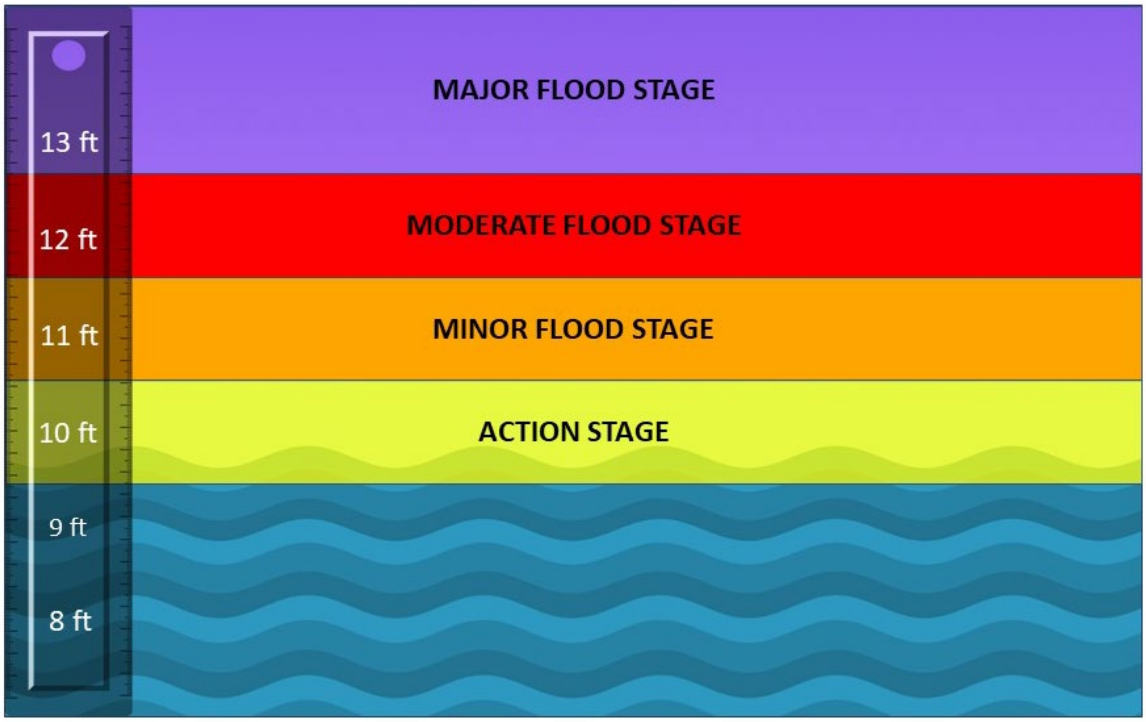

Figure 5. Flood categories for Hampton, NH, referenced to Mean Lower Low Water (National Weather Service Advanced Hydrologic Prediction Service, figure: Rayann Dionne)

3. RESULTS

Summary and Yearly Results

The high tide data show that at least one high tide over 10 feet occurred on approximately 30 to 40 percent of the days between 2013 and 2020 (Table 1). Every year since the gauge was deployed, the maximum high tide height has exceeded 11 feet, which is the NWS threshold for Minor flood Stage (Table 1, Figures 1 and 6). Five of the eight years had maximum heights of 12 feet or greater, representing a Moderate or Major flood. Due to an equipment failure, there is a large gap in data during 2016, and as a result, the maximum tide height may not have been captured for that year.

Table 1. Summary of high tide measurements with flood classifications per year.

Year	# of Days with Data	# of High Tides ≥10ft	# of Days with High Tide ≥10ft	Max Height (ft)	% of Days with Data & High Tide ≥10 ft
2013	309	144	113	11.78	36.57%
2014	365	180	138	12.34	37.81%
2015	365	145	117	12.43	32.05%
2016	93	35	27	11.70	29.03%
2017	365	158	119	12.15	32.60%
2018	365	193	143	13.24	39.18%
2019	244	136	104	12.00	42.62%
2020	365	166	133	11.84	36.44%

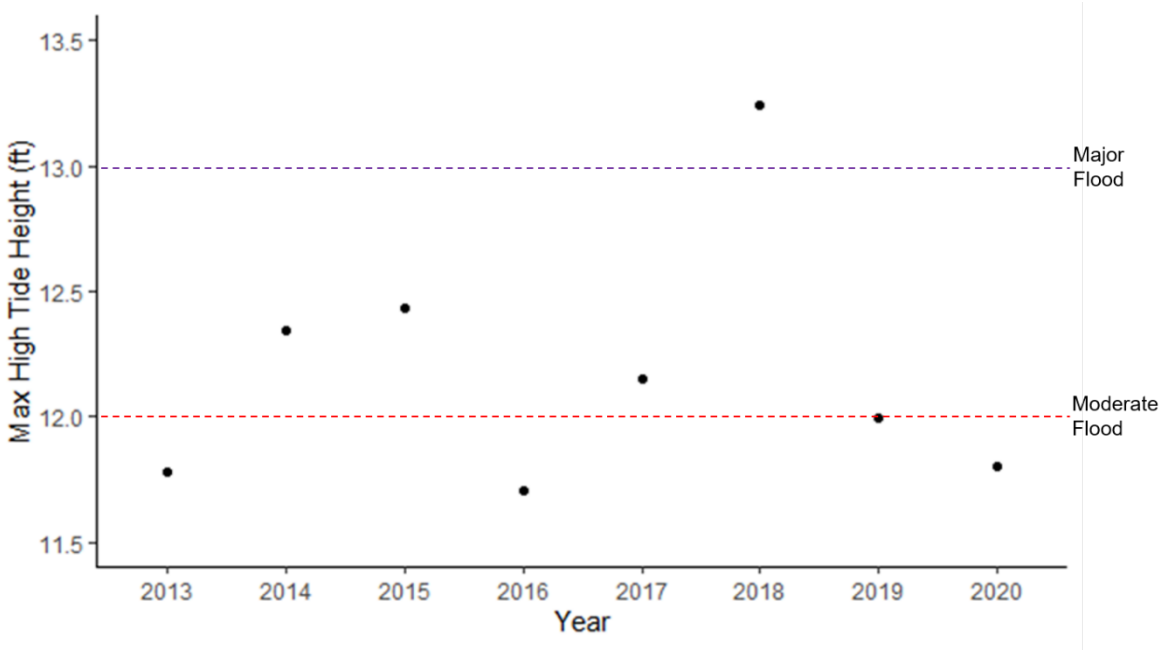

Figure 6. Annual maximum high tide heights, in feet above MLLW, from 2013-2020. Dotted horizontal lines represent the thresholds for different flood stages - Moderate flood, in red, is 12 feet and Major flood, in purple, is 13 feet.

When considering only years with data recorded continuously for 365 days, there were an average of 116 days per year with high tides at Action stage (10-10.99 feet), 26 days per year with high tides at Minor Flood stage (11-11.99 feet), and 1.4 days per year with high tides at Moderate flood stage (12-12.99 feet). There was only one occurrence of a high tide at Major flood stage (above 13 feet) during a Nor'easter storm in January 2018 that received a Major Disaster Declaration from the federal government (New Hampshire Homeland Security Emergency Management, 2018). At least 29% of days per year have a high tide that reaches the Action stage of 10 feet (Figure 7, Table 1). An average of 7% of days per year have a high tide that reaches the Minor flood stage of 11 feet, and less than 1 percent of days per year had a high tide at Moderate or Major flood stage (Figure 7). Independent review of the Hampton water level record completed by NOAA CO-OPS (data not shown) indicate that waters over 10 feet occur in Hampton for an average of 259 hours per year and waters over 11 feet occur for an average of 30 hours per year. During years with complete data records from the Hampton tide gauge, NOAA tide charts predicted that an average of 56 high tides per year would be at least 10 feet (NOAA Tides and Currents). No high tides were predicted to exceed 11 feet. During those same years, the tide gauge recorded 168 high tides that equaled or exceeded 10 feet. **These results confirm that high tide flooding is more prevalent than the NOAA tide charts might suggest, with high tide flooding occurring, on average, three times more often on an annual basis than tide chart predictions due to the added influence of weather.**

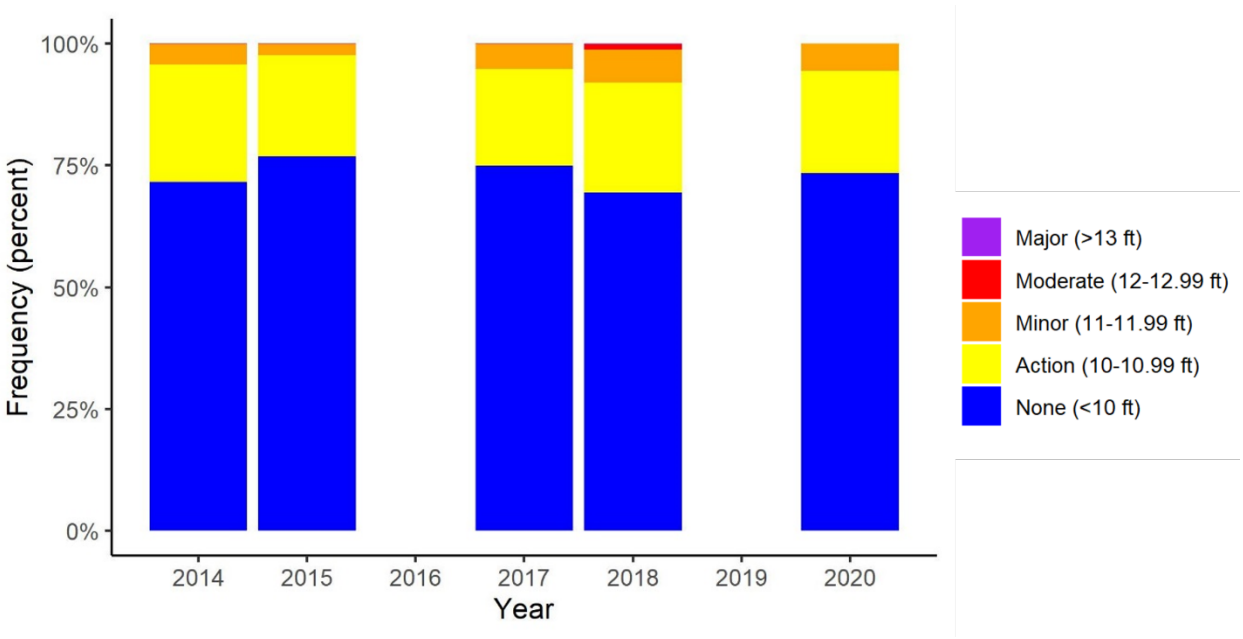

Figure 7. For each year with a full dataset, frequency of each flood stage classification was calculated as a percent. 75 percent or fewer of all high tides per year were below the Action stage of 10 feet. Frequencies were not calculated for years 2013, 2016, or 2019 because the incomplete data wold yield misleading results. One Major (>13 ft) flood was recorded during the time series, in 2018.

Seasonal Results

There was a lower overall frequency of high tides over 10 feet in winter, but there were more instances of severe flooding, likely due to the prevalence of Nor'easter storms in winter in the Northeast United States (Figure 8). Moderate flood stages were also observed in the spring of 2017 and 2018, potentially due to the persistence of winter weather and Nor'easter storms through March in many years. High tides did not reach the Moderate or Major flood stage (greater than 11.99 feet) in the summer or fall of any year.

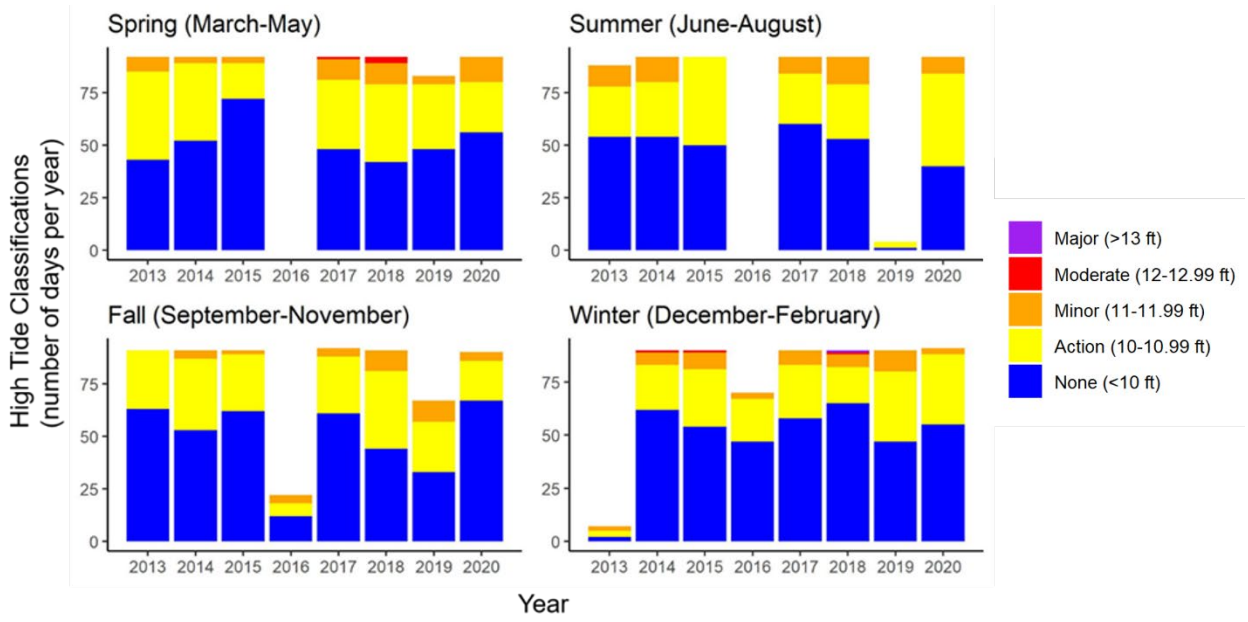

Figure 8. Number of days of each tide classification per season per year. There were large data gaps in 2016 and 2019 that resulted from equipment failure. The data record begins at the end of winter 2013, so there were incomplete data for this season of this year.

Future Conditions Analysis

Sea level in New Hampshire is rising and is projected to rise for centuries, however, the timing and magnitude of sea level rise remain uncertain beyond the year 2050 (Wake et al., 2019). Using the year 2000 as a baseline, New Hampshire guidance recommends planning for 1.3-2.3 feet of SLR by 2050, 2.9-6.2 feet of SLR by 2100, and 4.6-11.7 feet of SLR by 2150 (NH Coastal Flood Risk Science and Technical Advisory Panel, 2020).

To better understand how sea level rise will exacerbate high tide flooding in Hampton in the next 30 to 50 years, estimates of flood elevations under 1-foot and 2-feet sea level rise scenarios were calculated using a bathtub model approach, where the sea level rise scenario magnitude is added directly to the existing tide elevations (Table 3). Under a 1-foot sea level rise scenario, high tides at or above Action level (≥10 feet) would occur at least once per day on approximately 64% of days per year. Under a 2-foot sea level rise scenario, over 90% of high tides annually will reach or exceed Action level (≥10 feet) compared to an average of 24% of high tides exceeding 10 feet from 2013-2020 (Table 2). Interestingly, under a 2-foot sea level rise scenario, the analysis suggests that days with Minor flood stage tides (11-11.99 feet) will be more frequent than days with Action stage tides (10-10.99 feet). This method of predicting future flooding frequency does not take into consideration changes in the landscape that could increase or decrease flood resiliency, such as erosion of beaches and salt marshes as sea level rises, which could further increase the frequency of high tide flooding. Also not considered in this analysis, groundwater levels are predicted to rise in coastal New Hampshire as sea levels rise (Wake et al., 2019), which would further increase the severity of high tide and storm surge flooding in Hampton and other coastal communities.

Of particular concern is the increase in Major floods (>13 feet) between one foot and two feet of sea level rise (SLR). For all but one year (2018), the analysis indicates Major floods would occur once or not at all under one foot of SLR. **With two feet of SLR, the average number of days per year with Major floods (>13 feet) would increase to 27 days.** Only one Major flood occurred in the observed data. In January 2018, a major storm surge combined with the astronomical high tide resulted in major flooding with up to three feet of standing water on roadways, several homes inundated, and $1 million in property damage recorded (NOAA Storm Events Database). Under a two-foot SLR scenario, this level of inundation could occur for almost a month of non-consecutive days out of every year.

Table 2. Comparison of recorded high tides over 10 feet and projected high tides over 10 feet under 2 feet of sea level rise (SLR). New Hampshire guidance recommends planning for 1.3-2.3 ft of SLR by 2050 (NH Coastal Flood Risk Science and Technical Advisory Panel, 2020). Since there are typically two high tides per day, 705 high tides per year is a complete data set.

Year	# of High Tides Recorded	# of High Tides ≥10 ft	% of High Tides ≥10 ft	# of High Tides ≥10 ft with 2 ft SLR	% of High Tides ≥10 ft with 2 ft SLR
2013	595	144	24%	565	95%
2014	705	180	26%	677	96%
2015	705	145	21%	660	94%
2016	177	35	20%	164	93%
2017	705	158	22%	679	96%
2018	705	193	27%	672	95%
2019	469	136	29%	437	93%
2020	704	166	24%	671	95%
Average			24%		95%

Table 3. Estimates of flood stage frequency under 1 foot and 2 feet sea level rise (SLR) scenarios. As there are typically two high tides per day and these high tides can be in different flood stages, the total number of days per year exceeds the number of days with data. Due to a large data gap in spring and summer of 2016, flood projections using data from that year may be underestimated.

Year	Flood Stage	1 ft SLR # of tides	1 ft SLR # of days	2 ft SLR # of tides	2 ft SLR # of days
2013	Action (10-10.99 ft)	257	206	164	144
2013	Minor (11-11.99 ft)	120	101	257	206
2013	Moderate (12-12.99 ft)	24	23	120	101
2013	Major (>13 ft)	0	0	24	23
	Total above 10 ft	*401*		*565*	
2013	None (<10 ft)	194	149	30	26
2014	Action (10-10.99 ft)	273	225	225	180
2014	Minor (11-11.99 ft)	153	125	273	225
2014	Moderate (12-12.99 ft)	25	24	153	125
2014	Major (>13 ft)	1	1	26	24

Year	Flood Stage	1 ft SLR # of tides	1 ft SLR # of days	2 ft SLR # of tides	2 ft SLR # of days
	Total above 10 ft	*452*		*677*	
2014	None (< 10 ft)	253	188	28	27
2015	Action (10-10.99 ft)	289	239	226	183
2015	Minor (11-11.99 ft)	131	111	289	239
2015	Moderate (12-12.99 ft)	13	11	131	111
2015	Major (>13 ft)	1	1	14	12
	Total above 10 ft	*434*		*660*	
2015	None (<10 ft)	271	199	45	39
2016	Action (10-10.99 ft)	65	54	64	52
2016	Minor (11-11.99 ft)	26	24	65	54
2016	Moderate (12-12.99 ft)	9	9	26	24
2016	Major (>13 ft)	0	0	9	9
	Total above 10 ft	*100*		*164*	
2016	None (<10 ft)	77	55	13	13
2017	Action (10-10.99 ft)	333	255	188	156
2017	Minor (11-11.99 ft)	127	108	333	255
2017	Moderate (12-12.99 ft)	30	30	127	108
2017	Major (>13 ft)	1	1	31	30
	Total above 10 ft	*491*		*679*	
2017	None (<10 ft)	214	165	26	23
2018	Action (10-10.99 ft)	284	236	196	166
2018	Minor (11-11.99 ft)	145	123	284	236
2018	Moderate (12-12.99 ft)	40	38	145	123
2018	Major (>13 ft)	7	5	47	43
	Total above 10 ft	*476*		*672*	
2018	None (<10 ft)	229	176	33	28
2019	Action (10-10.99 ft)	167	141	134	108
2019	Minor (11-11.99 ft)	112	94	167	141
2019	Moderate (12-12.99 ft)	24	22	112	94
2019	Major (>13 ft)	0	0	24	22
	Total above 10 ft	*303*		*437*	
2019	None (<10 ft)	166	120	32	26
2020	Action (10-10.99 ft)	285	239	220	174
2020	Minor (11-11.99 ft)	133	111	285	239
2020	Moderate (12-12.99 ft)	33	29	133	111
2020	Major (>13 ft)	0	0	33	29
	Total above 10 ft	*451*		*671*	
2020	None (<10 ft)	253	187	33	33

4. CONCLUSIONS

Implications for Residents

The results confirm that Hampton Beach residents on low-lying streets are already impacted on a regular basis by coastal flooding due to both high tides and storm surges. An annual trend in frequency could not be determined from these data due to both the short length of the time series and the challenges posed by gaps in data. Best available science about sea level rise tells us that Hampton residents should expect more frequent and more severe flooding, increased property damage from flooding, and increased risks to public safety.

The most severe flooding has occurred in the winter and spring. Given the seasonality of Hampton Beach's population, the community may be buffered from the most severe risks of flooding because it occurs outside of peak season. This has both positive and negative implications. Flooding may not be impacting economically-important tourism activity in the summer or endangering the larger number of people inhabiting the area in the summer. On the other hand, the issue of high tide flooding may not be garnering as much attention and proactive action as it would if more landowners were present to experience its effects. It is likely that off-season renters experience significant impacts, such as damaged vehicles and safety hazards from high tide flooding. The off-season renter demographic can be especially at risk because it tends to be composed of transient residents with limited knowledge of the flood hazards, information sources, and support services in the area. Given that high tide flooding is occurring 3 times more frequently than the NOAA tide charts predict due to the influence of weather, residents, local decision-makers and emergency management officials should refer to the Hampton Harbor tide gauge 3-day forecast and real-time information in addition to the more commonly used NOAA tide charts to ensure a better understanding of coastal flood risk and appropriate responses. It is important that all residents, full time, seasonal, and off-season, prepare their homes for winter and spring flooding. It is also critical that the Town of Hampton and the State of New Hampshire take proactive steps to implement appropriate flood mitigation and community adaptation strategies for Hampton Beach in order to minimize harm to both people and property.

According to a recent survey conducted by the Seabrook-Hamptons Estuary Alliance (SHEA), residents and visitors to the Hampton-Seabrook Estuary are most concerned about development, loss of public access, and marsh infringement. Climate change impacts were mentioned less frequently. Given the estimated increase in frequency of Major floods accompanying 2 feet of sea level rise, unprecedented, damaging flooding will result in substantial changes to the Hampton Beach community and surrounding communities that depend on the area for employment, housing, and recreation. Dedicated advance planning and action can mitigate the impacts, but even the most extensive and costly flood mitigation strategies are unlikely to result in avoidance of serious impacts.

Recommendations for the Hampton Tide Gauge and Other Gauges

In light of the important findings summarized in this report and the potential uses and benefits associated with a longer-term tide gauge dataset, the Hampton, NH tide gauge should continue to be maintained. Funding should be allocated to increase reliability of the instrument and to support regular analysis of the dataset. An improved user interface featuring a water-level data visualization tool and/or an alert tool to notify stakeholders when water levels exceed a specific threshold would increase the functionality of this instrument for the residents and community members of Hampton. Deployment of

additional tide stations in the area and integration of the Hampton Harbor tide gauge into the NOAA system are recommended to provide more context for the data collected by the existing tide gauge. Realization of these recommendations will require a significant increase in funding, which could be achieved by a partnership between NOAA, NERACOOS, NHCP, and other local programs and municipalities.

5. METHODS

Tide Gauge Technology

A Micro pilot M FMR240 Level Radar tide gauge, located on a pier in Hampton Harbor northwest of Hampton Harbor State Pier, measures water level every 6 minutes with an accuracy of 1/16th of an inch. It was first installed in December 2012, when it was mounted to the outmost west-facing pylon of the standing portion of the pier. In August 2013, it was moved to a different pylon further away from the shore to measure extremely low tides (Figure 9). The gauge consists of a Endress+Hauser 26 GHz Microwave Radar transducer (2mm accuracy) coupled with an Onset Computer cellular-based data logger/telemetry unit and a solar charging system. The radar transducer produces a burst of microwave radiation and records the time that it takes for the multiple energy returns to be detected. The transducer then averages those times and determines the distance to the water surface. Multiple samples are taken to determine a water level measurement. The Hampton Harbor tide gauge operates with the NOAA sampling protocol (average of 181 samples at 1Hz, with exclusion of outliers, taken every 6 minutes).

Figure 9. The original tide gauge (left) was installed in December 2012 on the west-facing pylon of a pier in Hampton Harbor. In August 2013, the tide gauge was relocated to a different pylon further away from the shore in order to capture extremely low tides (right).

Lack of funding has limited the functionality of the Hampton Harbor tide gauge since it was installed. PREP sponsored the purchase and installation of the tide gauge in 2012, but no funding was identified for its maintenance beyond covering the cost of the cellular data plan. In 2016, the data logger ceased to function and the tide gauge went offline for several months. In the fall of 2016, funding was secured from NERACOOS to cover the cost of replacing the data logger, and NERACOOS has been funding the maintenance of the tide gauge since July 2017. From spring 2019 to fall 2019, the radar transducer was not functioning and the tide gauge was offline during that time until a replacement radar transducer could be purchased and installed.

Data Collected

Time points, measured to the second, and water level, measured in feet, were collected at 6-minute intervals from February 2013 to December 2020. Occasionally there are short gaps in the time series (i.e. <5 time points missing) or erroneous measurements (i.e. repeated identical height readings that were greater than 15 feet). These are assumed to be short term misreads of the instrument, and they were removed from the dataset. On five occasions, there were longer data gaps on the order of days to months that resulted from malfunctioning equipment and/or lack of maintenance funding. These gaps remained in the dataset and analyses were completed, where possible, with the remaining data.

Data Analysis and Quality Assurance Methods

Sub-daily high and low tides were identified using the Tides package (Cox and Schepers, 2018) in R, version 4.0.2. Following NWS designations, high tides were binned into Action, Minor, Moderate flood, and Major flood categories. High tides below 10 feet were classified as “none” as they do not typically lead to flooding in Hampton. The frequency of each classification was determined by year and by season. Seasons were classified as follows: Spring is March-May, Summer is June-August, Fall is September-November, and Winter is December-February.

The final dataset used for this report was quality-checked by staff at NOAA CO-OPS utilizing their inundation analysis tool to derive similar metrics to those presented here and to compare the results of the two analyses. An additional comparative analysis was completed using 6-minute data from a nearby tide station at Fort Point, NH in order to provide additional validation for the water level data reported by the Hampton gauge (see Appendix I). Fort Point data were retrieved using the Data_Retrieval Python scripts available on GitHub (Abrams, 2020). Datasets and scripts are available upon request by emailing coastal@des.nh.gov.

6. REFERENCES

Abrams, L. (2020). *Data_Retrieval [Python source code].* https://github.com/NOAA-CO-OPS/Dev_Tools_Python

Cox, T. and Schepers, L. (2018). *Tides: Quasi-Periodic Time Series Characteristics.* R package version 2.1. https://cran.r-project.org/web/packages/Tides/index.html

Hampton Beach Area Commission. (2021). *HBAC Symposium Report.* https://www.nhcaw.org/wp-content/uploads/2021/08/HBAC-Symposium-Report_Final5.24.21.pdf

National Weather Service. (2021). *Atlantic Coast at Hampton (in MLLW) Hydrograph*. Advanced Hydrologic Prediction Service. https://water.weather.gov/ahps2/hydrograph.php?gage=hpmn3&wfo=gyx

New Hampshire Employment Security. (2021). *Hampton, NH Community Profile*. Economic & Labor Market Information Bureau. https://www.nhes.nh.gov/elmi/products/cp/profiles-htm/hampton.htm

New Hampshire Homeland Security Emergency Management (2018). *State of New Hampshire Multi-Hazard Mitigation Plan Update 2018*. https://prd.blogs.nh.gov/dos/hsem/wp-content/uploads/2015/11/State-of-New-Hampshire-Multi-Hazard-Mitigation-Plan-Update-2018_FINAL.pdf

NH Coastal Flood Risk Science and Technical Advisory Panel (2020). *New Hampshire Coastal Flood Risk Summary, Part II: Guidance for Using Scientific Projections.* Report published by the University of New Hampshire, Durham, NH. https://scholars.unh.edu/cgi/viewcontent.cgi?article=1210&context=ersc

NH Department of Safety. (2021). *NH State Building Code.* Retrieved November 3, 2021, from https://www.nh.gov/safety/boardsandcommissions/bldgcode/nhstatebldgcode.html

NOAA. (2021). *Storm Events Database*. National Centers for Environmental Information. https://www.ncdc.noaa.gov/stormevents/

NOAA. (n.d.). *Tidal Datums*. Tides and Currents. Retrieved September 28, 2021, from https://tidesandcurrents.noaa.gov/datum_options.html

Office of Strategic Initiatives, NH Floodplain Management Program (2021a). *NH Communities with Standards Beyond Minimum NFIP Requirements.* https://www.nh.gov/osi/planning/programs/fmp/documents/communities-enforcing-nfip.pdf

Office of Strategic Initiatives, NH Floodplain Management Program (2021b). personal communication.

Rockingham Planning Commission (RPC). (2015). *Town of Hampton, New Hampshire Vulnerability Report* (Tides to Storms). http://www.therpc.org/application/files/6014/6920/2314/Hampton_Vulnerability_Assessment.pdf

Seabrook-Hamptons Estuary Alliance (SHEA). (2019). *Flooding in Hampton, NH Situation Assessment*. http://shea4nh.org/wp-content/uploads/2019/08/SHEA_SituationAssessment_Final.pdf

SLR Consulting (2021a). *Hampton Flood Mitigation Engineering Analysis Final Report*. https://www.hamptonnh.gov/DocumentCenter/View/4137/Final-Report-Meadow-Pond_SLR

SLR Consulting. (2021b). *Hampton New Hampshire 2021 Master Plan Update Coastal Resilience Report*. https://s3-us-west-2.amazonaws.com/mysocialpinpoint/uploads/redactor_assets/documents/aad561d13b90fdfc01f06da0d1d063c64642bdb7bf84f4d654568c65938f7489/37181/20210330_Coastal_Resilience_Report.pdf

Thompson, B. (2011). *A Change in Tide: A New Approach for Tide Forecasts and Coastal Flood Warnings* (Eastern Region Technical Attachment No. 2011-02). NOAA/National Weather Service.

Town of Hampton. (2014). *Code of Ordinances*. https://www.hamptonnh.gov/DocumentCenter

Wake, C., Knott, J., Lippmann, T., Stampone, M., Ballestero, T., Bjerklie, D., Burakowski, E., Glidden, S., Hosseini-Shakib, I., Jacobs, J. (2019). *New Hampshire Coastal Flood Risk Summary – Part I: Science*. Prepared for the New Hampshire Coastal Flood Risk Science and Technical Advisory Panel. Report published by the University of New Hampshire, Durham, NH. https://scholars.unh.edu/cgi/viewcontent.cgi?article=1209&context=ersc

U.S. Census Bureau (2019). *American Community Survey 5-year estimates.* Retrieved from *Census Reported Profile page for Hampton Beach, NH* http://censusreporter.org/profiles/16000US3333140-hampton-beach-nh/

7. APPENDIX I

Comparison between Fort Point, NH and Hampton, NH Tide Gauges

Water level data, measured at 6-minute intervals, were retrieved from the tide gauge at Fort Point, NH, in order to compare and validate results from the Hampton tide gauge. Located in New Castle, NH, approximately 13 miles from the Hampton tide gauge (Figure 10), the Fort Point tide gauge is the closest NOAA gauge. New Castle is an island situated at the mouth of the Piscataqua River, which separates Maine and New Hampshire, and the gauge is impacted by different riverine influences than the Hampton gauge. Given their proximity, the two gauges are expected to reflect similar weather patterns and water level conditions. Flood stages at the two stations differ due to the varying elevations and topography of the surrounding areas. New Castle (Fort Point) sits at a higher elevation than Hampton, so flooding and road inundation occurs at higher water levels than in the low-lying areas of Hampton. Fort Point data were analyzed using the same method as the Hampton data and annual frequency of high tides in each flood stage were compared (Tables 4-6). Based on the comparative analysis, the Fort Point and Hampton tide gauges appear to reflect similar water level data, save for a few data gaps in the record for each gauge, providing validation that the Hampton gauge is a reliable source of water level data for the region.

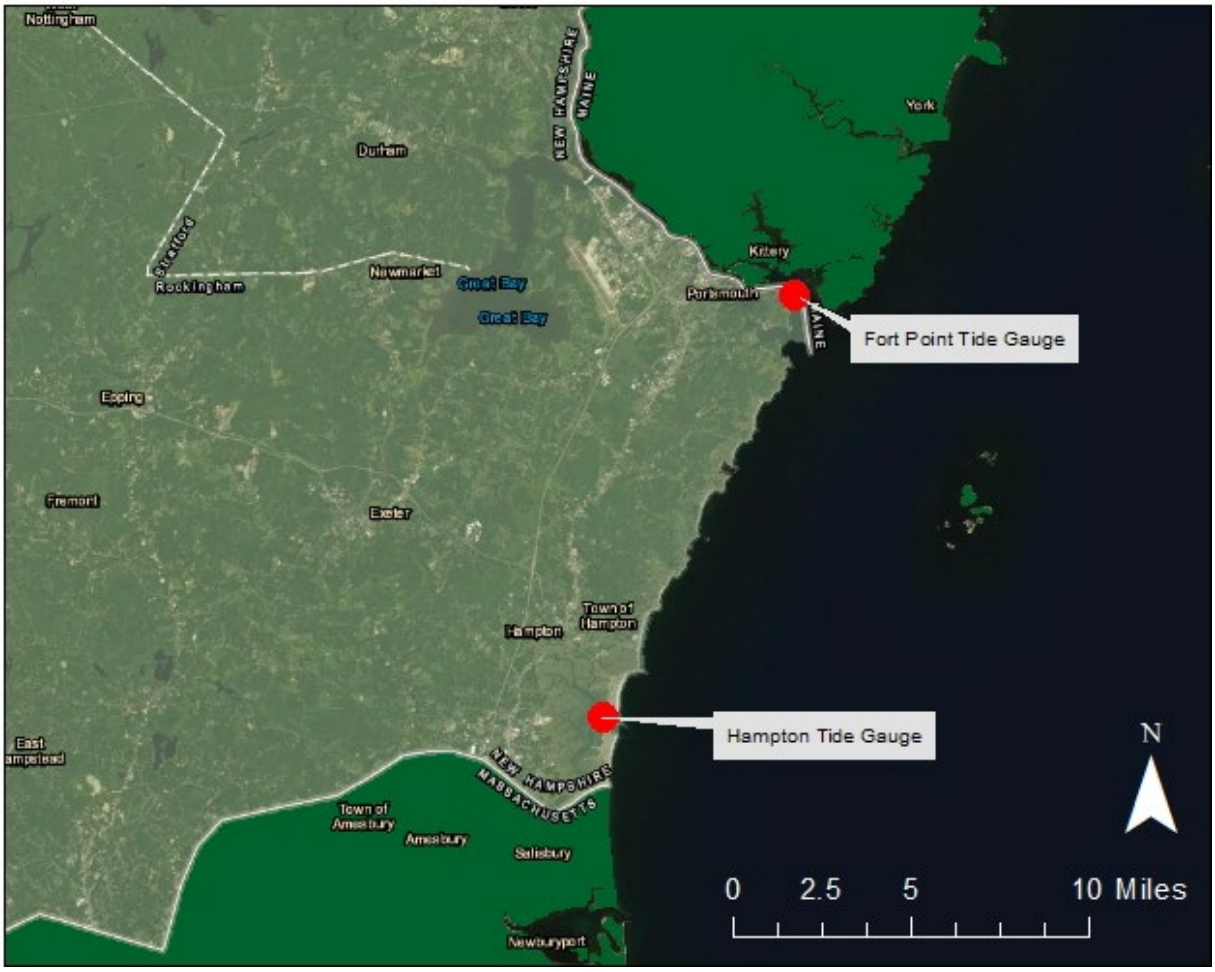

Figure 10. Map of coastal New Hampshire showing the locations of the Fort Point and Hampton tide gauges.

Table 4. Summary of high tide measurements at Fort Point, NH, with flood classifications. Data were not available at Fort Point for 2020. These results are comparable to Hampton measurements in Table 1. In both locations, the annual percentage of days with high tides greater than or equal to 10 feet range between 29 percent and 42 percent.

Year	# of Days with Data	# of High Tides ≥10ft	# of Days with High Tides ≥10 ft	Max Height (ft)	% of Days with Data & High Tides ≥10ft
2013	334	150	115	11.93	34.43%
2014	365	172	130	12.24	35.62%
2015	352	130	103	12.12	29.26%
2016	366	153	114	11.98	31.15%
2017	353	161	120	12.11	33.99%
2018	334	173	121	12.15	36.23%
2019	247	134	103	12.24	41.70%
2020	0	NA	NA	NA	NA

Table 5. Annual frequency of high tides and number of days in each flood stage category at Fort Point and Hampton, NH. Data were not available at Fort Point for 2020 and were incomplete for 2017-2019. Data were incomplete at Hampton for 2013, 2016 and 2019. The total number of days per year exceeds 365 if the two high tides on a given day are in different flood stages.

Year	Water Level (reference to MLLW)	# of Tides Fort Point	# of Tides Hampton	# of Days Fort Point	# of Days Hampton
2013	<10 ft	495	451	298	267
	10-10.99 ft	124	120	103	101
	11-11.99 ft	26	24	25	23
	12-12.99 ft	0	0	0	0
	≥13 ft	0	0	0	0
2014	< 10 ft	534	526	322	311
	10-10.99 ft	148	153	123	125
	11-11.99 ft	22	25	22	24
	12-12.99 ft	1	1	1	1
	≥13 ft	0	0	0	0
2015	<10 ft	551	560	325	328
	10-10.99 ft	120	26	100	24
	11-11.99 ft	9	13	9	11
	12-12.99 ft	1	1	1	1
	≥13 ft	0	0	0	0
2016	<10 ft	554	142	327	82
	10-10.99 ft	120	26	105	24
	11-11.99 ft	33	9	31	9
	12-12.99 ft	0	0	0	0
	≥13 ft	0	0	0	0
2017	<10 ft	518	547	309	323
	10-10.99 ft	129	127	108	108
	11-11.99 ft	29	30	29	30
	12-12.99 ft	3	1	3	1
	≥13 ft	0	0	0	0
2018	<10 ft	459	513	277	314
	10-10.99 ft	128	145	105	123
	11-11.99 ft	41	40	38	38
	12-12.99 ft	4	6	3	4
	≥13 ft	0	1	0	1
2019	<10 ft	336	333	211	204
	10-10.99 ft	115	112	96	94
	11-11.99 ft	17	24	17	22
	12-12.99 ft	2	0	2	0
	≥13 ft	0	0	0	0

Table 6. Total number of high tides over 10 feet annually at Fort Point and Hampton. Data were not available for Fort Point in 2020, and an extended data gap at Hampton in 2016 accounts for the discrepancy in number of high tides over 10 feet between the two locations during this year.

Year	# of Tides ≥10 ft Fort Point	# of Tides ≥10 ft Hampton
2013	150	144
2014	172	179
2015	130	145
2016	153	35
2017	161	158
2018	173	192
2019	134	136