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A Preliminary Assessment of Tidal Flooding along the New Hampshire Coast: Past, Present and Future

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A Preliminary Assessment of Tidal Flooding along the New Hampshire Coast: Past, Present and Future

A Final Report Submitted to

The New Hampshire Office of Emergency Management and the Office of State Planning Coastal Program

By

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CAUTIONARY NOTE AND DISCLAIMER

The maps and figures presented in this report are not designed to show site specific information nor are they intended for use in identifying individual properties that are presently flooded or may be at risk in the future to flooding due to tides, storm surges, or sea level rise. Rather, the maps, which are based on existing topographic information and predicted tidal flooding levels, identify general areas along the New Hampshire coastline with elevations lower than selected flood levels. However, not all of the low-lying regions would be subjected to tidal flooding under present conditions. For instance, there are some low-lying areas that are surrounded completely or nearly completely by higher land elevations that would serve as barriers against tidal inundation. In other instances, low-lying areas are located behind tidal restrictions that would reduce flooding. The scale of this project did not allow the actual risk of tidal flooding in these areas to be evaluated. At present, the best available information on actual flood risks in coastal areas is the Federal Emergency Management Agency (FEMA) National Flood Insurance Maps (FIRM) (see their web site).

EXECUTIVE SUMMARY

This report presents the results of a preliminary study that examines several critical coastal issues for New Hampshire including sea level fluctuations (past, present and future), shoreline migrations, and tidal flooding. Included are: 1) an analysis of sea level changes over the Holocene and resulting shoreline migrations, 2) an assessment of low-lying areas with elevations below selected tidal flooding datums in coastal areas, and 3) an assessment of increases in low-lying areas that are potentially at risk to tidal flooding over the next century due to sea level rise.

Major fluctuations in relative sea level (estimated to be on the order of 105 to 125 meters) occurred along the New Hampshire coast over the last 12,000 years (geologic period referred to the Holocene) as a result of the impact of the Wisconsin glaciation on the Gulf of Maine region. Due to the magnitude of the changes in sea level, the position of the New Hampshire shoreline shifted over 40 kilometers. During the maximum transgression (highest sea level and landward migration) some 12,000 years ago, the sea reached as far inland as approximately Barrington. During the maximum regression (lowest sea level and seaward migration) approximately 11,000 years ago, the coastline was closer to the Isles of Shoals. Since that time, the New Hampshire coastline first rapidly, then slowly, migrated landward to its present position. Assessing sea level fluctuations and resulting shoreline migrations over the last 12,000 years provides a perspective of the magnitude of changes that are possible along the New Hampshire coastline over long time intervals (millennia).

In order to evaluate the impact of future changes in sea level in New Hampshire and to examine present day tidal flooding, a surface elevation model was generated using GIS ArcInfo and ArcView using a recent (1998) U.S. Army Corps of Engineers (Northeast District) database. Based on this model and tidal datums for the coastal area in the vicinity of Hampton (U.S. Army Corps of Engineers 1999), land below mean high tide spring, maximum predicted astronomical high water, a 10-year tidal flood and a 100-year tidal flood were identified for the Portsmouth area, Hampton and Seabrook, New Hampshire. The results indicate that at present, the Portsmouth and New Castle areas have relatively limited

areas below these tidal flood datums, while Hampton and Seabrook have substantially more low-lying acreage. Hypsometric analyses based on the surface elevation model developed for this study indicate that Portsmouth has 70 acres (non-marsh) above mean sea level, but below the 10-year flood level, while Hampton has 551 acres and Seabrook has 266 acres. Similarly, Portsmouth has 102 acres (non-marsh) of coastal land above mean sea level, but below the 100-year tidal flood elevation, while Hampton has 709 acres and Seabrook has 367 acres. Collectively, the seven townships found along the New Hampshire Atlantic seaboard (Portsmouth, New Castle, Rye, North Hampton, Hampton, Hampton Falls and Seabrook) have approximately 1,424 acres (non-marsh) of coastal land with elevations low enough to be at risk for a 10-year flood and 2,017 acres for a 100-year tidal flood.

The final component of this study considered the impact of sea level rise on tidal flooding in Portsmouth, Hampton and Seabrook. A number of recent studies of global sea level change indicate the average level of the world’s oceans will increase significantly by the end of this century (2100). A two-foot rise is well within the predicted ranges. Although an increase of two feet in mean sea level by 2100 in itself does not seem overwhelming, it is important because of the extensive infrastructure found along coastline today. In addition, and important to studies of coastal flooding, the increase in mean sea level raises the base level from which astronomic tides, storm surges, and waves flood coastal environments. For example, two feet added to the presently predicted tidal flooding level for New Hampshire increases the 10-year tidal flood level to higher than the present 100-year tidal flood level. Although many other considerations have to be taken into account to determine how sea level rise would actually change tidal flood levels, the potential impact is evident.

As a first step in evaluating the impact of projected sea level rise on the New Hampshire coast, a two-foot increment was added to the 10-year and the 100-year tidal flood levels and coastal areas (non-marsh) with lower elevations identified. Hypsometric analyses of this database show that the area of land above present day sea level, but below the 10-year tidal flood after a two-foot rise in sea level, will increase from 70 to 140 acres in Portsmouth (a 100% increase); from 551 to 825 acres in Hampton (a 50% increase); and from 266 to 442 acres in Seabrook (a 66% increase). The area of land above mean sea level, but below the

100-year tidal flood level after a two-foot rise in sea level will increase from 102 to 193 acres in Portsmouth (a 89% increase); from 709 to 950 acres in Hampton (a 34% increase); and from 367 to 517 acres in Seabrook (a 41% increase). For all the municipalities along the New Hampshire coast the total land (non-marsh) above present day sea level, but with elevations less than the 10-year tidal flood after a two-foot sea level rise increases by 77% or 1,095 acres. The total increase for the 100-year tidal flood will be 997 acres or approximately a 50% increase.

Identification of coastal locations below selected tidal flooding levels is meant to be only the first step in evaluating areas at risk to tidal flooding, now and in the future. Simply determining low-lying areas does not determine actual flooding risks. For instance, not all of the areas identified as being below a selected tidal flood elevation would necessarily be inundated by the ocean during a flood event. Some low-lying areas are surrounded by topographically higher elevations that would provide protection. However, if these protective barriers were altered by man or eroded during storms, then these low-lying areas could be impacted. Also, tidal restrictions would affect tidal inundations. To identify areas likely to be inundated by present day and future tidal flooding, more refined flooding scenarios will have to be developed, rather than simply assessing areas at risk based on land elevation alone. At present, the best available information on present day coastal flooding is the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM).

Based on the results of this study, recommendations for future work include the following.

1) Verification and determination of the accuracy of the surface elevation model developed for this study.

2) Identification of topographic highs that may act as protective barriers around areas at risk for tidal flooding.

3) Identification of major coastal geomorphic and sedimentologic environments, which may act as washover channels during storms.

4) Assessment of the potential additional flooding that may occur during storms due to waves.

5) Assessment of wave refraction patterns along the New Hampshire coast and resultant impact on shore erosion.

6) Assessment of the impact erosion of beaches, dunes or other topographic highs would have on tidal flooding and identification of areas to be protected.

7) Assessment of the susceptibility of New Hampshire’s tidal wetlands to sea level rise.

REPORT FORMAT

The Executive Summary provides an overview of the project and a synthesis of the results. Chapter One and the first sections of Chapters Three, Four and Five provide background information for the project including brief literature reviews. Chapter Two presents a general description of the methodologies, while Appendices 1 to 3 provide more details on the GIS tasks. Chapters Three, Four and Five present the results of the work. Finally, Chapter Six provides the general conclusions. There are numerous figures and maps that make up a substantial portion of the report. For simplicity, all the figures for each chapter are at the end of that chapter. This was done to minimize the breaks in the text and to allow easy comparison among related figures.

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ACKNOWLEDGEMENTS

This study was funded by a grant from the New Hampshire Office of Emergency Management Mitigation Assistance Program and administered through the New Hampshire Office of State Planning Coastal Program. We gratefully acknowledge their support. We would like to thank Ted Diers of the Coastal Program for his assistance and insights into this project.

CHAPTER ONE: INTRODUCTION

The coastal areas of New Hampshire exposed to the Atlantic Ocean (Figure 1) are subjected to daily tidal inundations by astronomic tides (water level changes related primarily to the moon and sun), and periodically to elevated water levels associated with storm surges (created by low atmospheric pressure, winds and waves). When high astronomic tides (spring tides) combine with large storm surges, unusually high ocean water levels occur that often flood developed coastal areas. During these tidal flooding events man-made structures can be damaged and beach erosion may occur, both resulting in significant monetary losses (Rockingham Planning Commission 1986 and 1991, U.S. Army Corps of Engineer 1954, 1963, 1977 and 1979).

In the future, coastal flooding, erosion and storm impacts may be aggravated by an acceleration in the rate of sea level rise. Since earlier in this century (1929 to 1980) tide gauge records for Portsmouth show the mean level of the ocean in New Hampshire has been rising at 2.0 mm/yr (0.079 inches/yr) (Hicks et al. 1983). This seemingly slow rise in mean sea level ultimately increases flooding and erosion impacts when considered on time frames of decades or centuries. To compound this problem, recent studies by the United States Environmental Protection Agency (EPA), United States National Academy of Science (NAS), and the Intergovernmental Panel on Climate Change (IPCC) warn that not only will sea level continue to rise, but that the rate of rise will likely accelerate significantly due to global warming and the “greenhouse effect” (see Titus and Narayanan 1995 for a review). In New Hampshire, the increase in sea level will exacerbate tidal flooding and coastal damage (Shevenell Gallen and Associates 1987, Rockingham Planning Commission 1991).

As a first step in an effort to develop an understanding of the impacts of tidal flooding, storms, and sea level rise on the New Hampshire coast, a preliminary study was conducted that: 1.) determined changes in shoreline positions over the last 12,000 years due to sea level fluctuations; 2.) identified low-lying coastal areas in Portsmouth, Hampton and Seabrook with elevations below selected tidal flooding levels (now and after a two foot rise in sea level; and 3.) developed hypsometric curves for each township along the open ocean coast.

Collectively, these three assessments provide a perspective on the changes in the New Hampshire shoreline that occur over long-time frames (in terms of human life spans) and possible impacts of coastal flooding, now and in the future (the next century). This will be especially important if the sea-level rise predictions presented by the EPA, NAS, and the IPCC are correct.

Figure 1. Location map of the New Hampshire coast.

CHAPTER TWO: METHODOLOGY

Development of Maps

A major product of this study is a series of maps that illustrate: 1.) the movement of the New Hampshire coastline during the last 12,000 years in response to sea level changes; 2.) low-lying areas with elevations below selected present day tidal flooding levels in Portsmouth, Hampton and Seabrook; and 3.) low-lying areas with elevations below selected tidal flooding level after a two-foot rise in mean sea level. To develop these maps, three databases were required.

1. Elevation data of the New Hampshire coastal area between 70 meters (~230 feet) above (topographic) to 70 meters (~230 feet) below (bathymetric) mean sea level. The overall accuracy of the elevation data here was only required to be on the order of 6 meters (~20 feet), except for the interval between mean sea level and the 6 meter contour (20 feet). In this range, the elevation data needed be accurate to within approximately 1.5 meters (~5 feet) and preferably 0.6 meters (~2 feet).

2. Sea level curves valid for the New Hampshire area that show the elevation of mean water level with respect to the land for the following three periods: 1.) the Holocene period (or for about the last 12,000 years); 2. the last several decades; and 3.) future or predicted sea level to the end of this century (2100).

3. Elevations of present ocean water levels during high astronomic tides and storm surges (tidal flooding).

Surface elevation, sea level change and tidal flooding information were obtained from federal, state and local agencies, as well as literature and Internet searches. Subsequently, the information was synthesized and maps and animations developed using geographic information system technologies (ESRI ArcInfo and ArcView). General overviews of the approaches used to develop the maps and conduct the analyses are given in this section

(Methodology), more details on the procedures can be found in Appendix 1 through 3. Several frequently used terms or abbreviations are defined in Table 1. Information on the databases used for the elevation models are given in Table 2 and Figures 2 and 3. Tidal flooding levels are presented in Table 3. The sea level curves used for this study are presented in Figure 4.

Holocene Changes in Shoreline Positions

In order to illustrate the magnitude of the movement of the New Hampshire shoreline and the region that was impacted due to the large changes in sea level over the last 12,000 years (Holocene period), a series of maps depicting the probable approximate location of the coast at various times was developed. First, topographic and bathymetric maps of the New Hampshire coast were developed from elevation information obtained from the United States Geological Survey (USGS), National Ocean Survey (NOS), and the University of New Hampshire (UNH) Granit and Ocean Engineering programs (Figures 2 and 3 and Table 2). Using GIS, a surface elevation model was constructed for the entire coastal area between the 70 meter (~230 feet) contour above present day mean water level (Figure 5) to the 70 meter contour (~230 feet) below present day mean water level (Figure 6). Following the development of the bathymetric and topographic maps, the probable positions of the New Hampshire shoreline for various times during the Holocene period were determined by moving the land-sea interface (mean sea level) to the appropriate elevation for the chosen time period (as indicated from Figure 4a). Subsequently, a new series of maps were developed showing the position of the New Hampshire coast over various time intervals from 12,000 years ago to present (discussed in Chapter Three: Holocene Shoreline Migrations).

To make these illustrations, several important simplifications concerning the coast and sea level changes were made. For example, the model assumed the topography and bathymetry of the coastal region of New Hampshire has remained unchanged over the last 12,000 years. This ignores changes in the landscape that occurred due to geological processes such as erosion or deposition and implies elevations measured in surveys over the last several decades are representative of the past. It is also assumed the most recently published sea level curves for the last 12,000 years for southern Maine (Belknap et al. 1987, Kelley et al 1992, Kelley et al. 1995) are valid for the New Hampshire coast and shelf (Figure 4a and 4b). The sea level curve for the Maine coast was chosen because: 1.) it represents the latest findings for northern New England; 2.) the transgression that occurred in the early Holocene at approximately12,000 years before present is included; and 3.) the curve is readily available via the Maine Geological Survey web site given below. For this study, the sea level curves on the MGS web site were used.

http://www.state.me.us/doc/nrimc/pubedinf/factsht/marine/sealevel.htm

More details of the procedure to develop the shoreline migration maps are given in Appendix 1.

Coastal Areas with Elevations Below Selected Tidal Flooding Levels

In order to determine coastal areas below the selected tidal flooding levels, a series of topographic maps were prepared that synthesized the present coastal land elevation data from mean sea level to the 6-meter (20 foot) contour (Figures 7 and 8). Subsequently, the areas with elevations lower than the selected tidal flood level were identified and presented on a new set of maps for Portsmouth, Hampton and Seabrook (discussed in Chapter Four: Present Day Coastal Flooding).

The topographic maps were developed by creating a surface elevation model using GIS ArcInfo and ArcView based on a detailed elevation survey obtained from the United States Army Corps of Engineers (ACOE) for the New Hampshire coast (see Figure 2 and Tables 2). The accuracy of the surface elevation model created for this study was not determined. Therefore, the accuracy of the elevations and contours are unknown at this time. Further work is required to verify the elevation model. The tidal flooding datums (Table 3) were obtained from an ACOE report (U.S. Army Corps of Engineers 1999) for the Hampton area. It is assumed the tidal flooding levels presented in this report are valid for the entire New Hampshire coast and within the embayments. The areas with elevations lower than the selected tidal flooding levels were then identified and assigned individual colors from the topographic maps by querying the elevation models for values equal to and less than the tide level of interest. More details on how the surface elevation model and the maps were developed are given in Appendix 2.

Coastal Areas with Elevations below Selected Tidal Flooding Level after Sea Level Rise

The maps illustrating the additional areas along the New Hampshire coast below selected tidal flooding levels if a two-foot rise in mean sea level occurred were developed using the same approach described in the previous section. However, the impact of future sea level rise was displayed by adding two feet to the water levels. A two-foot rise in sea level was chosen based on reports by the United States Environmental Protections Agency, the Intergovernmental Panel on Climate Change, and the United States National Academy of Sciences (see Titus and Narayanan 1995 for a review). The potential and magnitude of sea level rise are discussed in Chapter Five: Sea Level Rise and Coastal Flooding.

Hypsometric Curves

To determine the amount of land with elevations above mean sea level, but below unusually high tides and a 10-year and 100-year tidal flood event, hypsometric analyses were conducted for each coastal town in New Hampshire with exposure to the Atlantic Ocean. Hypsometric curves, which relate area of land versus elevation, were constructed by converting the surface elevation model described above to point locations and coding for elevation. Subsequently, the necessary data was exported to Excel, sorted from least to greatest and then plotted on an XY axis. Due to the high density of location data, the dataset was first re-sampled to 90-foot cells (from 30 feet) and then converted. These points were then coded with their respective towns and were designated as non-marsh or marsh area based on National Wetland Inventory (NWI) coverages. The NWI classification allowed the exclusion of wetland area from the hypsometric curves. See Appendix 3 for a more detailed explanation.

Table 1. Glossary of Frequently Used Terms

ACOE: United States Army Corps of Engineers.

ArcInfo: Software manufactured by ESRI that allows complex manipulation of geographic data.

ArcView: Software manufactured by ESRI that allows geographic datasets to be viewed and a moderate level of manipulation conducted.

Coverage: A GIS layer usually aimed at a specific theme such as roads, boundaries or isolines. Coverages consist of point, line, polygon or annotation information.

DEM: Digital Elevation Model (DEM) is a standard surface elevation model similar to ESRI's GRID format. A standard 7.5 minute DEM has a square cell size of 30m x 30m and corresponds to USGS 1:24,000 quadrangle boundaries.

ESRI: Environmental Systems Research Institute (ESRI) is the distributor of GIS software such as ArcInfo or ArcView. (See www.ersi.com)

GIS: Geographic information system. Software that allows geographic datasets to be viewed and extensive manipulations and analyses conducted.

GRID: An ESRI format that represents data in a raster format consisting of cells, similar to that of a digital photograph. GRID datasets are useful to represent surfaces,but are limited to a cell size with only one value per cell.

IPCC: Intergovernmental Panel on Climate Change.

Layer: A general term for GIS themes that can be compiled. Includes coverages, grids, and TINS.

NAS: United States National Academy of Sciences.

NOS: United States Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Survey.

NRC: National Research Council. A component of the NAS.

TIN: Triangulated Irregular Network (TIN) is an ESRI format that represents surface information as a series of triangles suspended between points of varying elevation. Each face created contains both aspect and slope information.

USGS: United States Geological Survey.

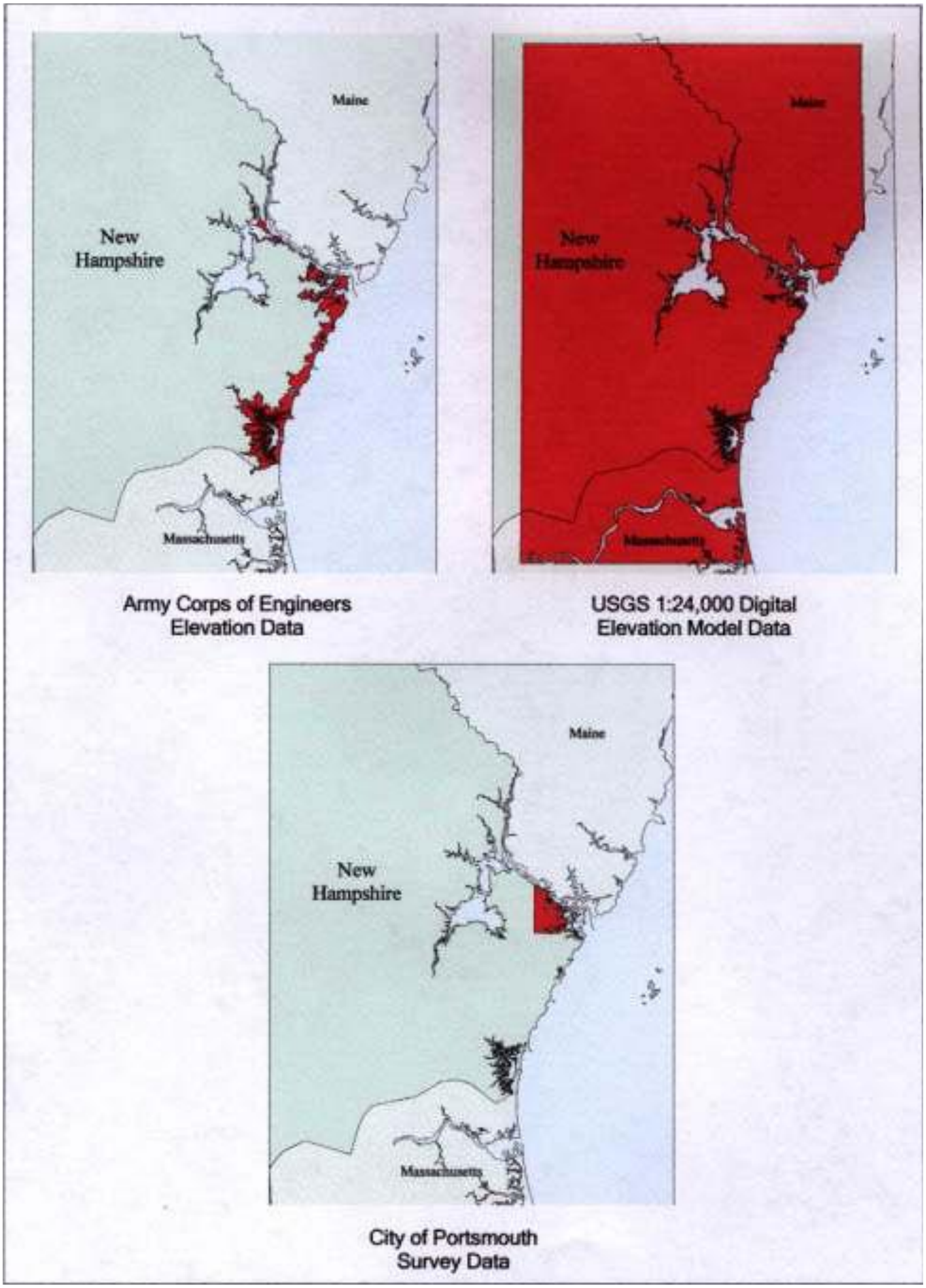
Table 2: Sources of Elevation Data

	Dataset	Source	Date	Form	Scale	Use for This Report	Contact or Source
Elevation	NH Coast Elevation Model	US Army Corps of Engineers (ACOE)	1998	ArcInfo TIN	From 1:12,000 photos ~ 2ft contours	Develop Primar Elevation Model for Tidal Flooding Evaluation	ACOE (Matt Walsh) matthew.t.walsh@usace.army.mil
	NH/ME Surface Elevation	US Geological Survey	1994	7.5 minute DEM	30m cells	Holocene Shore Migrations	Internet: GIS Data Depot: http://www.gisdatadepot.com/dem/
	City of Portsmouth, NH Elevation Data	City of Portsmouth	?	AutoCad DXF	2ft contours	Used to test Accuracy of the ACOE dataset	Portsmouth Public Works 603-427-1530 (David Allen)
Bathymetry	Great Bay Estuary Bathymetry	NOS	1998	7.5 minute DEM	30m cells	Holocene Shore Migrations	NOS Estuarine Bathymetry: http://sposerver.nos.noaa.gov/bathy/
	NH Nearshore Bathymetry	UNH GRANIT	1994	ArcInfo Coverage	From NOAA Charts 1:80,000	Holocene Shore Migrations and Tidal Animations	Internet:http://www.granit.sr.unh.edu/
	Hampton Harbor Bathymetry	C-COM	2000	ASCII coordinates	variable	Holocene Shore Migrations	http://derya.unh.edu/HamptonHarbor/default.htm
	NH Shelf Bathymetry	Compiled by UNH Jackson Estuarine Laboratory Coastal Geology	1999	ArcInfo GRID	50m cells	Historical Shoreline Migrations	Gulf of Maine Information System: http://woodshole.er.usgs.gov/project-pages/oracle/GoMaine/bathy/index.htm

Table 3. Tidal Levels at Hampton, New Hampshire

Values for each event determined by the U.S. Army Corps of Engineers (1999). The ACOE estimated the flooding levels from correlation to Boston, MA and Portland ME NOS Tide Gauges and the Corps of Engineers Tidal Flood Profiles, New England Coastline (dated September 1988).

Event	Tide Level Referenced To NGVD	
	(in meters)	(in feet)
100-year Frequency Flood Event	2.9	9.6
50-year Frequency Flood Event	2.8	9.3
10-year Frequency Flood Event	2.6	8.5
1-year Frequency Flood Event	2.1	6.9
Maximum Predicted Astronomical High Water	2.0	6.7
Mean High Water Spring	1.6	5.2
Mean High Water	1.4	4.6
Mean Tide Level	0.14	0.45
National Geodetic Vertical Datum (NVGD)	0.0	0.0
Mean Low Water	-1.1	-3.7
Mean Lower Low Water	-1.2	-4.1
Mean Low Water Spring	-1.3	-4.4
Minimum Predicted Astronomical Low Water	-1.8	-5.9

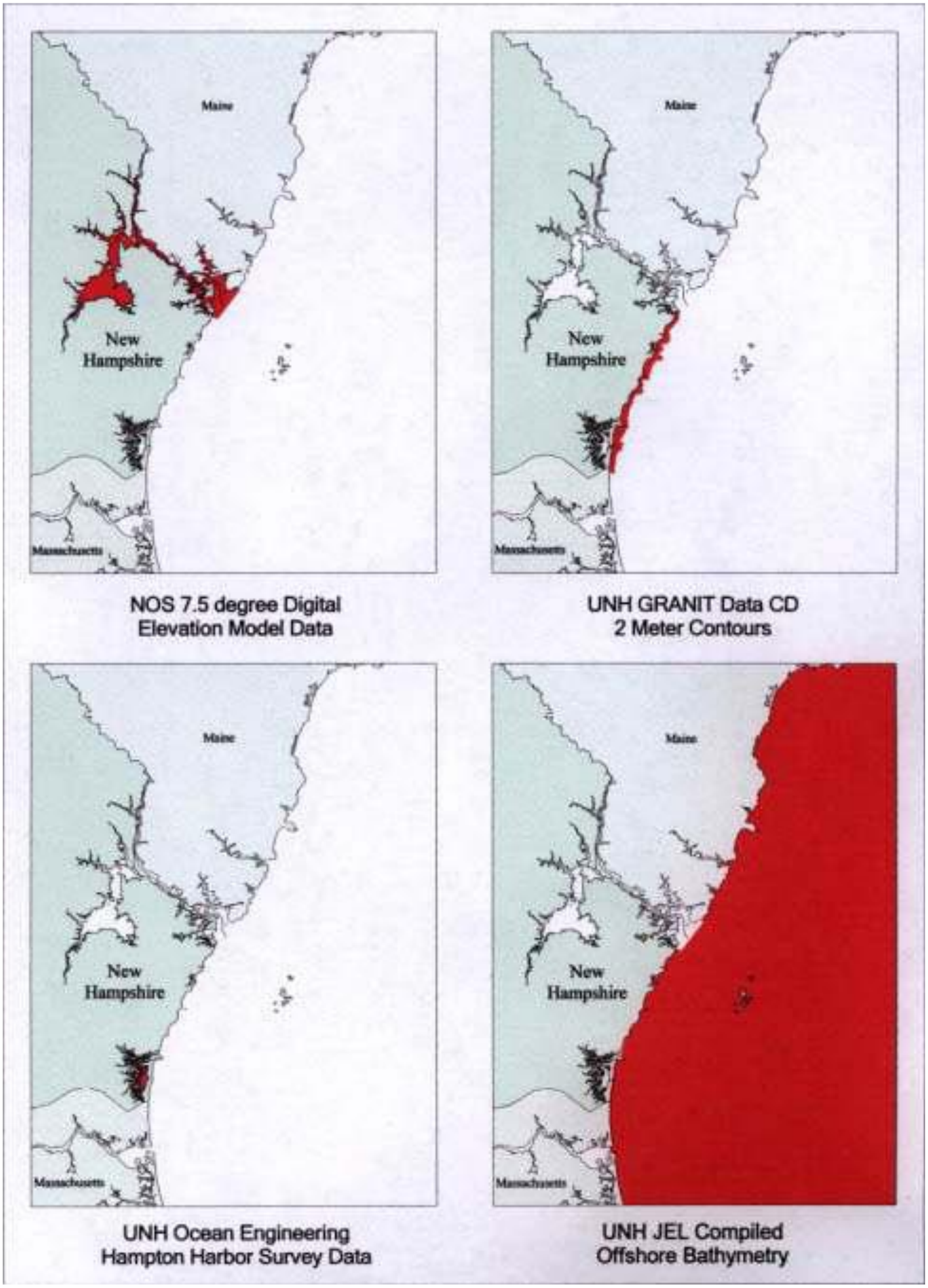


Army Corps of Engineers Elevation Data

USGS 1:24,000 Digital Elevation Model Data

City of Portsmouth Survey Data

Figure 2. Sources and geographic boundaries of topographic data used for this study. Coverages shown in red.



NOS 7.5 degree Digital Elevation Model Data

UNH GRANIT Data CD 2 Meter Contours

UNH Ocean Engineering Hampton Harbor Survey Data

UNH JEL Compiled Offshore Bathymetry

Figure 3. Sources and geographic boundaries of bathymetric data used for this study. Coverages shown in red.

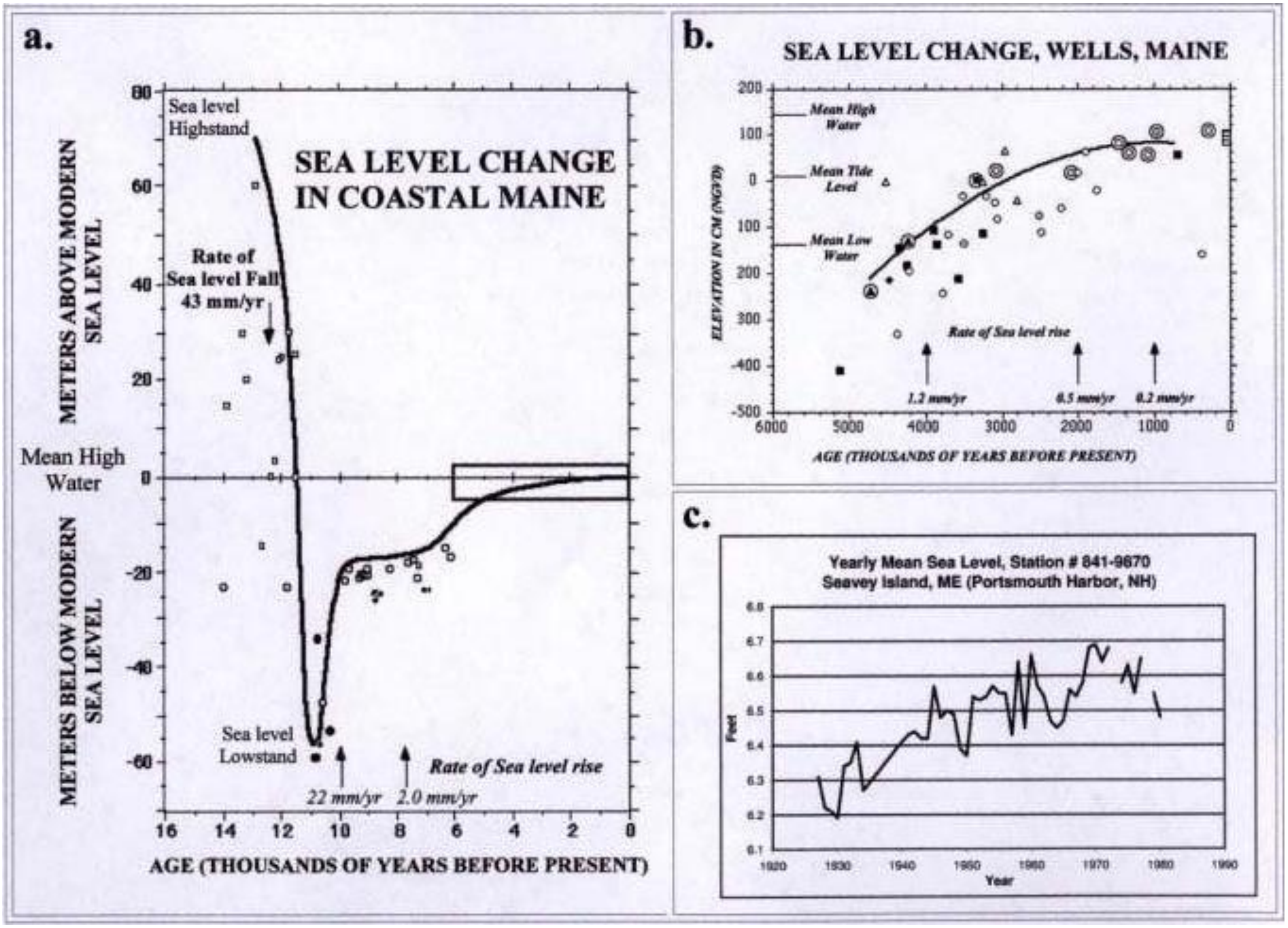


Figure 4. Sea level curve for the past 12,000 years (a), the past several thousand years (b) and this century (c). Figure 8a modified from Belknap et al. 1987 and Kelley et al. 1992. Figure 8b modified from Kelly et al. 1995. Figure 8c modified from Hicks et al. 1983.

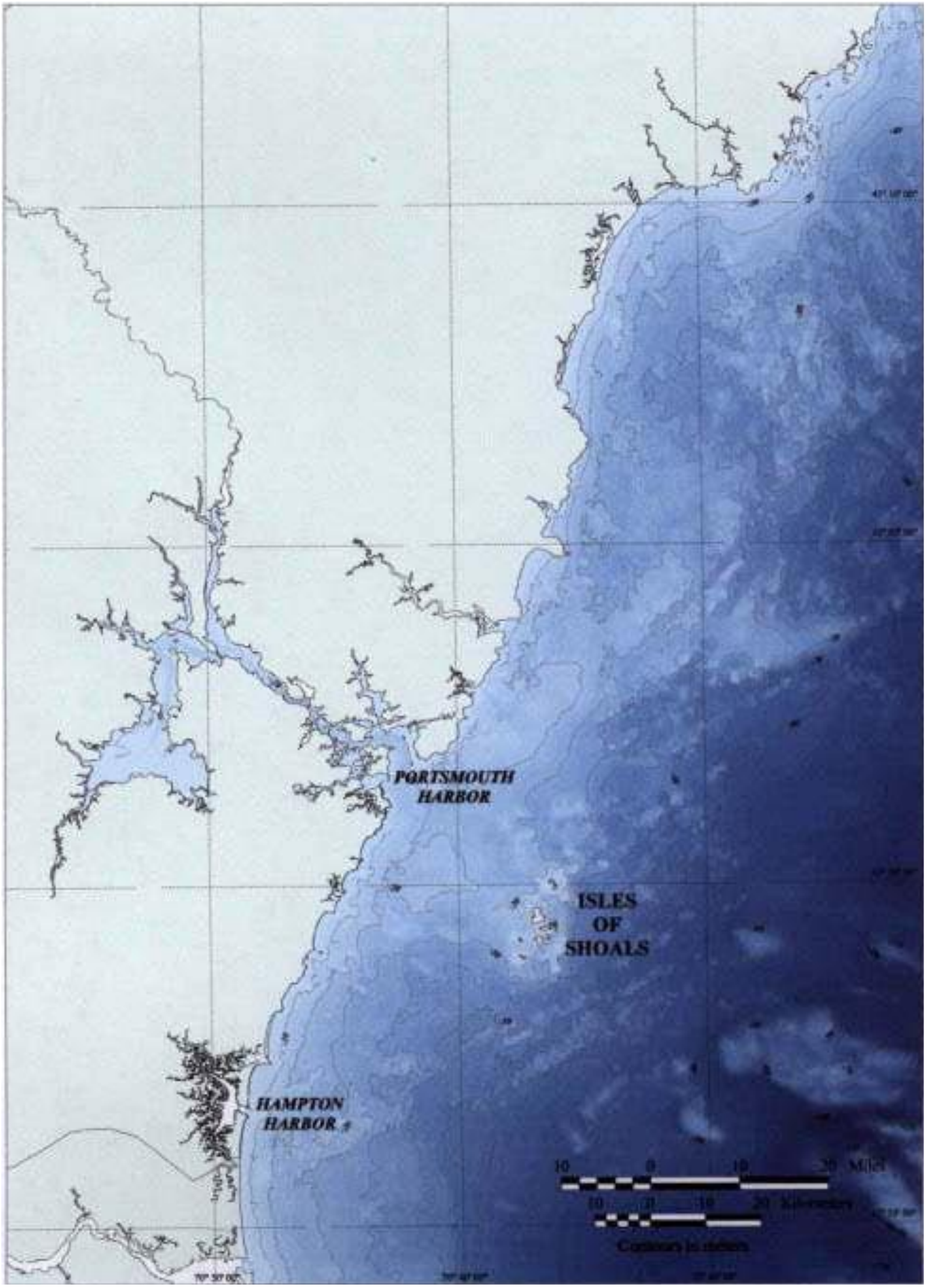


Figure 5. Bathymetric map of the New Hampshire shelf compiled for this study. See Table 2 for data sources.

Figure 6. Topographic map of coastal New Hampshire. See Table 2 for data sources.

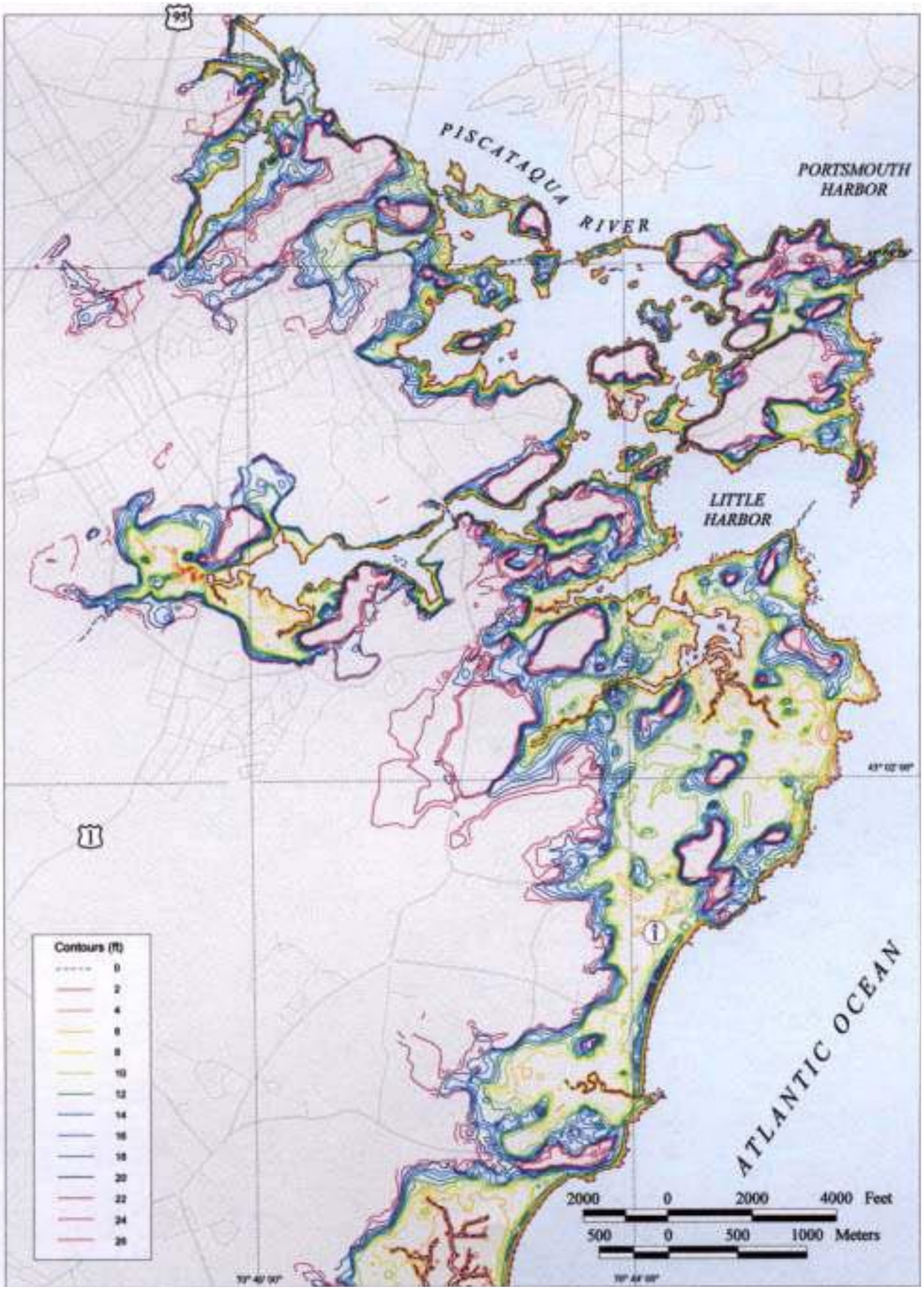


Figure 7a. Topographic map of Portsmouth, New Hampshire. Elevations greater than 26 feet not shown. See Table 2 for data sources.

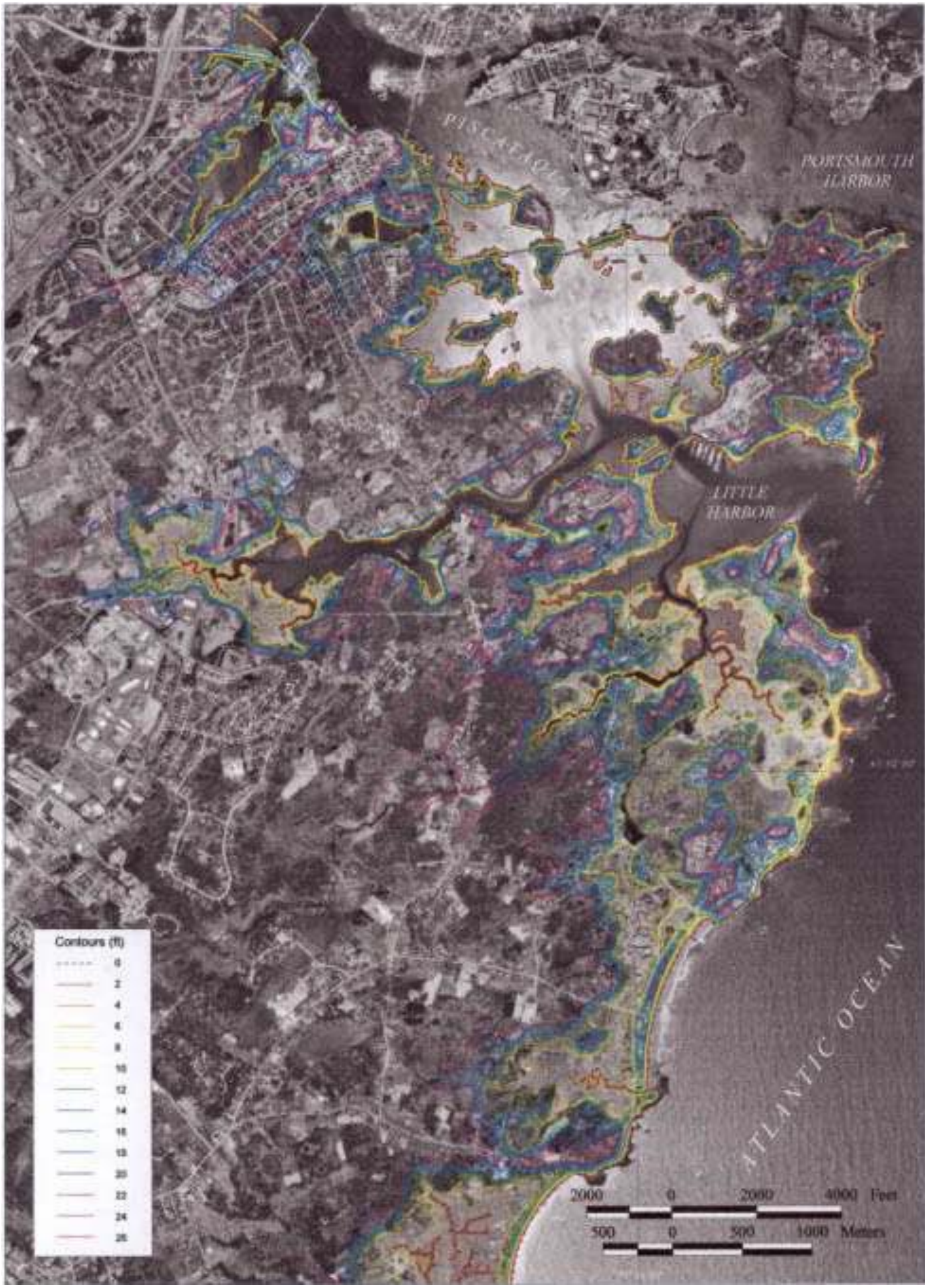


Figure 7b. Topographic map of Portsmouth, New Hampshire overlying aerial photo. Elevations greater than 26 feet not shown. See Table 2 for data sources.

Figure 8a. Topographic map of Hampton Beach and Seabrook Beach, New Hampshire. Elevations greater than 26 feet not shown. See Table 2 for data sources.

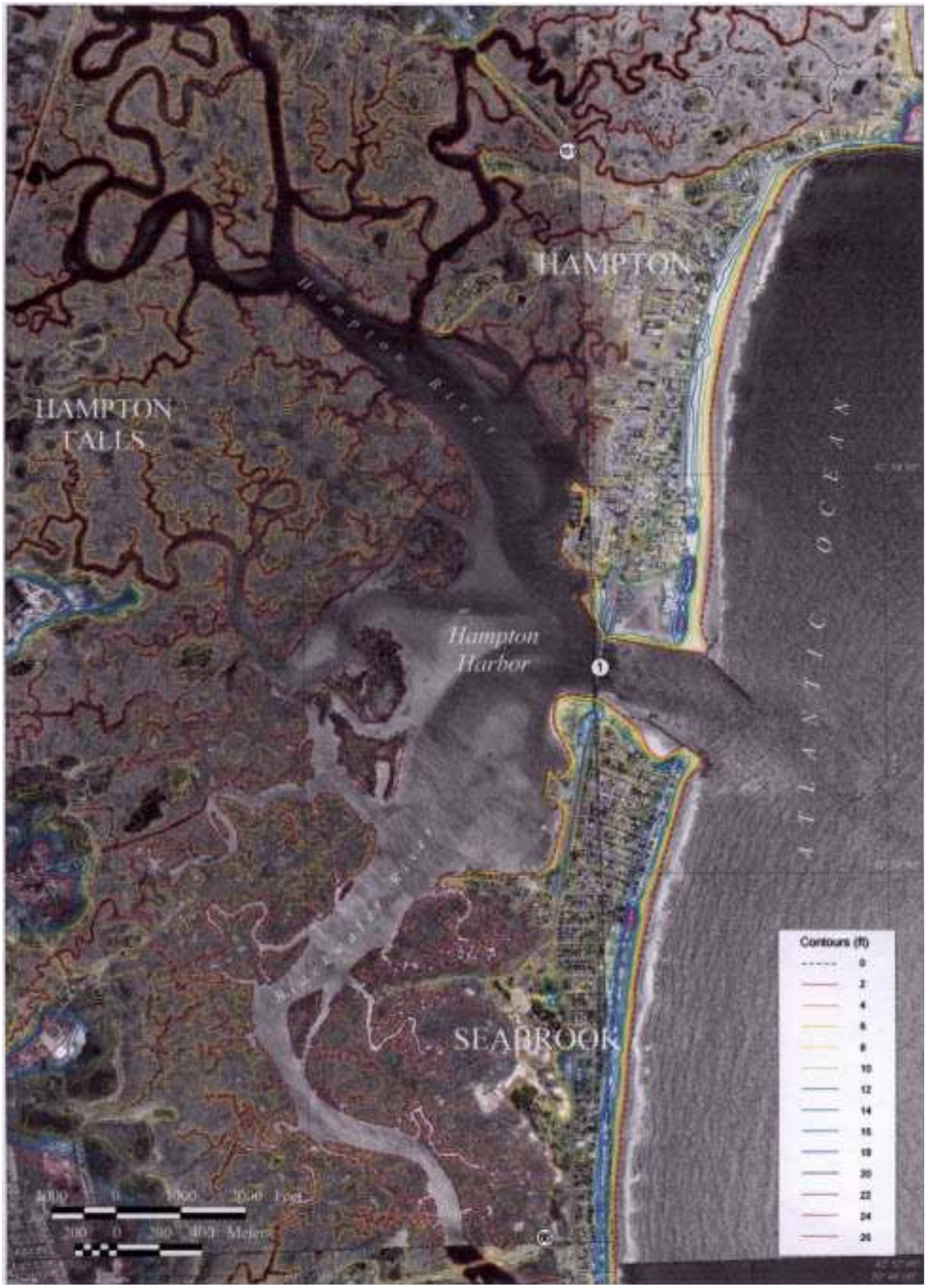


Figure 8b. Topographic map of Hampton Beach and Seabrook Beach, New Hampshire with aerial photo. Elevations greater than 26 feet not shown. See Table 2 for data sources.

CHAPTER THREE: HOLOCENE SEA LEVEL CHANGES AND SHORELINE MIGRATIONS

The Gulf of Maine region has a complex geologic history that includes glaciations, crustal adjustments, sea level changes and resulting migrations of the land-sea boundary. These large scale geologic processes had a major impact on the shape and characteristics of the New Hampshire coast. For instance, over the last 12,000 years the ocean invaded the land (transgression), then retreated seaward (regression), and then flooded the land again (transgression) (Belknap et al. 1987, Kelley et al. 1992, Kelley et al. 1995). The vertical change in the mean ocean level during this period resulted in extensive migrations of the New Hampshire shoreline.

New Hampshire's Complex Holocene Sea Level History

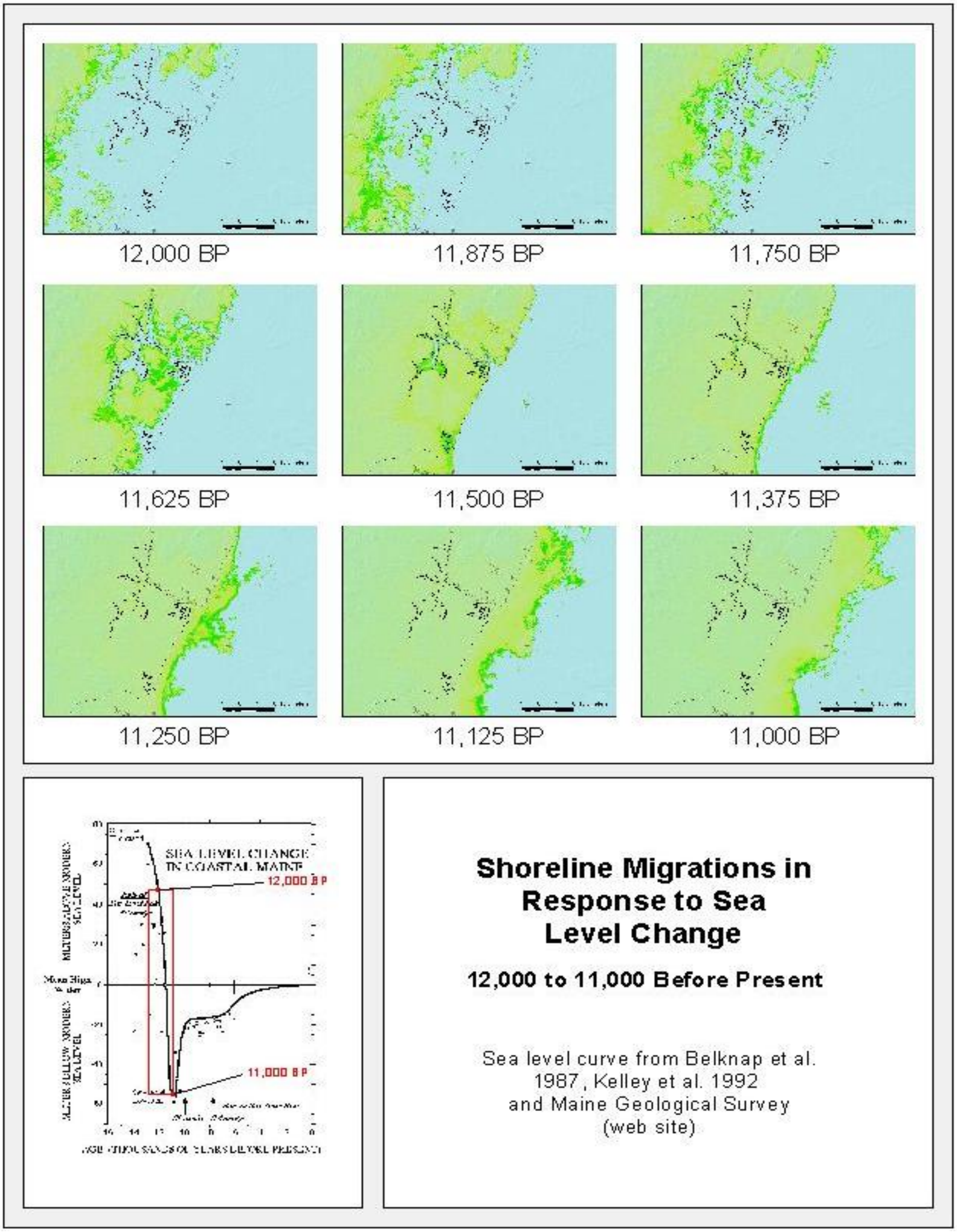
A relatively detailed sea level curve for southern Maine indicates the elevation of the ocean with respect to the land was approximately 70 meters (230 feet) higher 12,000 years ago than it is today (Figure 4a) (Belknap et al. 1987, Kelley et al. 1992, Kelley et al. 1995, MGS web site). At this time, the Wisconsin ice sheet terminus had retreated inland of today's coast and the sea had followed the ice margin landward. Subsequently, mean sea level dropped at an extremely high rate (~ 43 mm/yr or 1.7 inches/yr) reaching approximately 55 meters (~180 feet) below today's mean water level 11,000 years ago (Belknap et al. 1987, Kelley et al. 1992). Other sea level curves (Oldale et al. 1983 or Birch 1990) for New Hampshire and northern Massachusetts place this low stand or the lowest sea level at about 35 meters (115 feet) below present. In either case, sea level fell at an extremely high rate.

Following the low stand, sea level rose very quickly for about a millennium and reached approximately 20 meters (66 feet) below present mean water level (Figure 4a). Although the rate of sea level change between 11,000 and 10,000 years before present (22 mm/yr or 0.866 inches/yr) was less than the extremely rapid regression during the early Holocene, it was still fast in comparison to more recent rates. From 10,000 to approximately 1,000 years before present, the relative rate of sea level rise across the New Hampshire shelf slowed due to the decrease in glacial melting and a slowing of the isostatic adjustments of the crust (Figure 4a). For example, sea level rise decreased from 2.0 mm/yr (0.079 inches/yr) eight thousand years ago (Figure 4a) to 0.2 mm/yr (0.008 inches/yr) one thousand years ago (Figure 4b). In fact, most evidence indicates that mean water level was close to its present position approximately two to three thousand years ago and the coast began to take its present shape.

Unlike the slower rates over the last few millennia, more recent sea level rise rates have increased again. Although it is not clear when the increase occurred, recent tide gauge records from Portsmouth Harbor show the sea level rise to be approximately 2.0 mm/yr (from 1929 to 1980) in this area. This represents a 10-fold increase over the last 1,000 years! Furthermore, the rate of sea level rise is likely to dramatically increase again (Titus and Narayanan 1995). Future sea level rise is discussed in Chapter Five: Sea Level Rise and Future Coastal Flooding.

Changes in Shoreline Position and Elevation During the Last 12,000 Years

The large scale changes in the mean level of the ocean over the last 12,000 years caused major migrations in the location of the New Hampshire coastline. Twelve thousand years ago, when sea level was approximately 70 meters (230 feet) higher, the position of the coast was up to 25 kilometers (15 miles) inland from today's shoreline (Figure 9). Following the high stand (highest position of sea level), sea level dropped rapidly as the crust rebounded due to the removal of the weight of the Wisconsin ice sheet. Consequently, the position of the coast migrated seaward (regression) extremely rapidly from 12,000 to 11,000 years ago. Based on the sea level curve shown in Figure 4a and today's bathymetry, the land would have extended up to 15 kilometers (~9 miles) seaward of today's coastline. Overall, the map shown in Figures 9 indicates the New Hampshire shoreline migrated nearly 40 kilometers (25 miles) in some areas or as far inland as approximately Barrington, NH to as far seaward as close to the Isles of Shoals. Following the low stand approximately 11,000 years ago, the shoreline transgressed landward rapidly until about 10,000 years ago (Figure 10). The shoreline remained fairly stable from 10,000 to 6,000 years before present as sea level rise slowed for several thousand years. Over the last 6,000 years the New Hampshire coastline slowly transgressed reaching close to its present position a couple of thousand of years ago. The movement of the coast over the last 10,000 years is shown in Figure 11. The long time span this figure covers in comparison to Figures 9 and 10 results from the slow movement of the shore during this period.

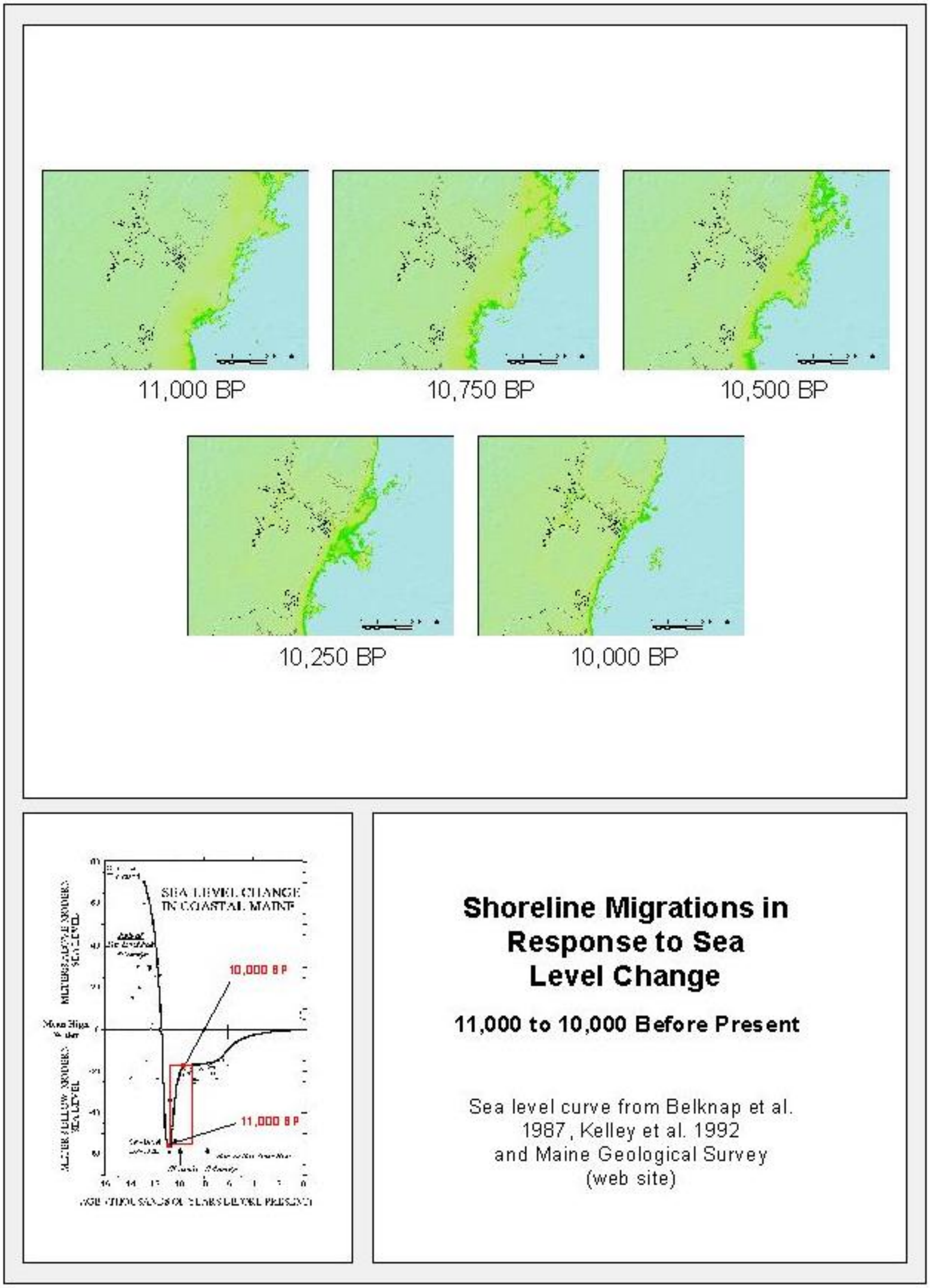


Shoreline Migrations in Response to Sea Level Change

12,000 to 11,000 Before Present

Sea level curve from Belknap et al. 1987, Kelley et al. 1992 and Maine Geological Survey (web site)

Figure 9. Migration of the New Hampshire coast from 12,000 to 11,000 years before present.



Shoreline Migrations in Response to Sea Level Change

11,000 to 10,000 Before Present

Sea level curve from Belknap et al. 1987, Kelley et al. 1992 and Maine Geological Survey (web site)

Figure 10. Migration of the New Hampshire coast from 11.000 to 10,000 years before present.

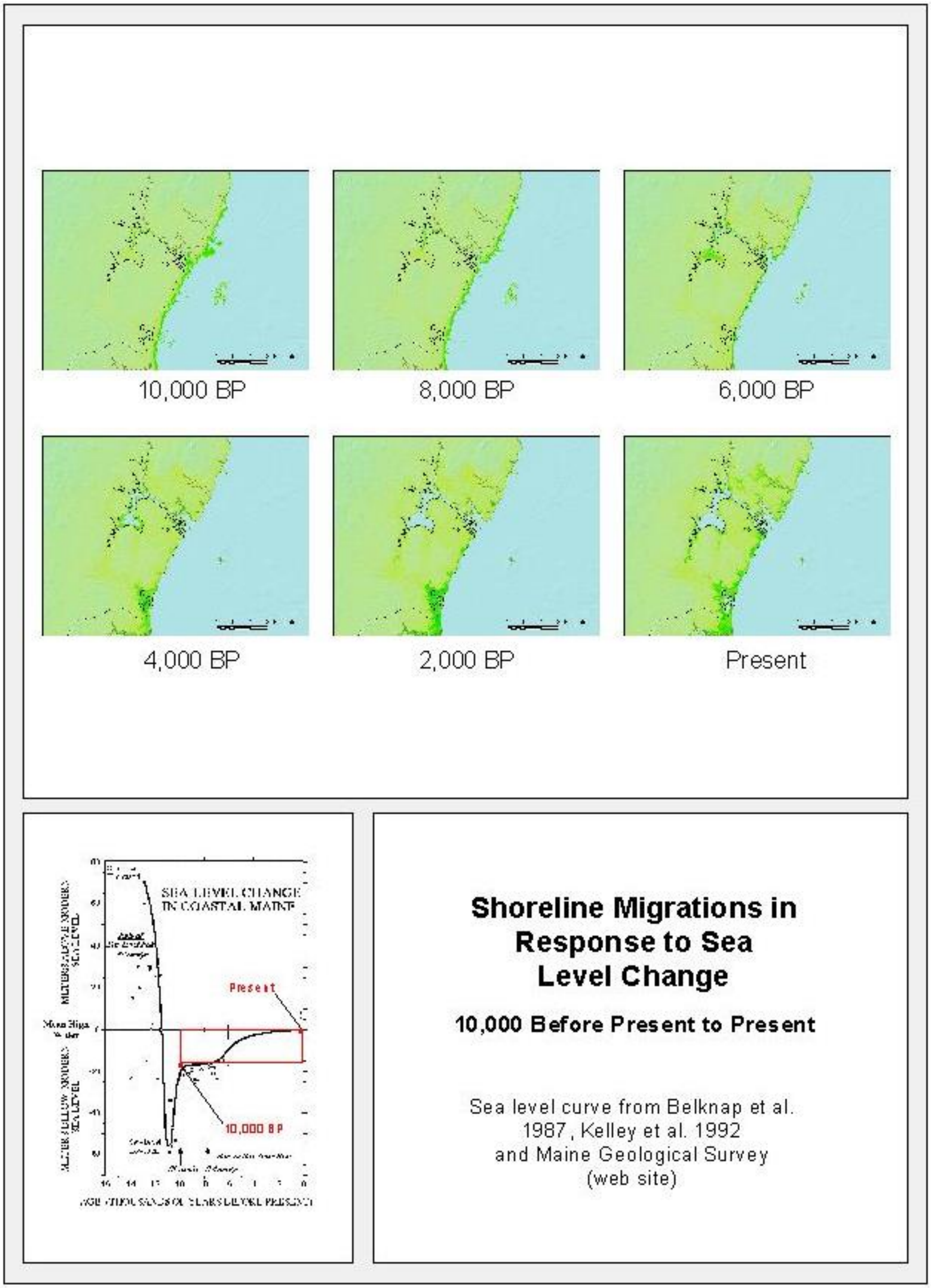


Figure 11. Migration of the New Hampshire coast from 10,000 years before present to today.

CHAPTER FOUR: PRESENT DAY COASTAL FLOODING

Causes of Coastal Tidal Flooding

The coast of New Hampshire is subjected to tidal inundations every approximately12.4 hours by the ocean due to astronomic forces (water level fluctuations due to the gravitational attraction of the moon, sun, etc.). This flooding varies depending on the tidal phase from neap tides (the smallest tidal ranges and the lowest high tides) to spring tides (the largest tidal ranges and the highest tides). Although spring tides occur approximately every two weeks, the tidal range and the elevation of the highest spring tides vary over the year due to the relationship between the orbits of the sun, moon, and earth (Komar 1998). The average range of the tides along the New Hampshire coast is approximately 2.6 meters (8.5 feet); the average spring tide range is around 3.0 meters (9.8 feet) (NOS 2001). The maximum predicted astronomic tidal range for the Hampton area is 3.8 meters (12.6 feet) (U.S. Army Corps of Engineers 1999). The average tidal elevations for Hampton are given in Table 3.

In addition to the semi-diurnal (approximately twice daily) flooding of the coast by astronomic tides, the elevation of tidal waters can increase during storms due to winds piling water up close to the shoreline and low atmospheric pressures (storm surges) (Komar 1998). Frequently, a storm surge occurs during a Nor'easter. Less frequently, but also important due to their intensity, hurricanes make their way to the New Hampshire coast and create storm surges. Some of the highest storm surges the New Hampshire coast has experienced in the recent past include the Blizzard of 78, Hurricane Bob, and the Halloween Nor'easter. Review of web sites for these storms indicate surges on the order of 1.2 to 1.5 meters (4 to 5 feet) on the open coast occurred. The Hurricane of 38, perhaps the most severe New England storm on record, caused extensive coastal flooding and may have had a larger storm surge. However, a record of this event for the New Hampshire coast was not found.

The flooding associated with astronomic tides is very predictable and essentially sets the boundaries between the marine and terrestrial environments (from a physical and biological perspective). However, when high astronomic tides coincide with storm activity, greater flooding occurs. This results because the increase in water level created by the storm surge is added to the normal astronomic tide. The highest water elevations or flooding, excluding consideration of waves, occurs when a large storm surge and maximum astronomic high tide coincide.

The end result of the high water level associated with a large astronomic tide and a storm surge is flooding of areas significantly above the normal reaches of the intertidal area. In undeveloped areas these inundations are of no concern. However, much of the New Hampshire open ocean coastline is heavily developed, often encroaching the terrestrial-marine boundary. Consequently, during higher than normal tides or storms, developed coastal areas are subjected to flooding. These coastal floods can damage private and government buildings and infrastructure (Rockingham Planning Commission 1986 and 1991, U.S. Army Corps of Engineer 1954, 1963, 1977 and 1979).

A recent report by the U.S. Army Corps of Engineers (1999) included tidal and storm surge elevations (combined) for the Hampton area (Table 3). In this report, the tidal flooding elevations, which are referenced against the NVGD (National Geodetic Vertical Datum), are given as a probability of occurrence in a given time interval (e.g., 1-year, 10-year, or 100-year events). For example, the water level for the maximum predicted astronomical high water is 2.0 meters (6.7 feet) above NVGD. However, the 10-year tidal flood event increases to 2.6 meters (8.5 feet) above NVGD due to the storm surge. A 100-year tidal flooding event reaches 2.9 meters (9.6 feet) above NVGD. It is important to understand that the flooding intervals for various tidal elevations are probabilities of occurrence. It does not necessarily mean that two or more 100-year floods could not occur in the same century, decade or even year.

Coastal Areas with Elevations Below Selected Tidal Flooding Levels (Portsmouth, Hampton and Seabrook)

Maps identifying low-lying areas in Portsmouth, Hampton and Seabrook with elevations below an unusually high astronomic tide (maximum predicted astronomical high water) and a tidal flooding event equivalent to a mean spring high tide and a 4.4 foot storm surge are shown in Figures 12, 13 and 14. A storm surge of this magnitude during a spring tide is approximately equivalent to a 100-year tidal flood event on the open ocean coast (see Table 3). In general, these maps show Portsmouth has a limited amount of area that falls below the selected tidal flood levels. However, typical of barrier island environments, Hampton and Seabrook have substantial low-lying areas that are subjected to tidal flooding.

In order to estimate the amount of low-lying areas below the 10-year and 100-year tidal flood levels, hypsometric curves were determined for each coastal township along the New Hampshire Atlantic seaboard (Figures 15 through 21). These hypsometric curves display the amount of land (above mean sea level) at each elevation (incrementally) between 0 and 6 meters (20 feet) above sea level. For these curves, the areas of the marshes were subtracted from the total areas in order to emphasize the actual amount of terrestrial land that is below tidal flood levels. Including the tidal marsh areas increases the acreage below the 6-meter (20 feet) contour significantly and tends to mask the terrestrial areas, at least in some townships like Hampton and Seabrook. Subsequently, these hypsometric curves were compared to the tidal flood datums for the open ocean coast near Hampton shown in Table 3. It is assumed the predicted tidal flood levels for the Hampton area are valid for all tidal areas along the New Hampshire coast that were reviewed in this study.

Results of the hypsometric analysis show Portsmouth and New Castle have the least amount of land of all the townships in New Hampshire with elevations less than either a 10-year of 100-year tidal flood (summarized in Table 4). The hypsometric analysis indicates the non-marsh area above mean sea level, but below the 10-year flood level in Portsmouth to be only 70 acres, while the area with elevations less than a 100-year flood is 102 acres. In contrast, Hampton has approximately 551 acres (non-marsh) below the 10-year tidal flood level and

709 acres below the 100-year flood level. Similarly, Seabrook has 266 acres below the 10-year tidal flood mark and 367 acres below the 100-year tidal flood.

It is important to note that not all coastal areas with elevations less than a given predicted tidal flood level will be inundated, even if the tide reaches that level. In this study, no consideration was given to the time it would take flood waters to inundate an area. Also, no consideration was given to areas that are surrounded by topographic highs that would stop or at least inhibit flooding. Also, wave activity was not taken into account. Therefore, the illustrations do not necessarily represent the exact areas that may be flooded. Wave impacts would cause erosion and increase the amount of flooding, especially on the seaward facing shores. On the other hand, tidal restrictions would decrease the amount of tidal inundation. Also, a number of low-lying areas are surrounded by land with higher elevations that would act as a barrier against tidal inundation. However, the illustrations do show potential flooding areas or areas at risk because of low elevations. Further studies will be required to assess the probable extend of tidal flooding, rather than simply assessing areas at risk based on land elevation alone. At present, the best information for tidal flooding risk is the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (see the FEMA web site).

Table 4. Results of Hypsometric Analyses

Township	Total Acreage*	Acreage Lower Than Tidal Flood Elevations[#]			
	Non-marsh and < 20’	Present Tidal Flood Elevations#		Adjustment for a 2’ rise in sea level	
		10-year (8.5’)	100-year (9.6’)	10-year plus 2’ (10.5’)	100-year plus 2’ (11.6’)
Portsmouth	709	70	102	140 (100% increase)	193 (89% incr.)
New Castle	242	51	68	85 (66% increase)	102 (50% incr.)
Rye	1,797	294	488	680 (131% increase)	840 (72% incr.)
North Hampton	520	106	141	181 (71% increase)	217 (54% incr.)
Hampton	1,674	551	709	825 (50% increase)	950 (34% incr.)
Hampton Falls	490	86	142	166 (93% increase)	195 (37% incr.)
Seabrook	907	266	367	442 (66% increase)	517 (41% incr.)
Totals	6,339	1,424	2,017	2,519 (77% increase)	3,014 (49% incr.)

* All acreage values refer to area above NVGD29 and selected elevation excluding marshes

[#] All elevations in reference to NVGD29

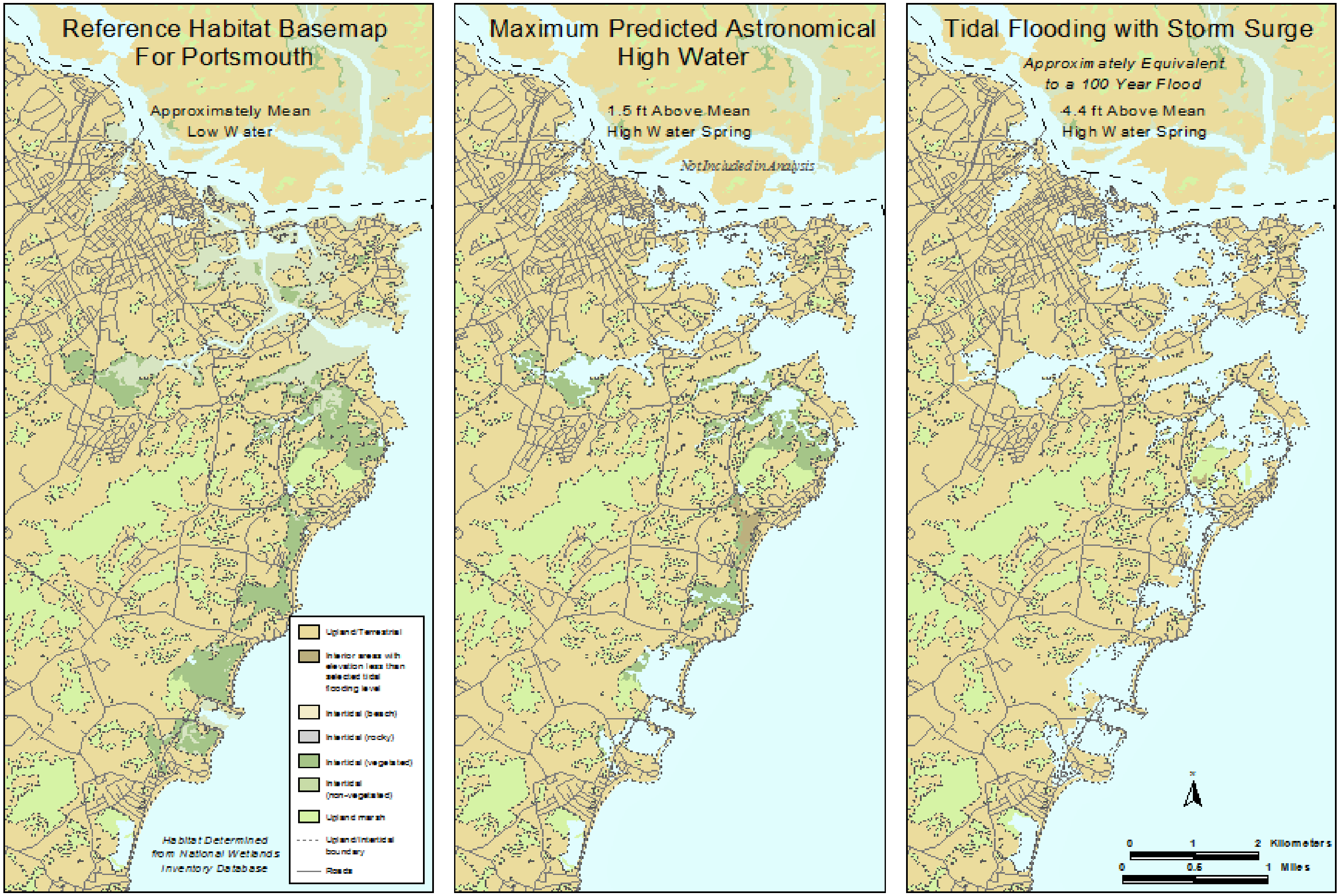


Figure 12. Maps illustrating low-lying areas around Portsmouth below tidal flooding elevations for maximum predicted astronomical water and approximately a 100-year tidal flooding event.

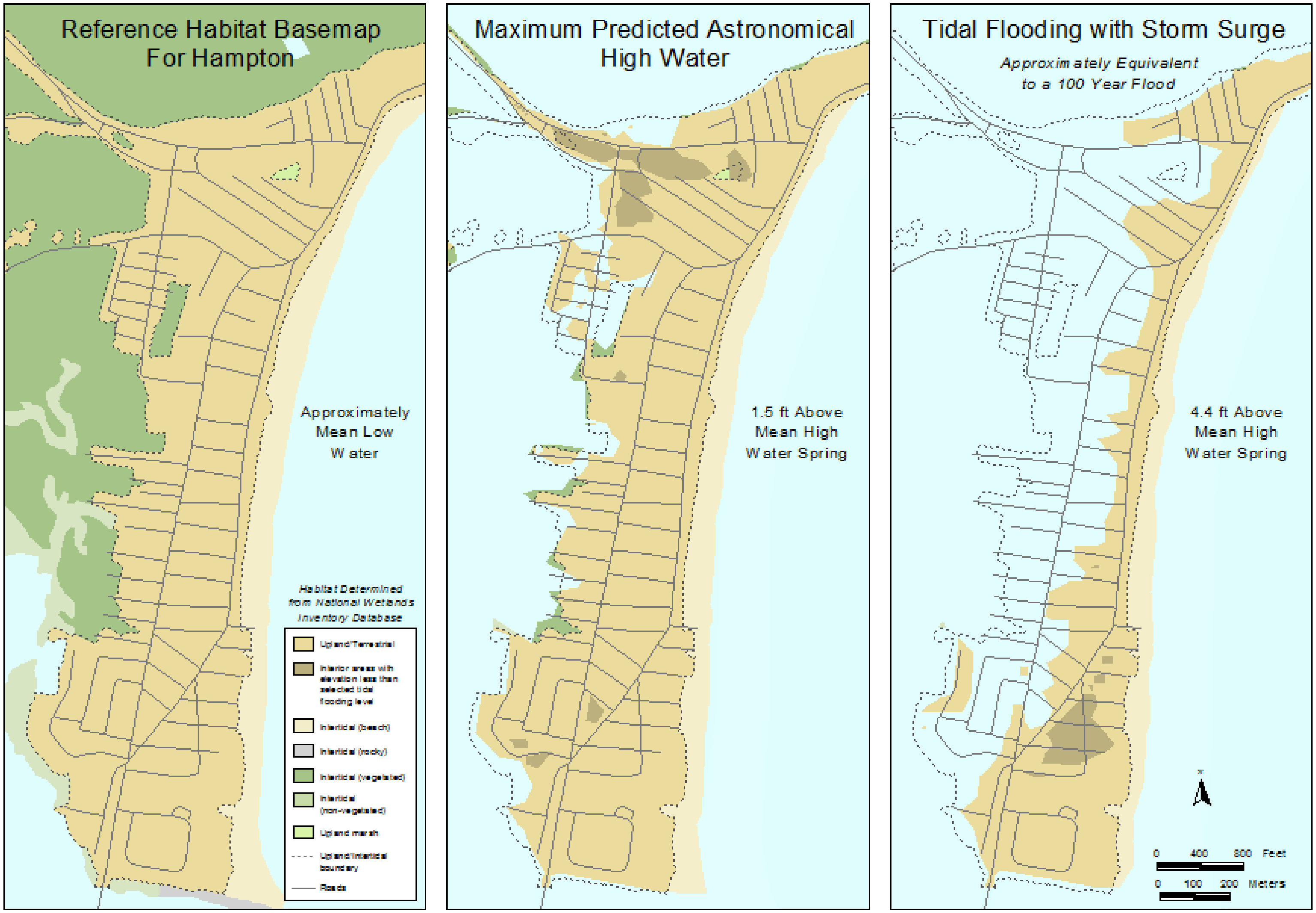


Figure 13. Maps illustrating low-lying areas around Hampton Beach below tidal flooding elevations for maximum predicted astronomical water and approximately a 100-year tidal flooding event.

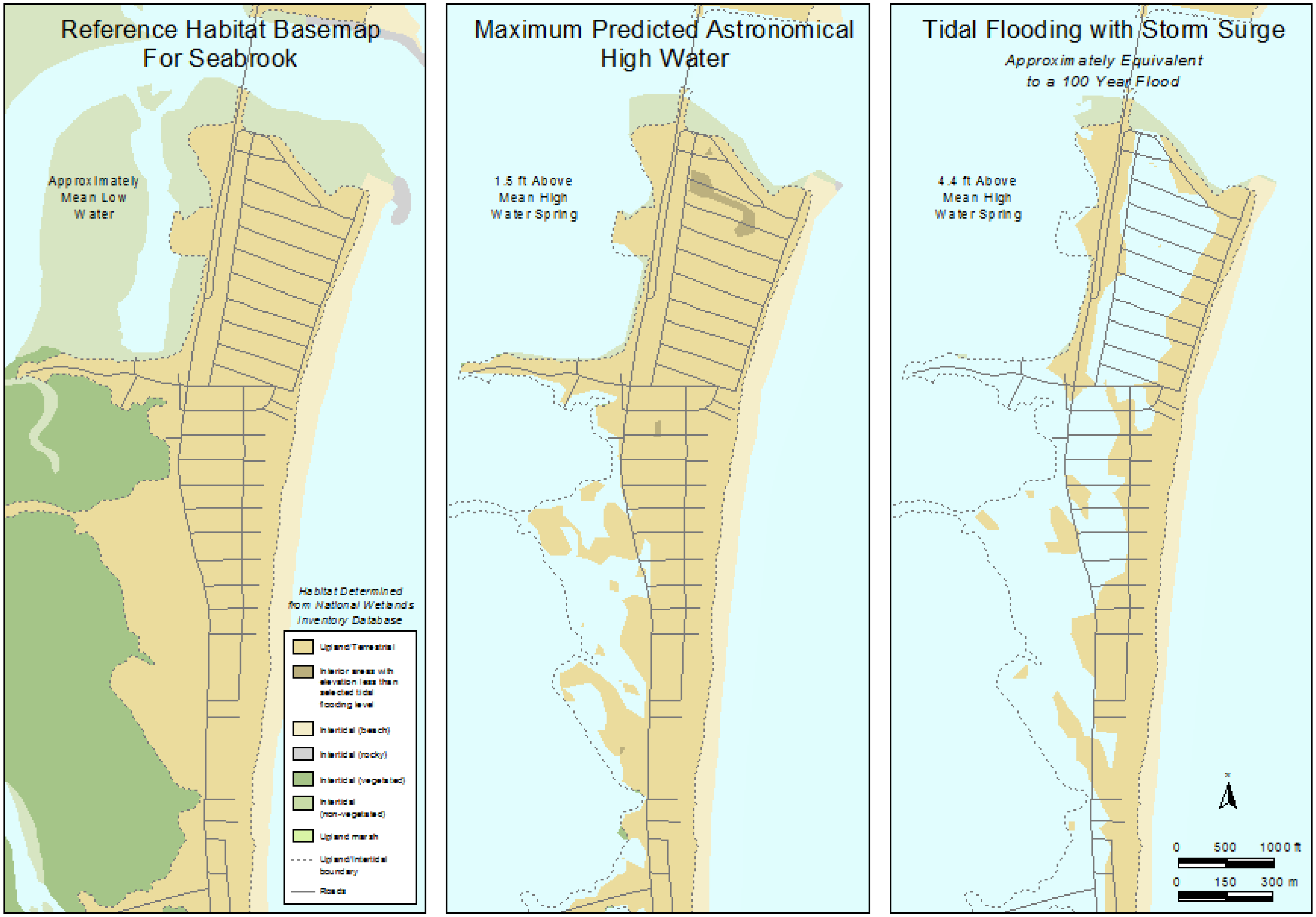


Figure 14. Maps illustrating low-lying areas around Seabrook Beach below tidal flooding elevations for maximum predicted astronomical water and approximately a 100-year tidal flooding event.

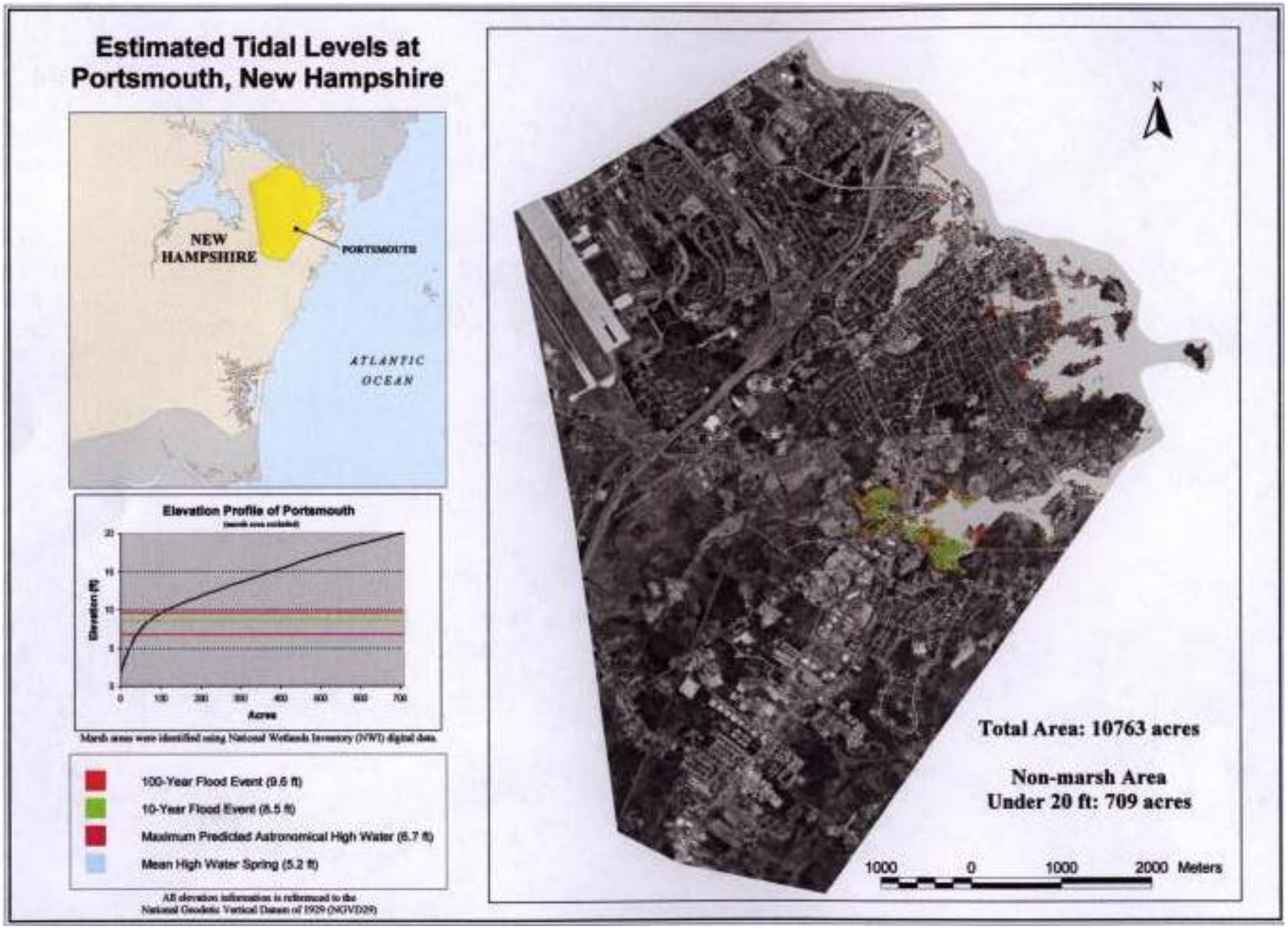


Figure 15. Hypsometric curve for Portsmouth and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

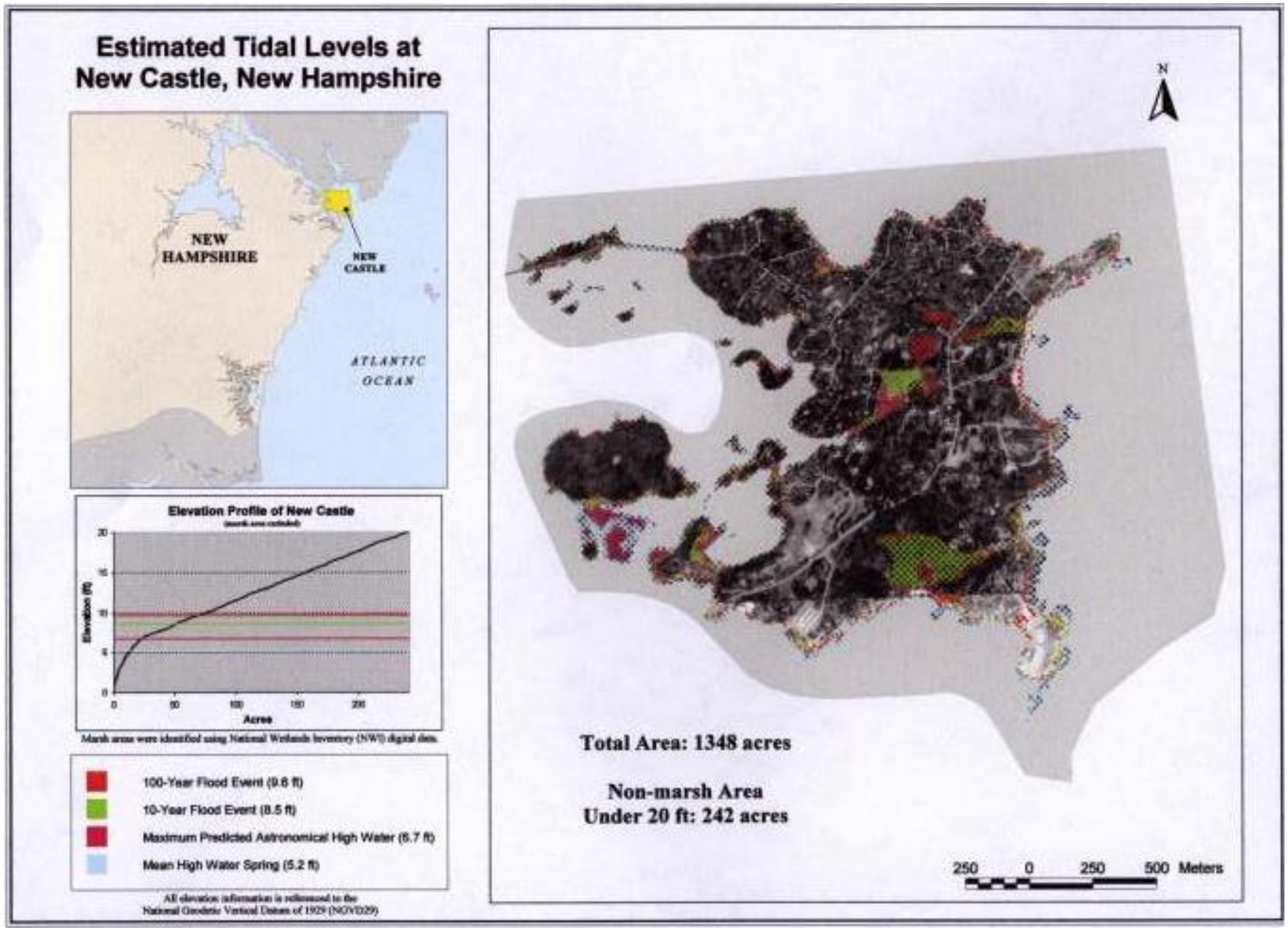


Figure 16. Hypsometric curve for New Castle and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

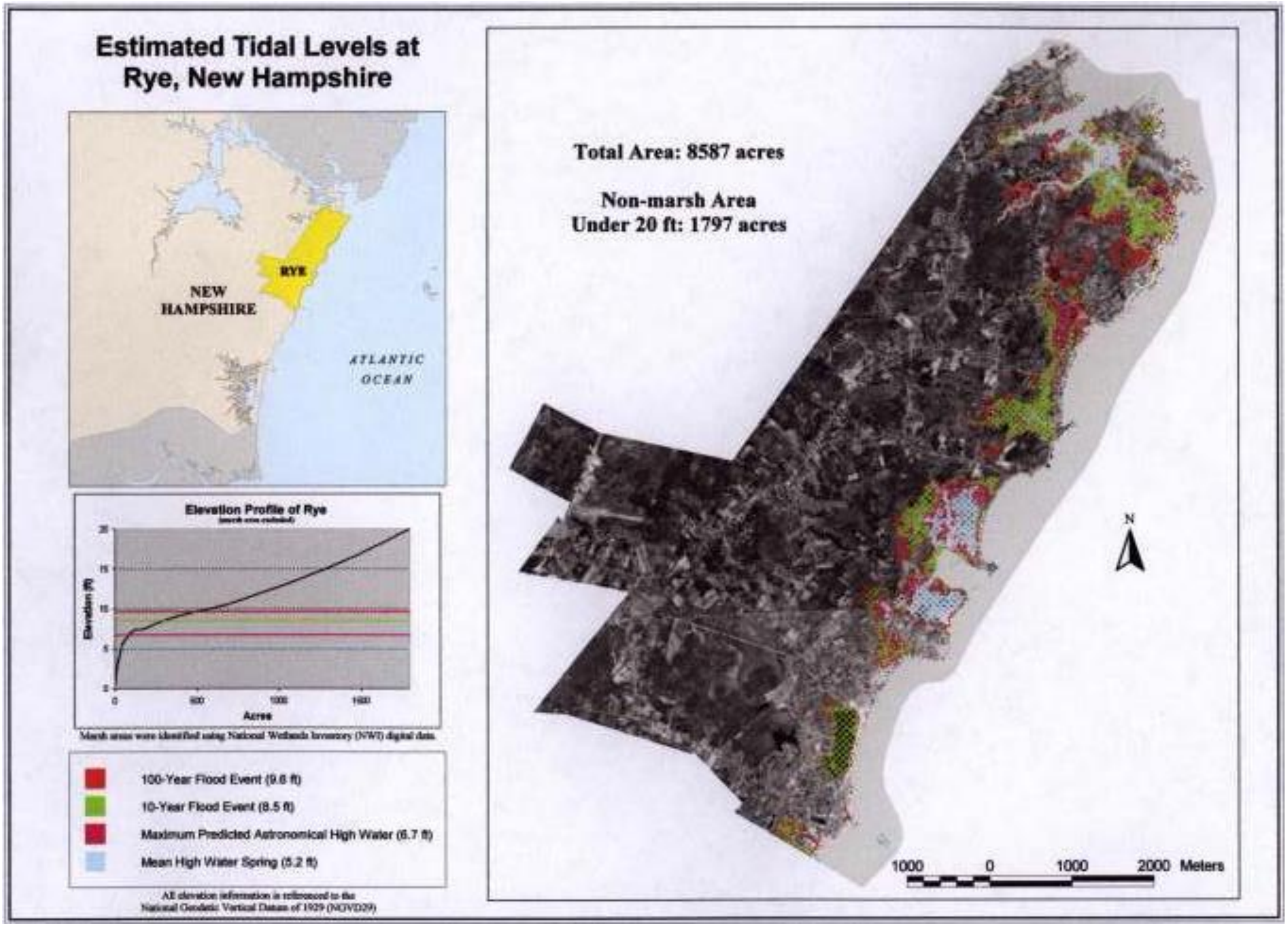


Figure 17. Hypsometric curve for Rye and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

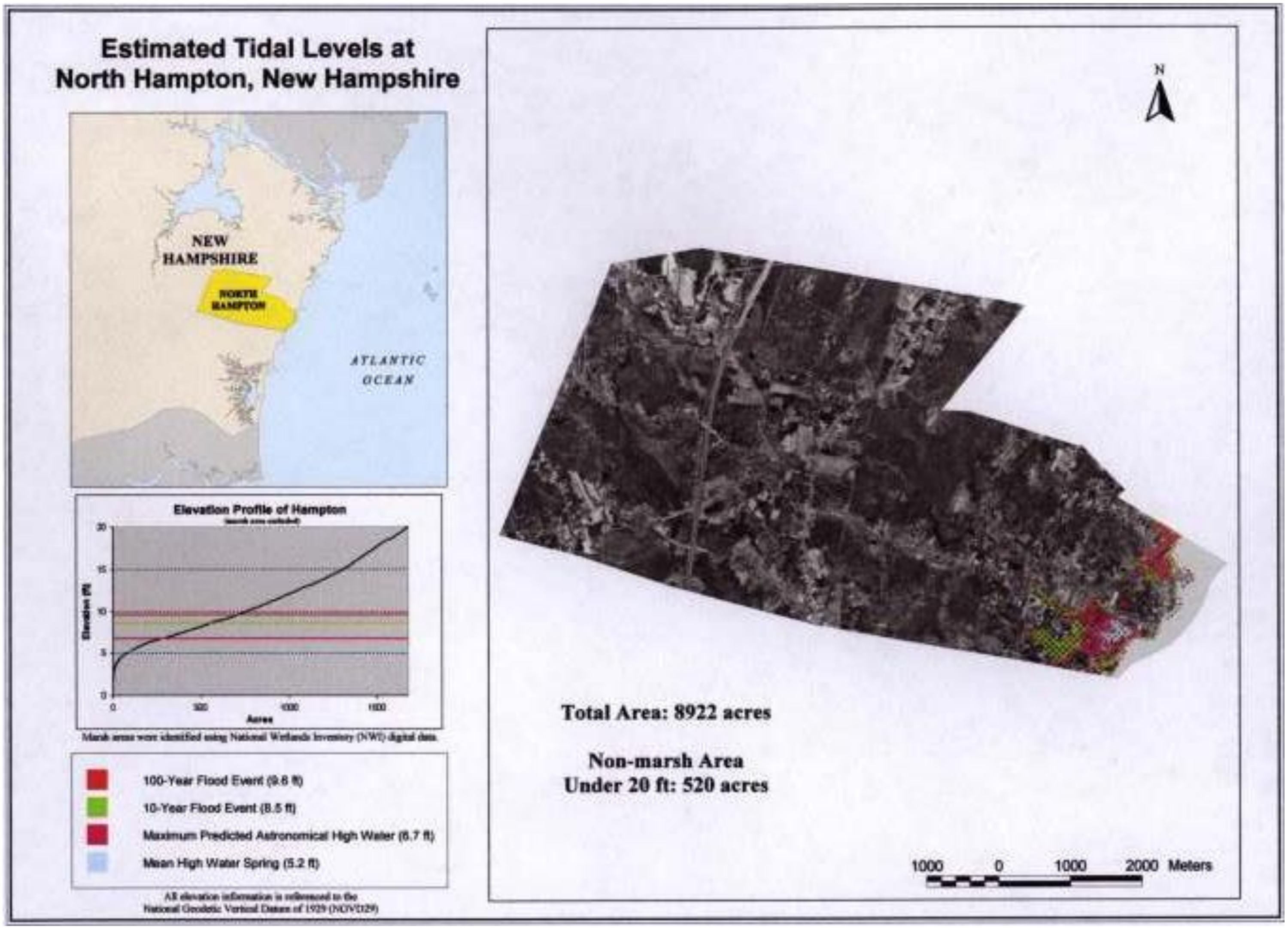


Figure 18. Hypsometric curve for North Hampton and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

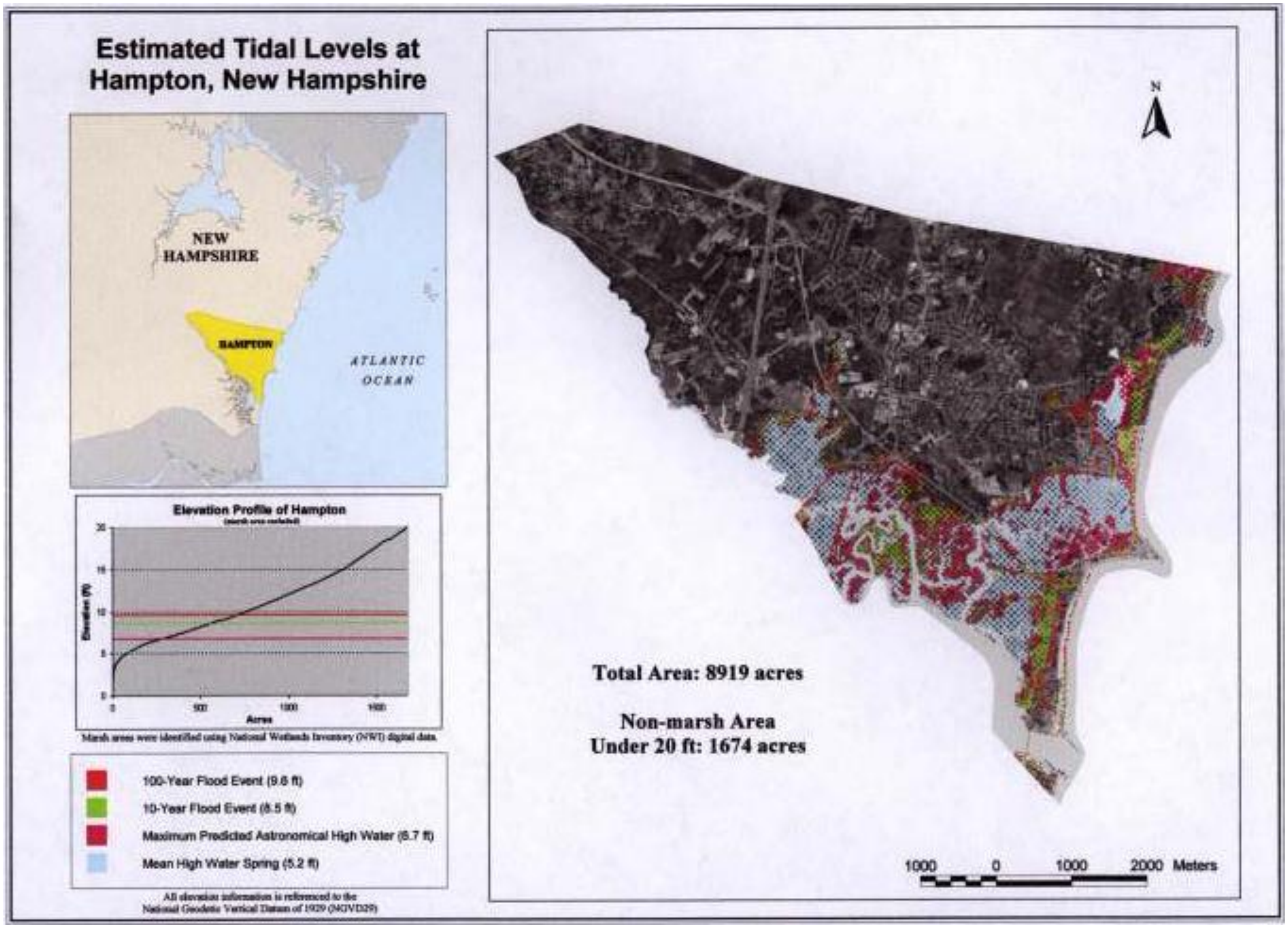


Figure 19. Hypsometric curve for Hampton and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

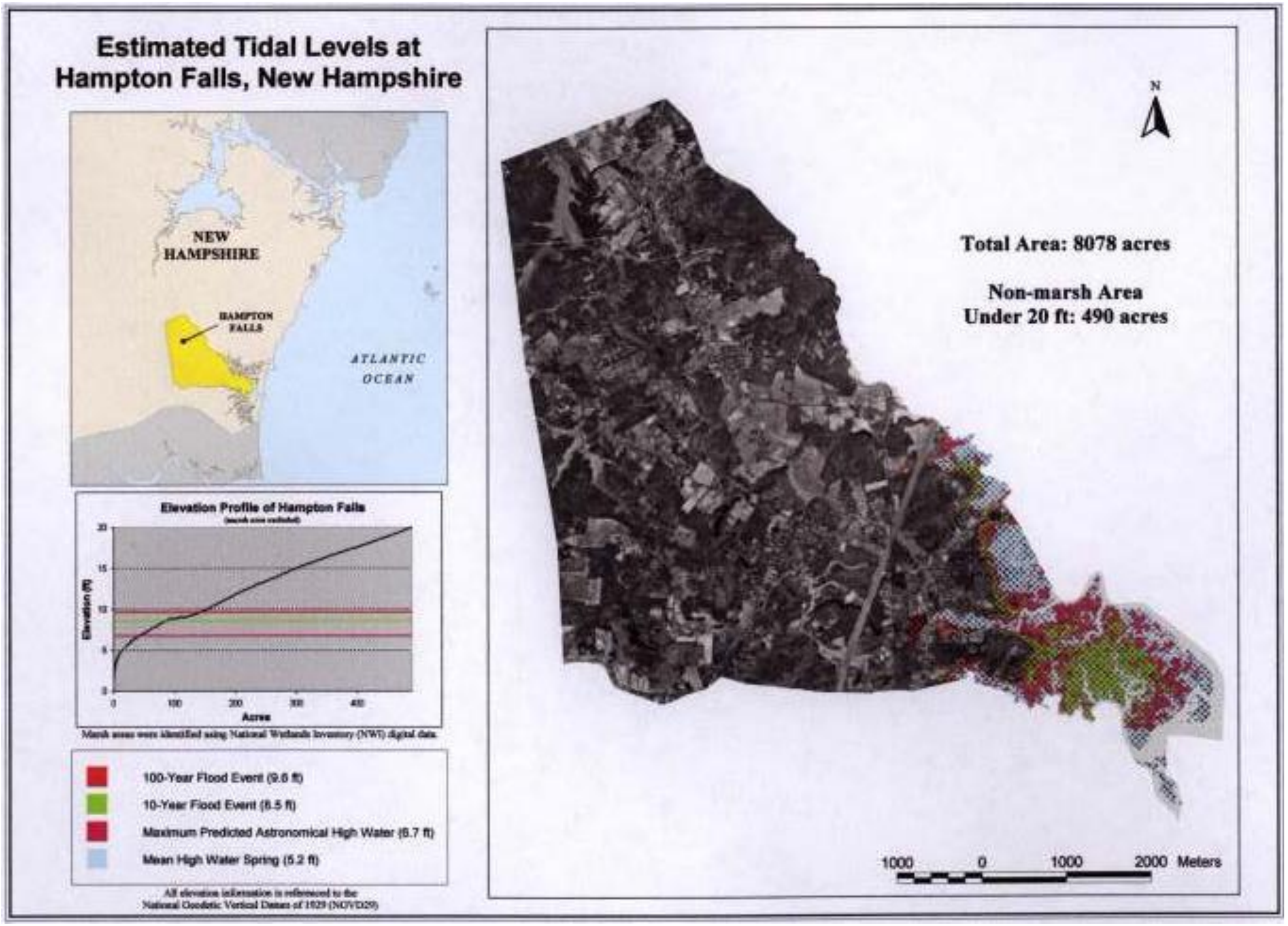


Figure 20. Hypsometric curve for Hampton Falls and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

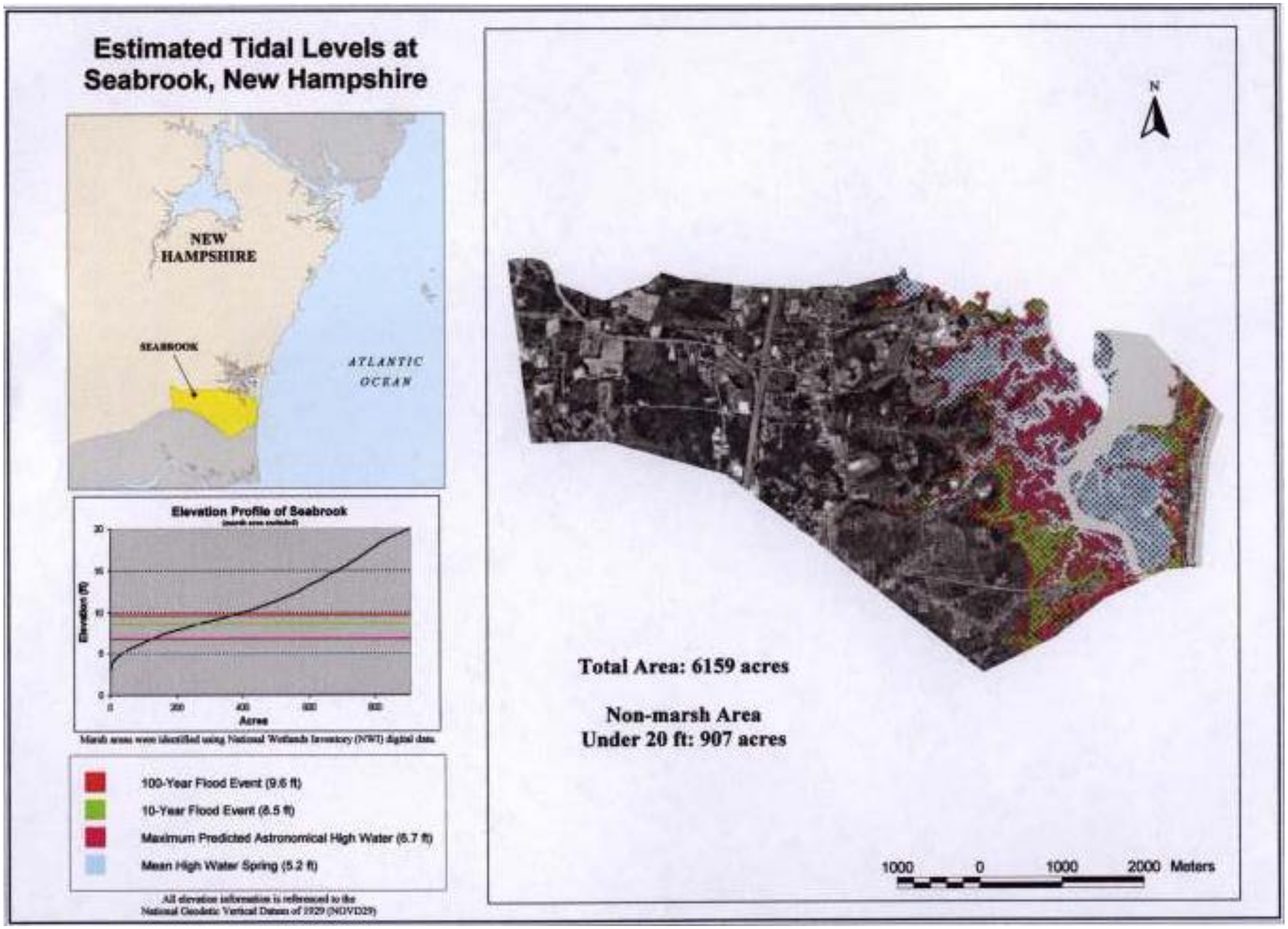


Figure 21. Hypsometric curve for Seabrook and areas with elevation below mean spring high tide, the maximum predicted astronomic high tide and 10-year and 100-year flood event.

CHAPTER FIVE: SEA LEVEL RISE AND COASTAL FLOODING

Present and Future Sea Level Rise

The rate of sea level rise along the New Hampshire coast decreased dramatically starting a few thousand years ago as glacial melting and isostatic adjustments slowed. For example, the sea level curve for nearby Wells, Maine published by Kelley et al. (1995) and shown in Figure 4b indicates the rate of sea level rise was only 0.2 to 0.5 mm/yr (0.008 to 0.020 inches/yr) during the last two thousand years. At the beginning of this period the New Hampshire shoreline had migrated close to its present position and somewhat stabilized (at least in comparison to the highest rates of change) (see Figures 9, 10 and 11). Following this period, the coast began to be sculptured by the waves and tides. In addition, the tidal marshes were forming and growing in size and the coast as we know it today was taking shape (Keene 1970, Trainer 1997, Zaprowski 1998).

However, the slowing of sea level a few thousand years ago is not the end of the story. Evidence suggests the rate of sea level rise has increased again, at least in this century (Figure 4c). Tide gauge measurements made in Portsmouth Harbor show the rate of sea level rise was 2 mm/year (0.079 inches/yr) from 1929 to 1980 (Hicks et al. 1983). Interestingly, even within that short period, the rate of relative sea level rise changes. For instance, averaging the tide record for Portsmouth Harbor for 1940 to 1980 instead of 1929 to 1980 changes the rate of sea level rise from 2.0 mm/yr to 1.3 mm/yr (0.079 to 0.051 inches/yr). In addition, within the entire period there are years when mean sea level was actually lower than the previous year (see Figure 4c). Regardless of the variability over the last several decades, the rate of sea level rise for this period is significantly higher than it was during the previous several thousand years, 1.3 to 2.0 mm/yr compared to 0.2 to 0.5 mm/yr.

It is clear that sea level change is a complex process influenced by a number of factors that operate on various temporal and spatial scales (Emery and Aubrey 1991, Komar 1998). Nevertheless, the most recent studies indicate that sea level is rising today at a higher rate than any other time over the last several thousand years (Gornitz and Lebedeff 1987, Emery and Aubrey 1991). In addition, there is compelling evidence from the Environmental Protection Agency, United States National Academy of Science, and the Intergovernmental Panel on Climate Change that the rate of eustatic sea level rise will increase, perhaps dramatically by the end of this century (Titus and Narayanan 1995).

Although there is considerable variability among reports, Titus and Narayanan (1995) estimate that there is a 50% chance that global warming alone will increase sea level by 35 cm (13.8 inches) by 2100. They further indicate that this estimate is on the low end and there is a 25% chance that sea level will increase by 80 cm (31.5 inches) and a 1% chance sea level will increase by 104 cm (41.0 inches) by 2100. Titus and Narayanan also project the rate of sea level rise will be between 4 mm/yr or 0.158 inches/yr (50% chance) to 10 mm/yr or 0.394 inches/yr (1% chance). These sea level rise rates represent a doubling to a 5-fold increase in the present rate by the end of this century.

It should be noted that the projections by Titus and Narayanan (1995) for sea level rise are fairly conservative in comparison to several other reports. It also should be noted that predicting global warming and sea level rise is difficult and there are some who argue that the scientific community does not have enough evidence to predict the magnitude of future sea level change. In fact, some argue that the changes we are seeing are related to natural cycles and unrelated to global warming. Despite the arguments, most studies indicate we can expect an increase in eustatic or global sea level of at least two or three feet by the end of this century (2100). Therefore, it is prudent to incorporate an understanding of both the probability and the magnitude of sea level rise for future planning.

It is important at this point to place in perspective the potential impact of sea level rise over the next century. An increase of two or even three feet in mean sea level by 2100 in itself does not seem overwhelming and certainly some time off. Although the magnitude of these changes are small in comparison to the large scale changes that have occurred in the last 12,000 years (see Figures 9, 10 and 11), they are important because of the present extensive infrastructure found along today’s coastline. In addition, and important to studies of coastal flooding, the increase in mean sea level raises the base level from which astronomic tides, storm surges, and waves flood the coastal environment. For instance, if a conservative estimate of sea level rise of two feet occurs, then the flood level estimated by the US Army Corps of Engineers (1999) for the Hampton area for a 10-year event will increase and become greater than the present 100-year flood!

Coastal Areas with Elevations Below Selected Tidal Flooding Elevations after a Two-Foot Sea Level Rise (Portsmouth, Hampton and Seabrook)

In order to assess how the potential rise in sea level could effect Portsmouth, Hampton and Seabrook, a series of maps (Figures 22, 23 and 24) were prepared that show the projected change in the area of land lower than the level of mean high water spring following a two-foot rise in mean sea level. Examination of Figure 12, 13 and 14 indicate this elevation is close to the boundary between the upland (terrestrial) and the marine environment in many places. In order to develop these maps, it was assumed the same magnitude of astronomic tidal flooding and storm surges that occur today will continue to occur at the end of this century (Table 3). Also, the coastal morphology and topography (elevations) will remain essentially the same as today. Although the assumptions that there will be no significant change by the end of this century to the coastal morphology or to the tidal flooding characteristics of the coast due to tides and storms is probably unlikely, assessing the additional areas that may be subjected, or at least at risk, to flooding is instructive.

The possible impact of a two-foot sea level rise also can be inferred from the hypsometric analyses. It is assumed for this exercise that the two-foot increase in mean water level will simply be added to the 10-year and 100-year tidal flood elevations. This increases the 10-year flood elevation from 8.5 feet to 10.5 feet and the 100-year flood elevation from 9.6 feet to 11.6 feet. The hypsometric curve for Portsmouth indicates the amount of low-lying land (non-marsh) with elevations above mean sea level, but less than a 10-year flood after a two foot rise in sea level increases by 70 acres or essentially doubles (from 70 to 140) (see Table 4); the area lower than a 100-year flood increases by 89% or 91 acres (from 102 to 193). Hampton and Seabrook’s increase is a somewhat smaller percentage, but has more acreage.

Low-lying areas (non-marsh) below the 10-year tidal flood elevation after a two-foot rise in mean sea level in Hampton increases by 50% or 274 acres (from 551 to 825); the area lower than the 100-year flood increases 34% or by 241 acres (from 709 to 950). The area of land in Seabrook with elevations below the 10-year flood level after a two-foot sea level rise increases by 66% or 176 acres (266 to 442); the increase for the 100-year flood is 41% or 150 acres (367 to 517).

Although the impact of sea level rise on tidal marshes was not assessed in this report, the steep upland areas characteristics of much of New Hampshire's coastal region may inhibit the landward transgression of the tidal wetlands as sea level rises. This problem will be exacerbated in locations where bulkheads, causeways and other man-made structures interfere with the transgression. Also, if the rate of sea level rise increases dramatically, then the salt marshes may not be able to match the change in vertical elevation. The Environmental Protection Agency warns that coastal marshes are very susceptible to sea level rise and substantial tidal wetland areas may be lost (Titus 1991). Therefore, the susceptibility of New Hampshire's tidal wetlands should be assessed in future studies.

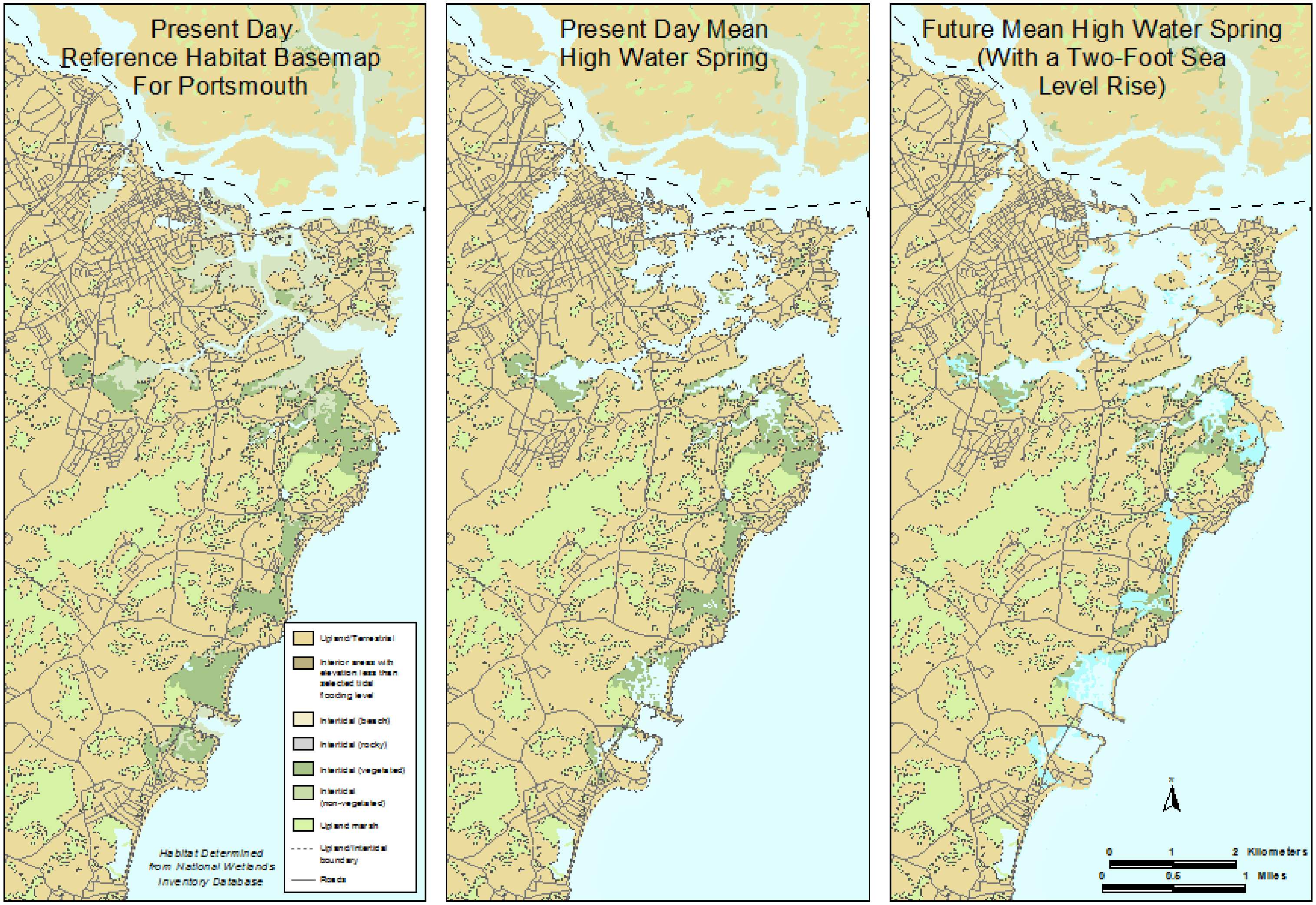


Figure 22. Maps illustrating low-lying areas in and around Portsmouth with elevations below mean high water spring before and after a two-foot rise in mean sea level. Darker blue indicates additional areas with elevations below mean high water spring after the two-foot sea level rise.

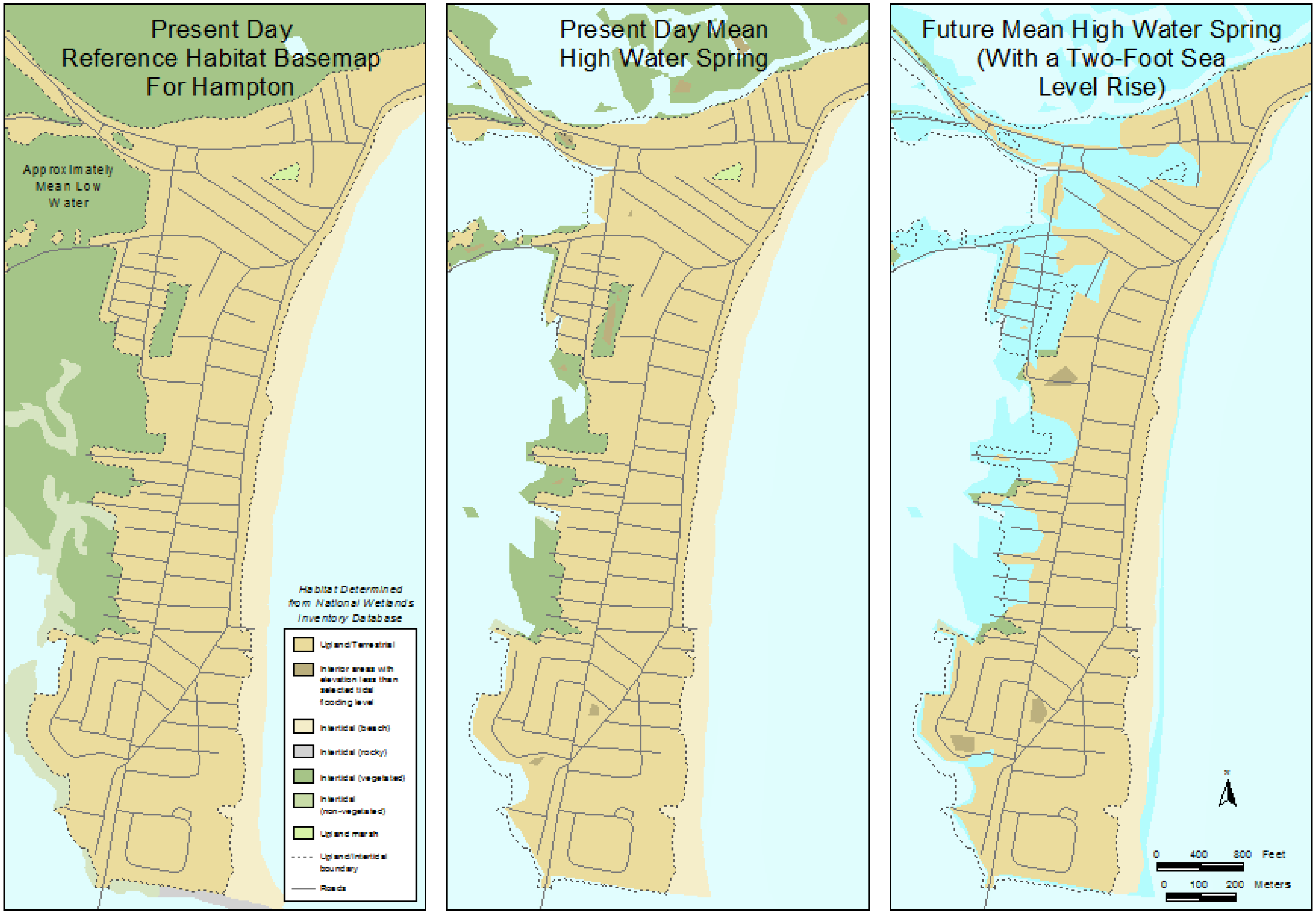


Figure 23. Maps illustrating low-lying areas in Hampton Beach with elevations below mean high water spring before and after a two-foot rise in mean sea level. Darker blue indicates additional areas with elevations below mean high water spring after the two-foot sea level rise.

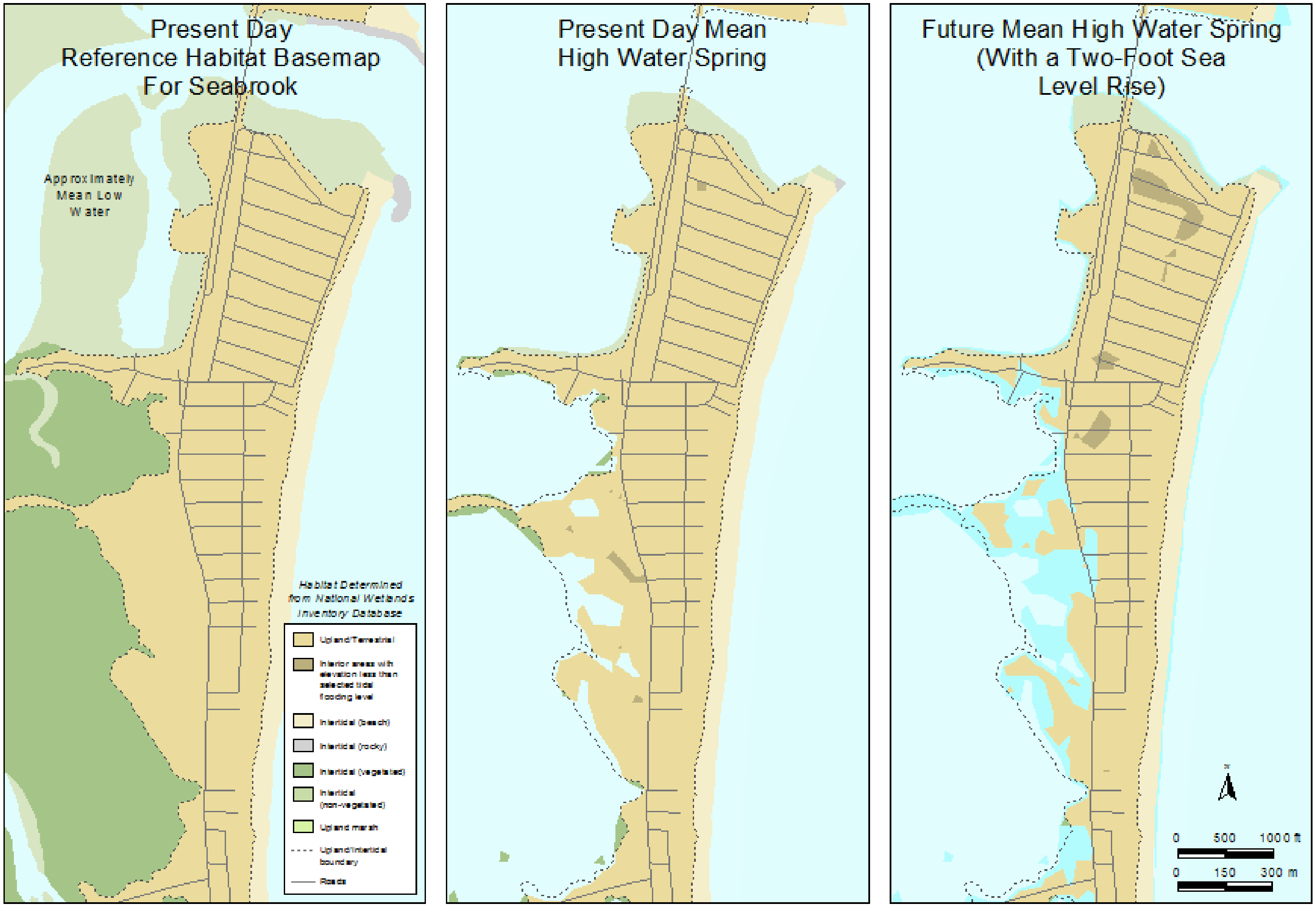


Figure 24. Maps illustrating low-lying areas in and around Seabrook Beach with elevations below mean high water spring before and after a two-foot rise in mean sea level. Darker blue indicates additional areas with elevations below mean high water spring after the two-foot sea level rise.

CHAPTER SIX: CONCLUSIONS

This study utilized GIS technologies and hypsometric analyses to: 1.) assess the long term changes in New Hampshire's shoreline due to sea level fluctuations; 2.) develop a preliminary assessment of coastal areas at risk due to low elevations to present day tidal flooding in Portsmouth, Hampton and Seabrook; and 3.) assess increases in areas at risk to tidal flooding in the future (~2100) due to sea level rise. Although additional work is needed to refine the results and improve the accuracy and detail of the mapping, several preliminary conclusions are given below. In view of the possibility of accelerated sea level rise due to global warming and changes that are likely to occur along the New Hampshire coast over the next several decades to centuries, these results are particularly timely.

1. The coast of New Hampshire has probably migrated on the order of 40 kilometers over the last 12,000 years in response to relative sea level changes.

2. Evaluation of land areas at risk due to their elevations being below the 10-year and 100-year tidal flood levels at present indicate limited impact in Portsmouth, but substantial low-lying areas in Hampton and Seabrook. However, some of these low-lying areas are surrounded by topographic highs or tidal restrictions that would effect tidal flooding. Consequently, more refined analyses of the risk of coastal flooding are warranted.

3. A two-foot rise in sea level by the end of this century (2100) will increase the amount of land area (non-marsh) above present mean sea level with elevations lower than the 10-year and 100-year tidal flood levels on the order of 34% to 100% along the New Hampshire coast. These results indicate it would be prudent to incorporate an assessment of the impacts of sea level rise in future planning.

4. GIS technologies provide useful tools to develop surface elevation models and to identify areas with elevations below selected tidal flood levels. However, determination of actual flood risks, now and in the future, will require a more refined approach.

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APPENDIX 1

Holocene Changes in Shoreline Positions

The following provides the series of the tasks that were needed to create a surface elevation model of the coast and inner shelf of New Hampshire and then manipulate the elevation model in order to illustrate shoreline migrations.

A. Obtain topography for NH coastal region and bathymetry for NH Shelf, Great Bay Estuary and Hampton Harbor.

1. New Hampshire Shelf bathymetry.
    - a. Download New Hampshire shelf bathymetry from the Gulf of Maine Information page (see Table 2 for the web site).
    - b. Create boundary coverage to limit the area of interpolation and to crop datasets.
    - c. Convert the downloaded text file into ArcInfo coverages.
    - c. Clip with the boundary coverage to minimize input data.
    - d. Interpolate an ArcInfo GRID surface model from point features within boundary.
2. Great Bay bathymetry.
    - a. Download Great Bay bathymetry from NOS estuarine bathymetry archive in DEM format (see Table 2 for the web site).
    - b. Convert DEM format to ArcInfo format.
3. Hampton Harbor bathymetry.
    - a. Download Hampton Harbor bathymetry in the ASCII text file from UNH's Ocean Engineering's Hampton Harbor web site (see Table 2 for the web site).
    - b. Import the information into ArcInfo and create point coverage.
    - c. Create the following additional data to help interpolation:
        - 1. a zero elevation contour to maintain the shoreline,
        - 2. a boundary coverage to limit the interpolation area.
    - d. Interpolate an ArcInfo GRID surface model from point features.

4. NH coastal region

    a. Download NH/ME 7.5 minute Digital Elevation Models from the USGS (see Table 2 for the web site).

    a. Download the data in Federal Governments SDTS (Spatial Data Transfer Standard) format.

    b. Convert the data from SDTS to ArcInfo's GRID format.

    c. Mosaic the models into one continuous surface.

    d. Fill gaps in data created by the mosaic process.

B. Merge bathymetric and topographic datasets into single surface elevation model.

1. Correct vertical datum of bathymetric models to match that of terrestrial model (NGVD 29).

- Offshore & Great Bay Estuary: Mean Low Water, -4.2 ft (Casco Bay, Portland Ref.)
- Hampton Harbor: NAVD 88 +0.72 ft (VERTCON – vertical datum correction tool - http://www.ngs.noaa.gov/TOOLS)

2. Resample data to uniform cell size (100 ft).

3. Merged data to create continuous model referenced to NGVD29.

4. Filtered data to smooth out transitions and make more presentable.

C. Alter Shoreline Positions to Different Elevations.

1. Manipulate the position of the shoreline for the chosen time periods by adding or subtracting values based on the sea level curve shown in Figure 4a.

    a. For the period from 12,000 BP to 11,500 BP subtract the selected elevation to simulate a higher shoreline position.

    b. For the period from 11,500 BP to present, add the selected elevation to simulate a lower shoreline position.

(Use a single color scheme to give the models context relative to the new shoreline position.)

APPENDIX 2

Identification of Coastal Areas with Elevations Below Selected Tidal Flooding Elevations

The following provides the series of the tasks that were needed to create a surface elevation model (SEM) of the coast of New Hampshire and then manipulate the elevation model in order to illustrate those areas below selected tidal flooding levels.

A. Obtain topography for NH coastal region from U.S. Army Corp of Engineers (see Table 2 for source).

B. Create surface elevation model for NH coast from mean sea level to 24 feet.
1. Assemble data into TIN model using ArcInfo.
2. Obtain additional information that will be needed to maintain land/water boundaries:
    a. a zero contour to maintain the shoreline.
    b. additional points of zero elevation to maintain the water surface:
        – low density for offshore areas.
        – high density for harbors and estuaries (Rye, Portsmouth, Hampton).
    c. a boundary polygon to limit the area of interpolation.
3. Reassemble the data with the control information included.
4. Convert the TIN format to a GRID format.
5. Edit the GRID model to reestablish broken roadways.

C. Flood surface elevation model to desired elevations to mimic coastal flooding
1. Query the elevation models for values equal to and less than the tide level of interest to create a layer that when colored will simulate the area covered by tidal flooding.
2. Combine the colored layers for various flood levels and the surface elevation models to show flooding levels.

APPENDIX 3

Development of Hypsometric Curves for New Hampshire Coastal Townships

The following provides the series of the tasks that are needed to create hypsometric curves for New Hampshire's townships bordering the Atlantic Ocean and lower Portsmouth Harbor (Portsmouth, Newcastle, Rye, North Hampton, Hampton, Hampton Falls and Seabrook).

A. Obtain topography for NH Coastal Surface Elevation Model, State of NH Town Boundaries Coverage, and NWI Digital Wetlands Coverage.

1. See Appendix 2 for development of NH coastal surface elevation model.
2. Download NH political/administrative boundaries from GIS Data Depot at http://www.gisdatadepot.com.
3. Download NWI digital wetland coverage from GIS Data Depot (see above).

B. Create Hypsometric Curves

1. Resample the ACOE model from 30x30ft cells to 90x90ft cells.
2. Convert the 90x90ft model to a point coverage coded for elevation.
3. Use the town boundaries coverage to divide the points into town units.
4. Use the NWI coverage to divide the points into marsh/non-marsh units.
5. Export attribute data from point coverage for each town, excluding marsh data.
6. Import data into Excel.
7. Sort data based on elevation from least to greatest up to 20ft.
8. Add area column based on square cell size (90x90ft = $8100ft^2$ = 0.186 acres): increment up to maximum elevation (20ft).
9. Create XY line graph of elevation (Y) vs. Area (X).
10. Add horizontal guides marking various tidal or flooding levels including:
    - Mean High Water Spring.
    - Maximum Predicted Astronomical High Water.
    - 10-Year Frequency Flood Event.
    - 100-Year Frequency Flood Event.

11. Export to image files for use in ArcView.
12. Query elevation model for above mentioned tidal levels (step 10).
13. Display queried tidal levels with hatch pattern over air-photo base to represent inundated areas.