Identify, Interpret, Integrate

FEMA Region I Coastal Erosion Study – Rockingham County

June 30, 2022

Prepared for:

Federal Emergency Management Agency
US Department of Homeland Security
FEMA Region 1
99 High Street, Sixth Floor
Boston, MA 02110

Submitted by:

Compass PTS JV
a JV led by AECOM and CDM Smith
3101 Wilson Boulevard, Suite 900
Arlington, VA 22201

Document History

Revision History

Version Number	Version Date	Summary of Changes	Team/Author
1.0	May 25, 2022	Draft	Jeremy Mull, P.E./Elena Drei-Horgan, C.F.M./Amanda Oi, E.I., C.F.M.
2.0	June 30, 2022	Final Draft	Jeremy Mull, P.E. /Amanda Oi, E.I., C.F.M.

Review History

Version 1.0 of this document has been reviewed by the following persons:

Role	Organization/Name	Title	Review Date
Quality Assurance Review	Compass /Darryl Hatheway, C.F.M.	Coastal Scientist	June 21, 2022

Client Distribution

Client	Organization	Location
FEMA Region I Risk Analysis Branch Chief	FEMA	FEMA Region I

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List of Acronyms

DEM	Digital Elevation Model
DOC	Depth of Closure
EPR	Endpoint Rate
ESRI	Environmental Systems Research Institute
FEMA	Federal Emergency Management Agency
FIMA	Federal Insurance and Mitigation Administration
FIRM	Flood Insurance Rate Map
LiDAR	Light Detection and Ranging
LRR	Linear Regression Rate
GIS	Geographic Information Systems
HWL	High Water Line
MHHW	Mean Higher High Water
MHW	Mean High Water
NAVD88	North American Vertical Datum of 1988 (NAVD88)
NOAA	National Oceanographic and Atmospheric Administration
NCMP	National Coastal Mapping Program
NPF	Natural Protective Feature
NYDEC	New York Department of Environmental Conservation
SFHA	Special Flood Hazard Area
SLR	Sea Level Rise
TMAC	Technical Mapping Advisory Council
TWL	Total Water Level
USGS	U.S. Geological Survey

01 Introduction

Coastal erosion is a hazard that threatens lives, property, and resources along much of the US coastlines (Figure 1). According to the Technical Mapping Advisory Council (TMAC), erosion is generally expected to accelerate due to future sea level rise (SLR), putting more areas at risk (TMAC 2015). To help address the risk that this poses to communities, Compass has completed a Study, funded by the Federal Emergency Management Agency (FEMA) Region I, to investigate future coastal erosion due to SLR and produce future coastal erosion hazard maps. These maps consider multiple SLR scenarios and future timeframes to provide stakeholders with information to plan mitigation actions and build resilience in the face of a changing climate. The technical analysis and mapping were initiated in a Pilot Study of distinct shorelines in Massachusetts, Rhode Island, and New Hampshire. After completion of the Pilot Study, the technical analysis and mapping were expanded to other areas of Region I. This report summarizes the overall purpose of this Study and the technical methodology and the findings for Rockingham County, New Hampshire. The maps are recommended as non-regulatory products to be used by communities as a tool to identify areas where coastal erosion is a hazard, plan future mitigation actions and ultimately facilitate the reduction of future erosion risk.

Figure 1. An example of coastal bluff erosion that has since been armored. Historical coastal bluff erosion has destroyed homes, roads, and other resources in this area. The example is from the shore of North Hampton, New Hampshire, and there are several similar sites throughout New England.

1.1 Study Purpose

The general purpose of this Study was to develop future coastal erosion hazard area maps for Rockingham County, New Hampshire. Compass applied a technical methodology, developed in a previous Pilot Study of sections of coastline in Massachusetts, Rhode Island, and New Hampshire, to analyze historical trends in shoreline change, evaluate multiple future SLR projections and timeframes, estimate future erosion rates, produce Flood Risk (i.e., non-regulatory) maps of future coastal erosion hazard areas, and synthesize a technical approach that could be expanded to other areas (Compass 2017). The overall Study and maps also meet several detailed objectives and fulfill multiple critical needs. Most importantly, there is a need for coastal communities to understand their risk from future SLR. Currently, FEMA Flood Insurance Rate Maps (FIRMs) only show the current flood risk to the 1-percent-annual chance coastal storm event for each particular area of the coast. They do not account for future SLR or long-term coastal erosion. Therefore, they are missing key information on a significant coastal hazard. Many communities look to FEMA as an authority on flood risk due to extreme coastal storms and it makes sense that FEMA would provide information on risks due to SLR. During some public meetings, community members have requested that FEMA investigate SLR and provide information on mapping products.

The Study and maps also meet multiple agency goals. In 2017, The Federal Insurance and Mitigation Administration (FIMA) began proposing two “moonshots” for the future. These ambitious goals include doubling the amount of insurance policies and quadrupling the amount of mitigation actions by the year 2023. Furthermore, the TMAC completed a study and found that future coastal erosion and SLR most likely pose a significant risk to homeowners (TMAC 2015). The final report made recommendations that FEMA provide Flood Risk products with information on future conditions, specifically SLR and coastal erosion. Finally, the Heinz Center completed a study also concluding that coastal erosion posed a significant risk to communities and had a significant negative impact on the National Flood Insurance Program (NFIP), recommending that FEMA begin to investigate coastal erosion (Heinz Center 2000). This Study can help meet all of these agency goals and recommendations.

Finally, the Study and maps meet several technical objectives. In terms of size and scope, no similar studies of future coastal erosion due to SLR have been completed in the New England area. Although different agencies have investigated future coastal flooding and inundation due to SLR, none have addressed the related but distinct hazard of future shoreline retreat. This is important to highlight because there are several communities at relatively high coastal bluff elevations that are not directly vulnerable to future coastal flooding, per se, but are directly vulnerable to future coastal bluff retreat. Investigating only future flooding due to SLR likely underestimates the risk that these communities face. There have also been investigations into future shoreline change, but these rely on historical rates of erosion and do not incorporate the effects of future SLR. SLR is widely expected to accelerate coastal erosion and excluding this component most likely underestimates the risks. This Study presented an opportunity for FEMA to develop and apply a study methodology that incorporates these aspects and that can be expanded to other Regions. STARRII (2017) provided a review of SLR pilot studies conducted for FEMA in other regions. This Study also meets several specific TMAC technical recommendations, which are discussed later in this technical report.

1.2 Technical Study Elements

Compass filled in several technical gaps to develop a new methodology that is technically sound and applicable to the remaining Region I shoreline. These aspects are summarized in some detail in Section 2 (Technical Methodology), presented in full detail in the Pilot Study Report (Compass 2017), and are briefly listed here:

Sea Level Rise: The Study produced future coastal erosion hazard areas that account for historical trends in shoreline change and also account for future projections of SLR. The Study uses the National Oceanic and Atmospheric Administration (NOAA) SLR projections, developed in 2017, as recommended by TMAC (2015). The global SLR projections were adjusted for local conditions.

Multiple Timeframes: The Study incorporated multiple future time frames (2030, 2050, and 2100) to meet the needs of different community members. Shorter timeframes (2030 and 2050) were included to be of use to current home mortgage holders and longer timeframes (2100) were included to be of use to community planners and engineers.

Coastal Bluff Erosion: In addition to sandy beach and dune erosion, the Study analyzed and predicted future rates of coastal bluff erosion. This is critical as several communities, particularly in North Hampton and Rye, New Hampshire, have been developed on tall coastal bluffs. Structures and lands within these communities will not be threatened by flooding due to future SLR, but will be vulnerable to bluff retreat due to future SLR.

Historical Shoreline Change Datasets: Compass analyzed historical (i.e., observed) rates of shoreline change at sandy dunes, beaches, coastal marshes, and coastal bluffs. Instead of a simple endpoint rate (EPR) calculation, which consists of determining the distance between two historical shorelines or bluff edges and using the time between surveys to calculate a rate, Compass used multiple historical data points to determine linear regression rates (LRRs). LRRs take more data into account, reduce the impacts of historical outlier shoreline change events (such as extreme storms or beach nourishments), and are more accurate for long-term trends (Crowell et al. 1997; Crowell and Leatherman 1999; Hapke et al. 2010). In addition, Compass utilized all available historical shoreline and bluff edge data available (from the mid-1800's to 2011). This added more data points, reduced noisy alongshore variability in erosion rates, increased statistical confidence, and captured long-term trends.

Hybrid Erosion Analysis: Compass applied different erosion models at sandy shorelines (e.g., dunes and beaches) and bluff-backed shorelines. These two classes of shoretypes have different geomorphologies and are expected to respond differently to future SLR. After reviewing preliminary mapping, Compass determined that a hybrid erosion model was necessary at coastal bluffs fronted by a wide sandy beach. The bluff-backed beaches on the shoreline of Rye, New Hampshire are an example of one of these areas. At these sites, there are areas of rapid bluff erosion and areas where the beach is eroding but the bluffs have historically been stable. Applying the beach erosion model to these stable bluff areas did not account for the fact that the bluffs, in the future, would erode more slowly than a sandy beach. Compass developed a hybrid erosion model with Study subject matter experts.

1.3 Study Area

The initial Pilot Study areas offered a wide-variety of geomorphological conditions and the opportunity to develop a sound technical approach for different shoretypes. The shoreline geomorphologies included eroding sandy dunes and beaches, accreting sandy dunes and beaches, coastal marshes, rocky ledges, and eroding coastal bluffs. The Rockingham Study site includes the entire open coast shoreline of the Rockingham County (Figure 2). Many areas are developed. The central and southern shorelines are similar and generally consist of steep beaches with pockets of coastal bluffs and rocky ledges. There are sandy beaches and dunes along the shoreline that have been historically stable.

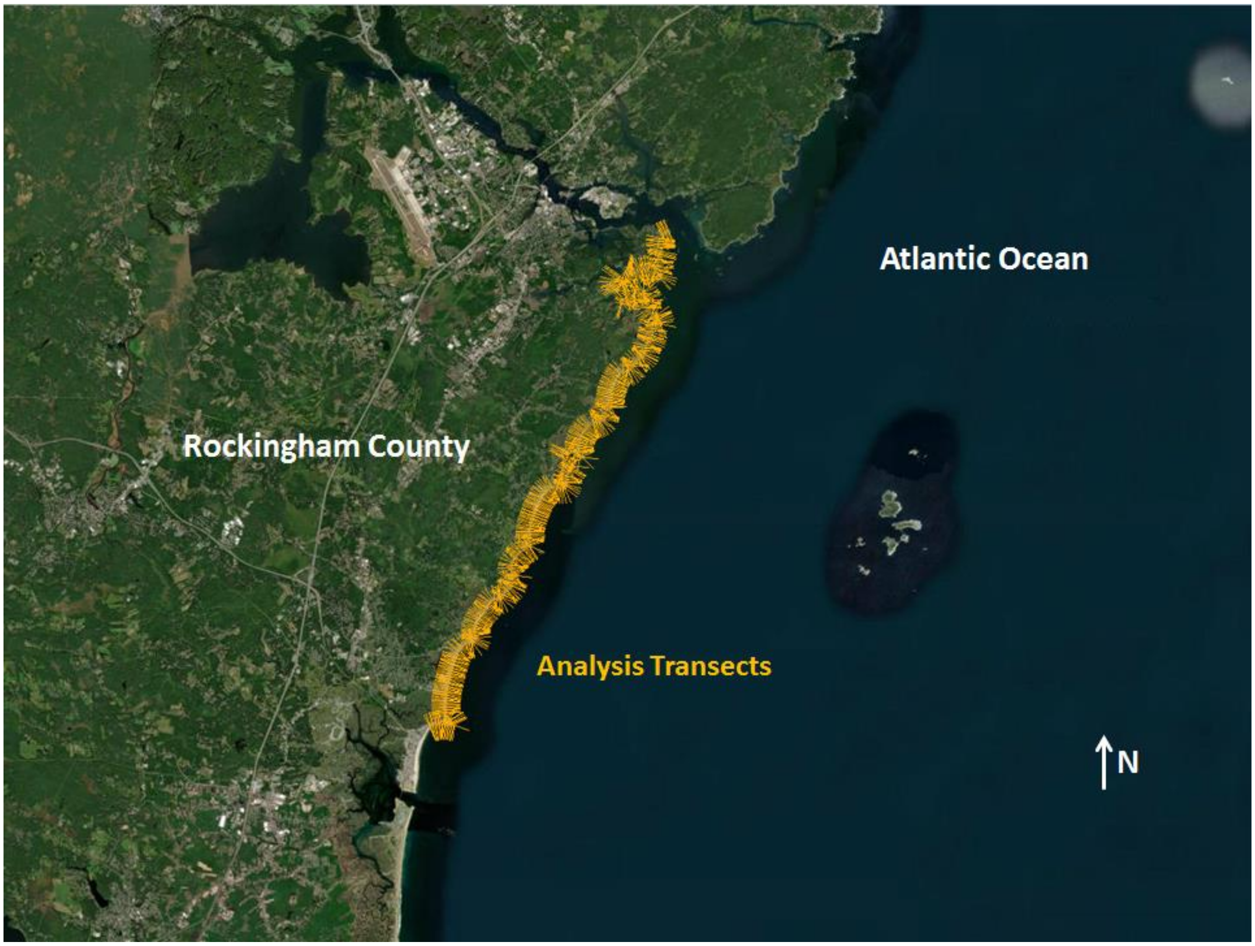


Figure 2. The Rockingham County Study area includes the entire open coast shoreline of Rockingham County.

Within the Study area a variety of specific shoretypes were identified: sandy dunes (Figure 3), sandy beaches (Figure 4), coastal bluffs (Figure 5), coastal marshes (Figure 6), and rocky ledges (Figure 7).

Figure 3. An example of a sandy beach backed by dunes in FEMA Region 1. Coastal dunes are tall, well-formed, and vegetated.

Figure 4. An example of a wide sandy beach in FEMA Region 1. The beach has a low vegetated ridge but no tall, well-formed sand dune.

Figure 5. An example of a sandy beach backed by a tall coastal bluff in FEMA Region 1. Many bluffs in this Region have historically eroded.

Figure 6. An example of a coastal marsh in FEMA Region 1. Coastal marshes are low lying, vegetated land along the shoreline.

Figure 7. An example of a rocky ledge in FEMA Region 1. Rocky ledges are hard coastal rock formations, common in the northeast, that are relatively resistant to wave erosion.

02 Technical Approach

This section provides details on the technical approach developed and applied to determine the historical trends in shoreline change and predict future shoreline change due to SLR.

2.1 General Technical Approach

As the technical approach consisted of many steps, this section provides a general outline. A workflow diagram is presented in Figure 8. Details on each step are presented in the following sections.

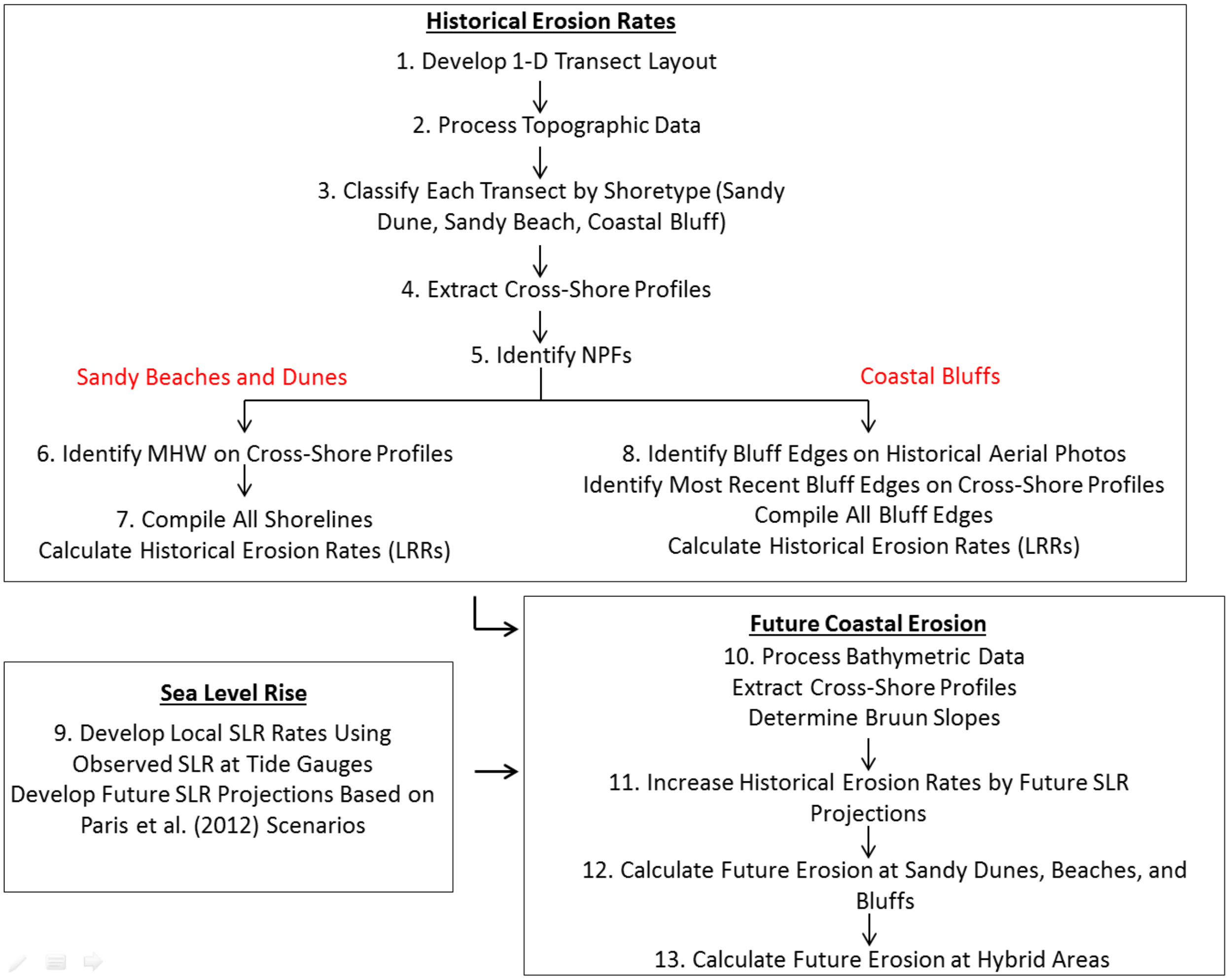


Figure 8. A general workflow diagram outlining the technical analysis steps. Note that coastal marshes were treated as sandy beaches as dunes and rocky ledges were treated as coastal bluffs.

1. Compass implemented a one-dimensional (1-D) transect-based approach, where transects were placed approximately every 50 meters and oriented perpendicular to the shoreline (Figure 9). All analysis and calculations were done along each transect. Compass initially began with the transect layout developed by Hapke et al. (2010) for the U.S. Geological Survey (USGS) National Assessment of Shoreline Change in areas where this previous study had been completed. In areas with no USGS transect layout, Compass placed new transects. After initial placement, transects were then shifted, oriented, added, and removed to suit the specific needs of this Study.
2. Recently collected topographic light detection and ranging (LiDAR) data sets were downloaded and processed for each site. These were used to establish current coastline conditions and provide a baseline for future erosion projections.
3. The transects were classified by shoretype based on the shoreline geomorphology (sandy beach, sandy dune, coastal marsh, rocky ledge, and coastal bluff) using aerial images, a digital elevation model (DEM) developed from the airborne topographic LiDAR data, and field site visits.

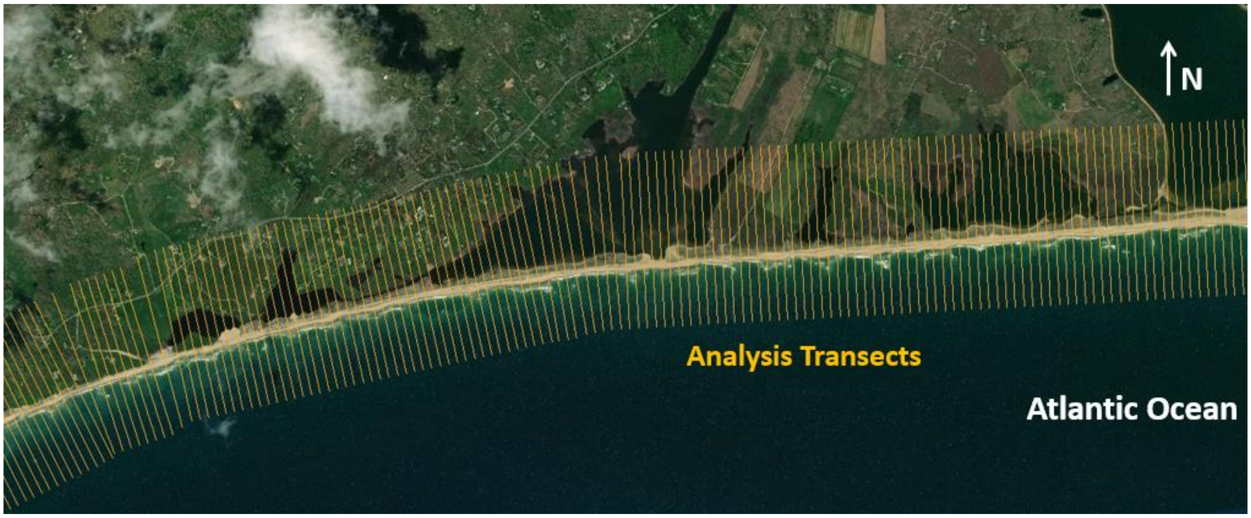


Figure 9. An example of a transect layout along a section of the FEMA Region I shoreline. For this Study, a one-dimensional (1-D) transect-based approach was implemented, where transects were placed approximately every 50 meters and oriented perpendicular to the shoreline.

4. Cross-shore profiles were extracted from the topographic LiDAR data along each transect line.
5. To establish a baseline to project future erosion hazard zones from, the current natural protective feature (NPF) was identified on each cross-shore profile. NPFs consisted of beach scarps, dune crests, marsh edges, rocky ledge vegetation lines, or bluff edges, depending on shoretype.
6. Mean high water (MHW) was identified on each cross-shore profile.
7. At sandy beaches, marshes, and dunes, historical shoreline data was compiled from Hapke et al. (2010) and the New Hampshire Geographically Referenced Analysis and Information Transfer System (GRANIT). These historical shoreline data points were combined with MHW points to calculate historical shoreline change rates (LRRs) for each transect.
8. At bluff-backed beaches, historical bluff edges were identified from georeferenced historical aerial photos at each transect. The most recent bluff edge was identified on each cross-shore profile and combined with the historical bluff edges to calculate historical shoreline change. At rocky ledges, vegetation lines were identified from aerial imagery.
9. Global SLR projections developed by NOAA in 2017 (Sweet et al. 2017) were adjusted using local rates of SLR observed at tide gauges near each site.
10. Recently collected bathymetric data sets were downloaded and processed for each site. Cross-shore profiles were extracted from the bathymetry data and were used to determine nearshore profile slopes (Bruun slopes) used for future erosion projections with SLR.
11. The local relative rates of SLR and future projections of SLR were then used to adjust the historical rates of shoreline change (LRRs) and project future shoreline change.
12. The technical approach applied at sandy beaches, dunes, and coastal bluffs was used from the FEMA Region IX Pilot Study (BakerAECOM 2016).

13. Compass developed and applied a hybrid erosion model to predict future erosion at sandy beaches or coastal marshes backed by erodible coastal bluffs that are currently stable.

Mapped future erosion hazard areas were created based upon four NOAA SLR scenarios (Low, Intermediate-Low, Intermediate, and High) over three future time frames (the years 2030, 2050, and 2100).

2.2 Analysis of Current Bathymetric and Topographic Data

The first step in the technical analysis was to obtain and process recently collected bathymetric and topographic data. Recently collected bathymetric data sets were necessary to calculate nearshore profile slopes (Bruun slopes), which are used in future erosion projections with SLR. Recently collected topographic data were required to identify the current NPFs (beach scarps, dune crests, coastal marsh edges, rock ledge edges, or bluff edges), MHW at sandy beach , coastal marsh and dune transects, and to calculate historical rates of change. The topographic data sets were particularly important because they established the baseline shoreline conditions for projecting long-term future shoreline change. To predict long-term future shoreline change, it is critical that the topographic data be representative of typical shoreline conditions, and not representative of recent episodic shoreline change events, including large coastal storms or nourishment projects (Crowell et al. 1997; Crowell and Leatherman 1999). In 2012, Superstorm Sandy eroded several sandy beaches within Region I and there were multiple post-storm airborne topographic LiDAR surveys of the coast. Many of these beaches were temporarily eroded and may recover so that post-storm surveys are likely not representative of long-term shoreline change. Therefore, Compass identified and used topographic 2011 LiDAR that was recent, but collected a sufficient amount of time before or after Superstorm Sandy so that the conditions represented had sufficiently recovered post-storm.

Table 1 summarizes the bathymetric and topographic data sets analyzed in this Study area. The airborne topographic LiDAR data were collected in 2011. These data established the baseline shoreline conditions for future erosion calculations. It is important to clarify that even though the data were not collected at the time of this study, the projections of future erosion are valid and will still be valid in the future. This is because the year associated with the LiDAR collection were also taken as the baseline year for projecting future erosion to 2030, 2050, and 2100. Theoretically, the Study could be repeated in the future with a new baseline year and topographic data and the same results would be achieved, if shoreline change trends continue as forecasted. For bathymetry data, it is not known if the USGS Topobathymetric DEMs include post-Superstorm Sandy bathymetric data; however, it is likely they do not as all source hydrographic survey data cited in the included metadata was older than 2012.

Table 1. Summary of Recently Collected Bathymetric and Topographic Data Sets.

County	Bathymetric Data	Topographic Data
Rockingham County	USGS Topobathymetric DEM 1887 - 2016	2011 USGS Topobathymetric LiDAR

Note: All data are publically available and were obtained from NOAA's Digital Coast Website: https://www.coast.noaa.gov/digitalcoast/

All bathymetric and topographic data were processed and analyzed in Universal Transverse Mercator (UTM) Zone 19 coordinates and relative to the North American Vertical Datum of 1988 (NAVD88). Cross-shore profiles were extracted from the topographic data along each transect (Figure 10).

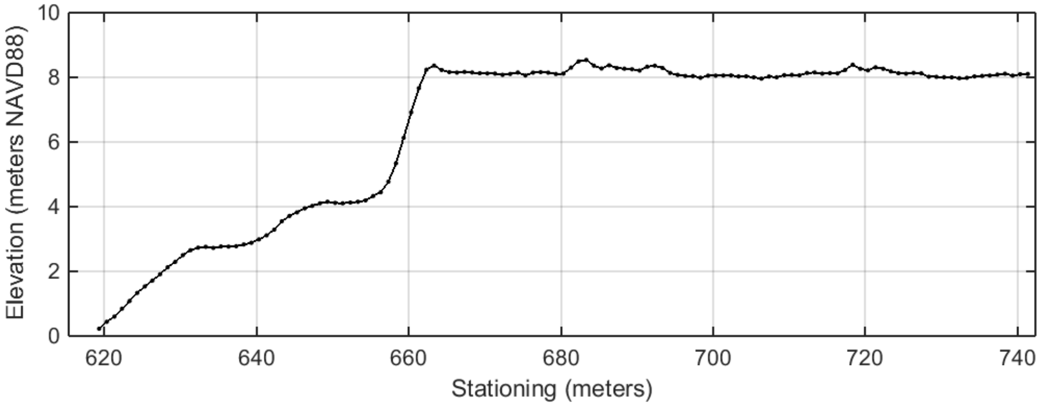


Figure 10. An example of a cross-shore topographic profile extracted along a 1-D transect line. Cross-shore profiles were extracted in meters horizontally and meters relative to NAVD88 vertically.

2.3 Coastal Shoretypes

Once cross-shore topographic profiles were extracted along each transect, they were classified by shoretype (sandy dunes, sandy beaches, coastal marshes, rocky ledges, and coastal bluffs). Each shoretype was defined following a framework detailed in the following sections. The purpose of this step was to establish the type of future erosion response at each transect (sandy shoreline versus erodible bluff). Once the shoretype was defined for a particular transect, the NPF (dune crest, beach ridge, marsh edge, rocky ledge vegetation line, or bluff edge) was identified on each cross-shore profile. The NPF is the current active natural barrier to coastal erosion during typical conditions. The purpose of identifying the NPF on each transect was to establish the baseline for future erosion projections on the transect. In later stages during the final mapping, the NPFs along all transects were mapped as the current coastal boundary. Both the shoretype classification and NPF identification were completed visually using a combination of the cross-shore profile data, the DEM, publicly available current and historical aerial photographs, and field site visits. Details are provided in the following sections.

2.3.1 Sandy Dunes

For sandy shorelines (dunes and beaches), Compass generally defined the NPF as the approximate landward limit of the coastal total water levels (TWLs) over typical or average conditions (not during an extreme storm event). Coastal TWLs are the combination of astronomical tides, storm surge, wave setup, and wave runup, and are ultimately the driver for coastal erosion. The approximate landward limit of the TWL along each transect was not calculated, but estimated visually based on several aspects. These included the location of a beach scarp or dune ridge in the cross-shore profile and DEM, and the presence of wrack lines and High Water Lines (HWLs) in aerial photos and field site visits. Each NPF is the current natural barrier along a transect to coastal erosion during typical conditions. Coastal erosion during an extreme storm might project far inland and does not establish an accurate baseline for future long-term shoreline change analysis. The landward limit of average coastal erosion is more representative of typical conditions and an accurate baseline for future long-term shoreline change analysis (Crowell et al. 1997; Crowell and Leatherman 1999; Hapke et al 2010).

Dunes were identified at sandy beaches backed by a well-formed, continuous sand dune with a clear geometry (i.e., easily identifiable dune toe, crest, and heel on the cross-shore profile) (Figure 11). For this Study, dunes were required to be at least two meters tall (from toe to crest) to distinguish between small dune hummocks and coastal foredunes. It was reasoned that coastal dunes should be tall enough to provide some short-term protection against coastal flooding. This criterion was simply used to avoid categorizing small dune hummocks as dunes and did not impact the analysis or mapping in the alongshore. The NPF was identified at the dune crest, which was nearly always vegetated. In some areas, the most seaward crest appeared as a ridge rather than a peak. On cross-shore profiles with multiple dune crests, the NPF was identified as the most seaward dune crest, to represent the current barrier to coastal erosion.

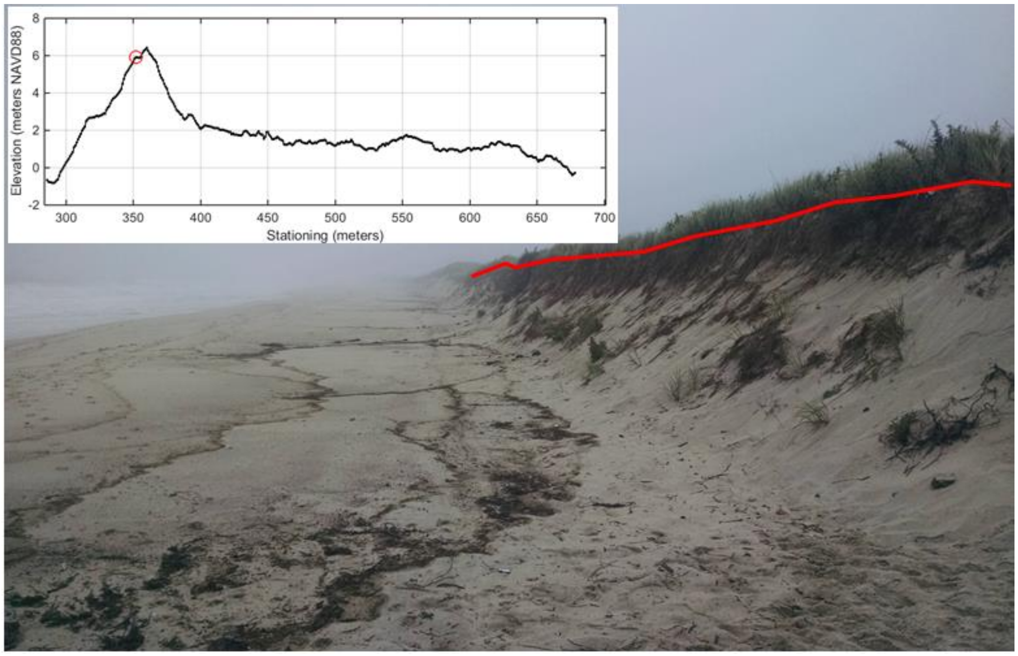


Figure 11. An example of a sandy coastal dune from FEMA Region 1. The dune is well-defined and over two meters tall. The most seaward crest (red line) was identified as the NPF on a cross-shore profile from the site. In some areas, the most seaward crest appeared as a ridge rather than a peak. The wrack line in the photograph indicates that the vegetated dune ridge is the current boundary to coastal erosion and the TWL.

2.3.2 Sandy Beaches

Transects placed at wide sandy beaches with no well-defined coastal dunes were categorized as sandy beaches (Figure 12). These beaches were typically wide and flat, with a distinct scarp that delineated the active coastal erosion boundary. Often, the scarp was vegetated along the ridge. In some areas there were small dune hummocks that had not yet developed into continuous coastal dunes. At many sites these were less than one meter tall.

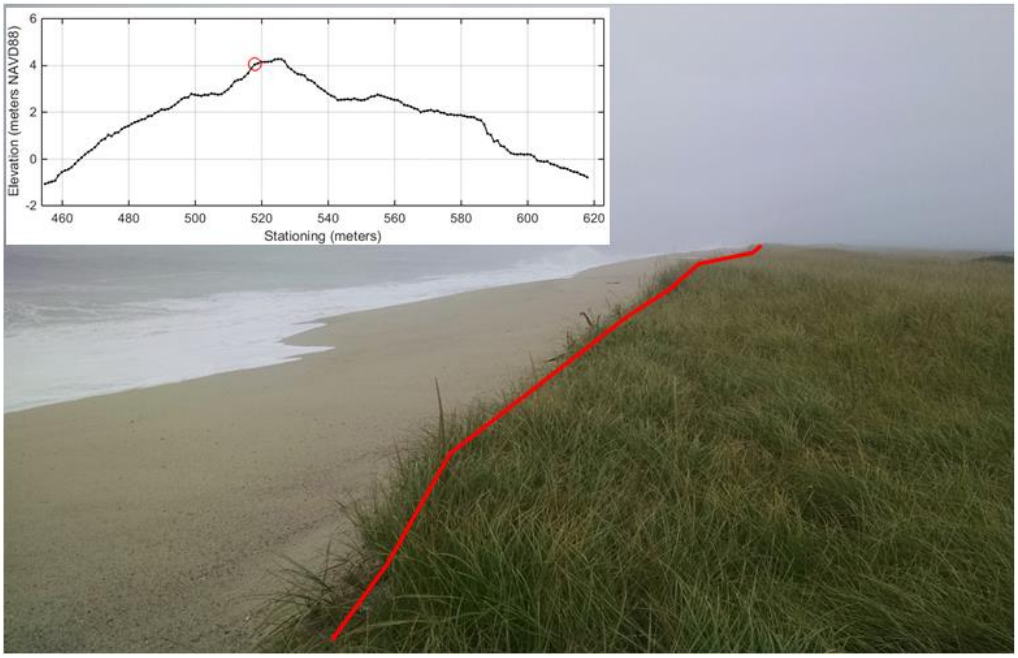


Figure 12. An example of a wide sandy beach from FEMA Region 1. The beach is wide and flat. There is no dune present although there is a small, vegetated scarp (red line) that defines the active coastal erosion boundary. The ridge at this scarp was identified as the NPF.

It is critical to highlight that the distinction between the dune and beach classification had no impact on the analysis or mapping in the alongshore. Both types of sandy shorelines were analyzed for future erosion in the same manner. Furthermore, in areas of transition between beaches and dunes, the beach ridge aligned with the most seaward dune crest in the alongshore and delineated the active coastal erosion boundary (Figure 13). Therefore, there was no transition between the NPFs and the mapped future erosion hazard areas. The shoretype classifications were adopted only to accurately categorize the existing shoreline geomorphology of each transect.

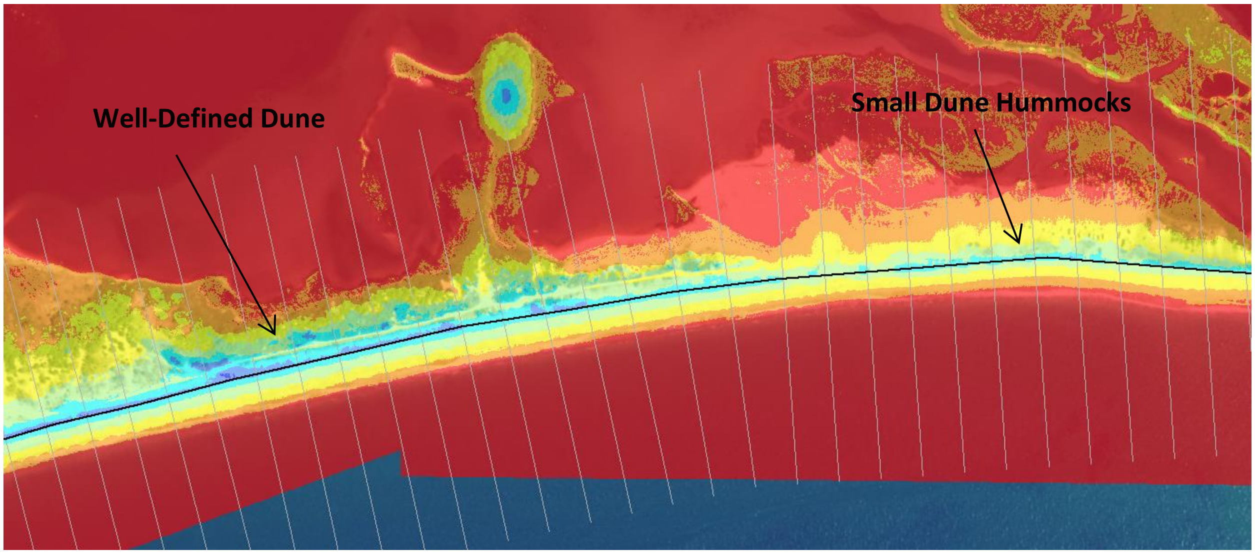


Figure 13. An example of a transition area between well-defined coastal dunes and sandy beaches with small dune hummocks at a sandy spit within FEMA Region I. Analysis transects are shown in grey and the NPF line is shown in black. There are tall well-defined dunes to the left of the figure and small, segmented dune hummocks to the right. The most seaward dune crest aligned with the most beach ridge in the alongshore and delineated the active coastal erosion boundary, such that the change in shoretype classification had no impact on the analysis and mapping. The shoretype classifications were adopted only to accurately categorize the existing shoreline geomorphology of each transect.

2.3.3 Coastal Bluffs

Transects placed at actively eroding coastal bluffs were categorized as coastal bluffs (Figure 14). On each cross-shore profile, the bluff edge was selected as the NPF and active coastal erosion boundary.

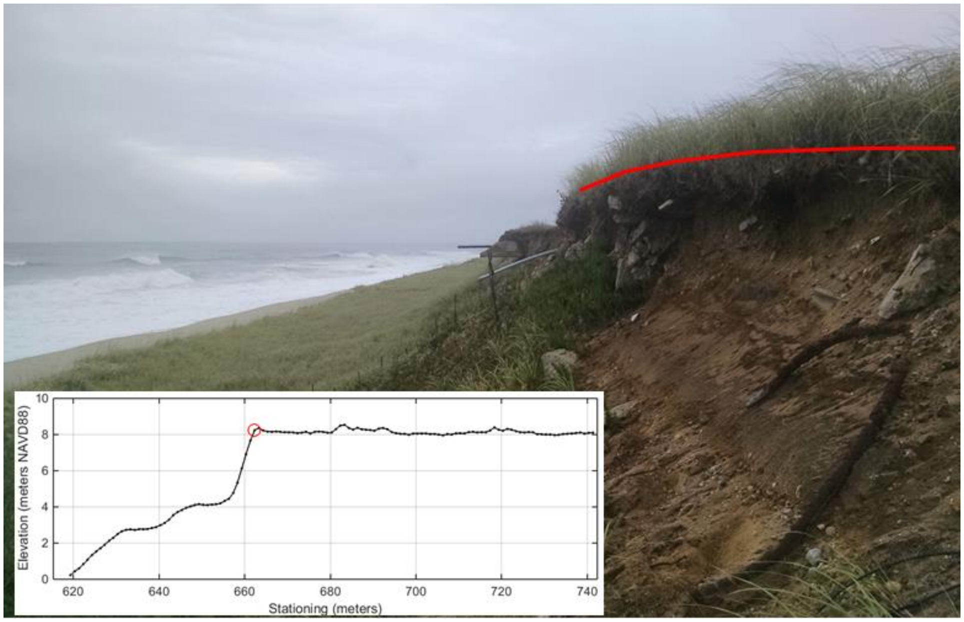


Figure 14. An example of a coastal bluff from FEMA Region I. The bluff edge (red line) was selected as the NPF and active coastal erosion boundary.

2.3.4 Coastal Marshes

Transects placed along coastal marshes were categorized as coastal marshes. For the erosion analysis described in a later section, coastal marshes were generally treated the same as sandy beaches.

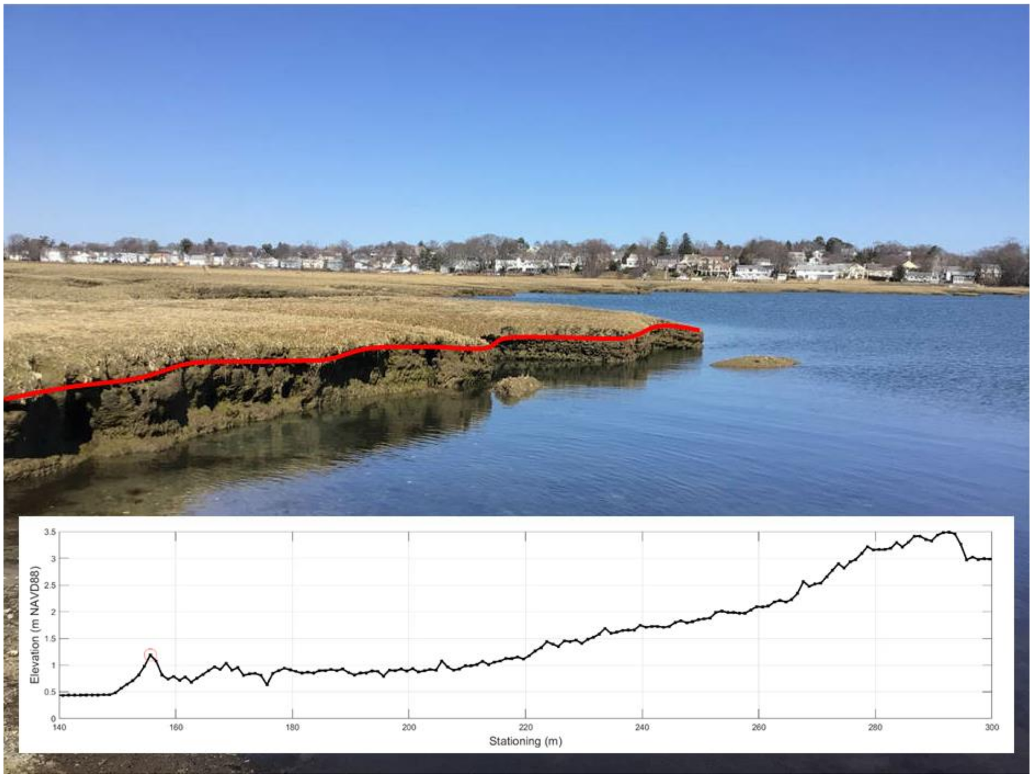


Figure 15. An example of a coastal marsh from FEMA Region I. The marsh edge (red line) was selected as the NPF and generally corresponded to the seaward edge of the marsh, where historical shoreline surveys had been conducted.

2.3.5 Rocky Ledges

Transects placed along rocky outcrops or ledges were classified as rocky ledges. Rocky ledges are composed of hard rock material, like basalt, and are relatively resistant to erosion (Benumof and Griggs 1999; Allan and Priest 2001; Premaillon et al. 2018). The NPF was identified at the vegetation line. For the erosion analysis described in a later section, rocky ledges were generally treated the same as coastal bluffs with an assigned minimum erosion rate.

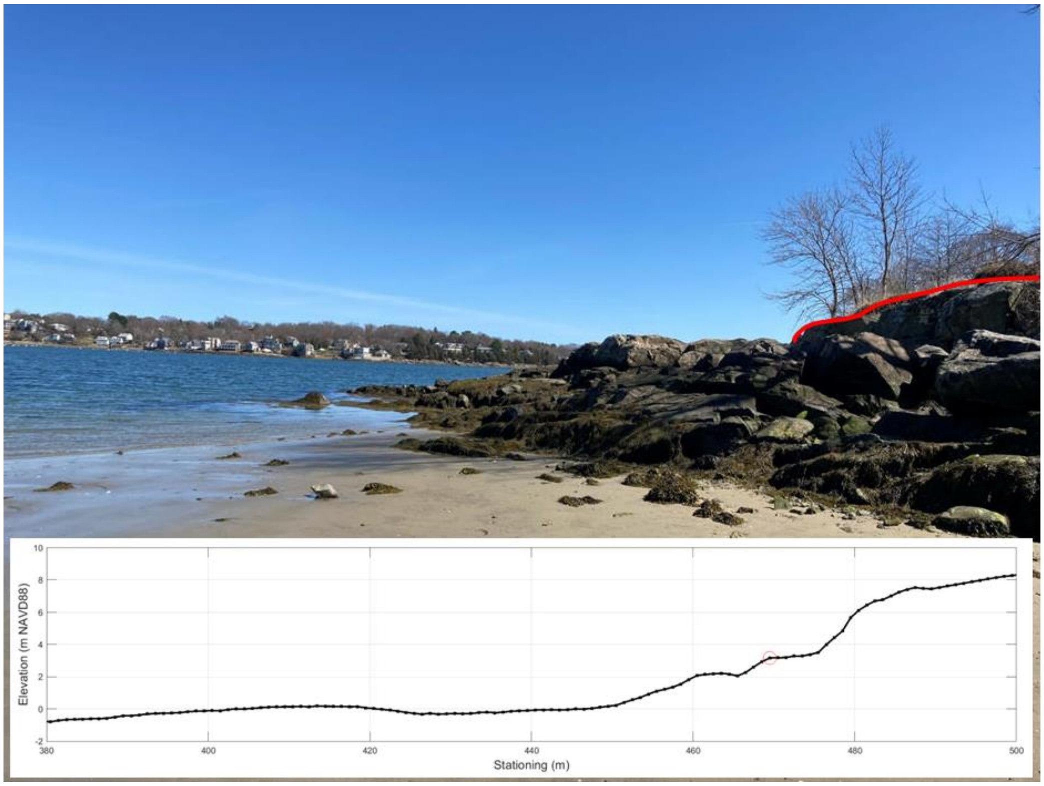


Figure 16. An example of a rocky ledge from FEMA Region I. The edge (red line) was selected as the NPF along the vegetation line.

2.4 Determination of Historical Shoreline Change Trends

This section details the calculation of historical shoreline change trends. Historical shoreline data was used to calculate historical erosion or accretion rates of sandy beaches, dunes, and coastal marshes. Historical bluff edge data was used to calculate historical erosion rates of coastal bluffs.

2.4.1 Historical Data

Compass used historical data to determine historical shoreline change rates. For sandy shorelines (dunes, coastal marshes, and beaches), Compass used historical shoreline data in GIS format from the USGS National Shoreline Assessment (Hapke et al. 2012) and the New Hampshire GRANIT. Older data included historical shorelines derived from NOAA T-Sheets and from aerial photographs. These shorelines were delineated by visual identification of the high water line (HWL) during historical surveys or during the processing and analysis of the aerial photographs.

For coastal bluff areas, Compass used historical aerial photos of the coastline from the publicly accessible USGS Earth Explorer. The historical bluff edges were visually identified on the aerial photos. More recent bluff edges were visually identified on each cross-shore profile extracted from the airborne topographic LiDAR data. Table 2 summarizes the historical data sets used in the Study.

Table 2. Historical Shoreline and Bluff Edge Data used to Determine Historical Shoreline Change Trends.

County	Historical Sandy Shoreline Data Year (Data Type)	Historical Coastal Bluff Edge Data Year (Data Type)
Rockingham County	1866-1867 (HWL - NOAA T-Sheet) [1,4] 1894 (HWL – USGS Topography Map) [4] 1912 (HWL - NOAA T-Sheet) [1,4] 1920 (HWL - USGS Topography Map) [4] 1934 (HWL - USGS Topography Map) [4] 1953 (HWL - NOAA T-Sheet) [1,4] 1960 (HWL - Aerial Photograph) [2,4] 1962 (HWL - Aerial Photograph) [4] 1973-1974 (HWL - Aerial Photograph) [2,4] 1977 (HWL - Aerial Photograph) [2] 1992 (HWL - Aerial Photograph) [4] 1998 (HWL - Aerial Photograph) [4] 2000 (MHW - LiDAR) [1,4] 2005 (HWL - Aerial Photograph) [4] 2007 (MHW - LiDAR) [4] 2010-2011 (MHW - LiDAR) [4]	1960 (Bluff Edge - Aerial Photograph) [2] 1973 (Bluff Edge - Aerial Photograph) [2] 1977 (Bluff Edge - Aerial Photograph) [2] 2011 (Bluff Edge - LiDAR) [3]

Notes: Data sources include 1 – USGS National Shoreline Assessment (Hapke et al. 2010); 2 – USGS Earth Explorer (https://earthexplorer.usgs.gov/); 3 – NOAA Digital Coast (https://coast.noaa.gov/); 4-New Hampshire GRANIT (https://www.granit.unh.edu/).

2.4.2 Sandy Beaches, Coastal Marshes, and Sandy Dunes

To calculate historical rates of shoreline change at sandy beaches, coastal marshes, and dunes, Compass compared historical HWLs derived from T-Sheets and aerial photographs to more recent MHW positions on LiDAR-derived cross-shore profiles. Many previous studies have utilized HWLs for shoreline change analysis (Crowell et al. 1993). Ruggiero (2009) found that when comparing HWLs from photos, T-Sheets, or beach surveys (proxy-based shorelines) to MHW (a tidal datum-based) shoreline, a correction needs to be applied for wave effects (Figure 17). This is necessary because visually identified HWLs include the effects of wave setup and wave runup, while the position of MHW is based on astronomical tides alone. On any given day, the HWL will be further inland than MHW because of wave setup and runup. The USGS Shoreline Change Assessment (Hapke et al. 2010) includes averaged correction factors for all historical HWL shorelines derived from T-Sheets and photos based on typical wave and beach slope conditions. In areas with USGS Shoreline Change Assessment data, Compass used these correction factors to adjust the historical HWL data.

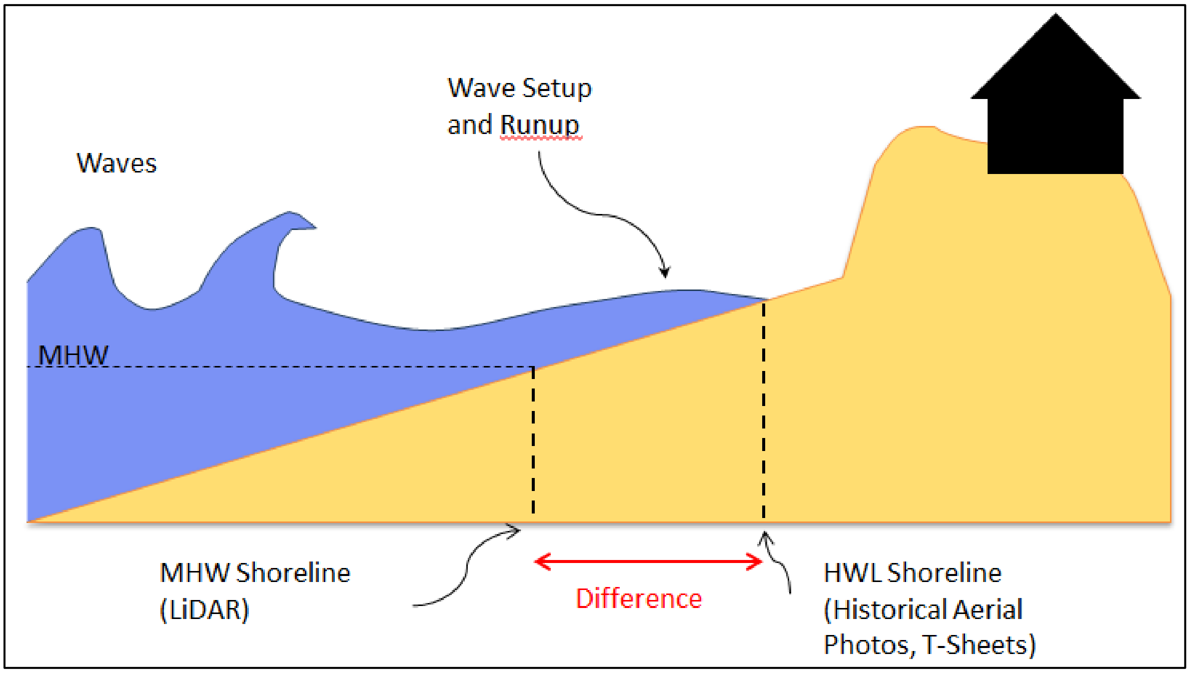


Figure 17. A conceptual diagram of the comparison between HWL shorelines, derived from aerial photographs, T-sheets, or beach surveys, and MHW. HWL shorelines include the effects of wave setup and wave runup while MHW is a tidal-based datum shoreline and includes the effects of astronomical tides only. The HWL shorelines were adjusting using correction factors from the USGS National Shoreline Assessment (Hapke et al. 2010).

In areas with no USGS shoreline change assessment data, including the majority of the Rockingham County shoreline, Compass calculated correction factors following the USGS approach and using local wave and cross-shore profile data. Wave setup and runup heights are typically a function of wave height, wave period, and beach or coastal barrier slopes (Stockdon et al. 2006). For wave characteristics, Compass first obtained historical wave data from proximate NOAA National Data Buoy Center (NDBC) buoys and U.S. Army Corps of Engineers Wave Information Studies model output stations (Figure 18). For slope characteristics, Compass calculated the beach slope within +/- 1.5 meter of MHW on each cross-shore profile derived from the 2011 LiDAR data. The correction factor for each transect was then obtained by calculating the height of wave setup and runup using the Stockdon et al. (2006) empirical formula, which is widely used in coastal studies:

$$Bias = R_{2\%}/\beta_f = 1.1\left[0.35\beta_f\sqrt{H_0L_0} + \frac{\sqrt{[H_0L_0(0.563\beta_f{}^2+0.004)]}}{2}\right] \div \beta_f \qquad \text{(Equation 1)}$$

where $R_{2\%}$ is the two-percent exceedance wave setup and runup height, H_0 is the average deepwater significant wave height, L_0 is the average deepwater wave length, and β_f is the slope around MHW.

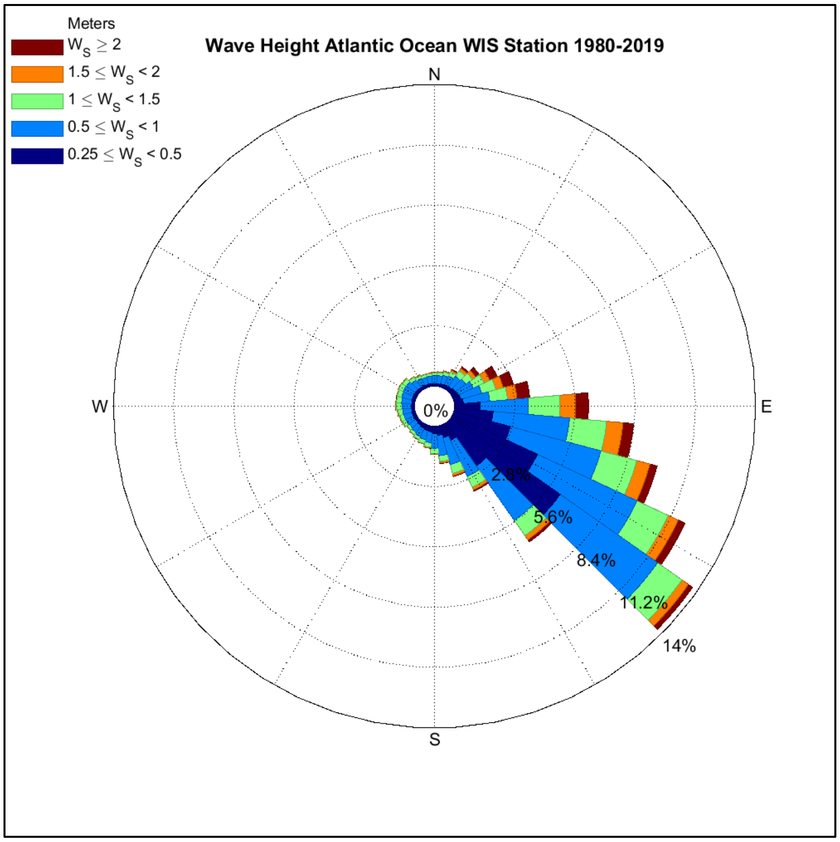


Figure 18. An example of wave data used for the study area. The rose plot shows wave heights and directions for the years 1980 – 2019 from the USACE WIS Station ST63044. This station is located offshore of Rockingham county. The plot is an example of the data that were used to calculate average wave heights and wave periods to estimate the correction factors between HWL and MHW in historical shoreline change analysis.

Compass added a more recent historical shoreline at each site from the 2011 airborne topographic LiDAR data (Table 2). The shoreline was found statistically by fitting a linear regression through profile data at each cross-shore profile around the MHW elevation, and then using the best fit linear regression equation to calculate the cross-shore position of MHW (Stockdon et al. 2002; Hapke et al. 2010). The technique is more accurate than simply visually identifying MHW on each cross-shore profile, particularly on flatter profiles with undulations near the shoreline. Table 3 summarizes the MHW elevations for each site. Weber et al. (2005) analyzed tide gauge data along several US coastlines and established MHW elevations for shoreline change analysis. Mean higher high water (MHHW) elevations were used to calculate the Bruun slopes in the future erosion analysis and are also presented in Table 3.

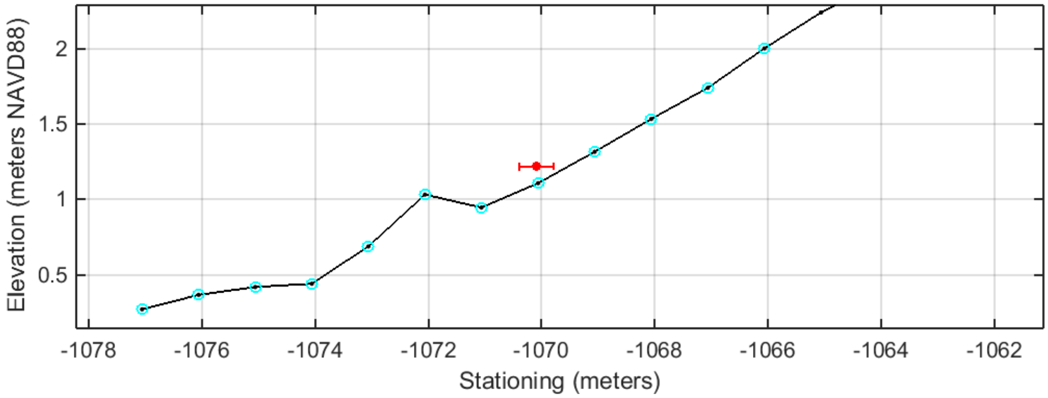


Figure 19. An example of how MHW was found statistically on cross-shore profiles of sandy beaches, coastal marshes, and dunes. A linear regression was fit to profile data within 1.5 meter of the MHW elevation (1.22 meters NAVD88 – turquoise circles) and the resulting best-fit equation was used to calculate the cross-shore position of MHW. The predicted MHW location is shown in red with 90-percent confidence intervals (red circle and bars). The approach was developed by Stockdon et al. (2002).

Table 3. MHW and MHHW Elevations used in the Technical Analysis

County	Tidal Datum	Elevation (meters NAVD88)	Source
Rockingham County	MHW	1.160	NOAA Station #8419870 [1]
	MHHW	1.285	NOAA Station #8419870 [1]

Notes: 1 – Data available at https://tidesandcurrents.noaa.gov/

2.4.3 Coastal Bluffs

To calculate historical rates of shoreline change at coastal bluffs, Compass georeferenced historical aerial images (Table 2). The photos were georeferenced using Environmental Systems Research Institute (ESRI) GIS tools, following a procedure developed in the New York Department of Environmental Conservation (NYDEC) study (AECOM 2013).

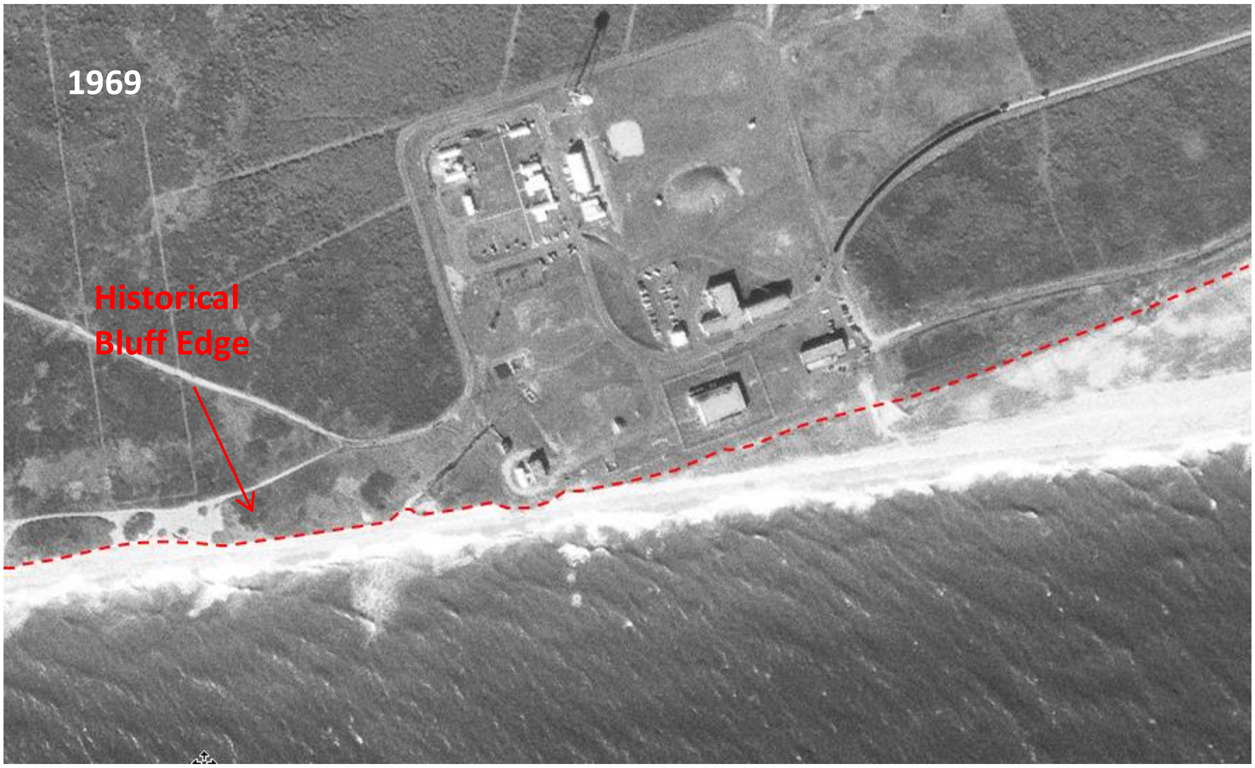


Figure 20. An example of a georeferenced historical aerial photograph from FEMA Region I. The georeferenced historical aerial photograph was used to identify the historical bluff edge (red dashed line).

2.4.4 Linear Regression Rates (LRRs)

In the Pilot Study, Compass performed an investigation to determine the most appropriate method to calculate historical shoreline change rates, ultimately selecting LRRs, which are widely used in shoreline change analysis (Crowell et al. 1997; Crowell and Leatherman 1999; Hapke et al. 2010). LRRs are statistically determined by fitting a line through multiple historical shoreline data points. The slope of the best-fit line is the shoreline change rate (meters/year) (Figure 21). LRRs naturally incorporate more data points than an endpoint rate approach, which only uses the most recent and most historical shoreline data points, and are therefore less impacted by short-term variability in shoreline change and better suited to calculate long-term trends. For example, sandy beaches can go through seasonal and inter-annual periods of erosion and accretion. Even beaches that have been eroding in the long-term may have brief periods of accretion. Figure 21 illustrates an example of this from a sandy beach transect. Furthermore, by including additional shoreline data points, LRRs reduce the impacts of outlier points. Outlier points can be either erosional or accretionary, due to nourishments or storms, and they are not representative of long-term trends. Although Compass avoided more recent LiDAR survey data collected after Superstorm Sandy, we were unable to discern if any of the historical shorelines were outliers. Finally, LRRs also provide a degree of statistical confidence on the historical erosion or accretion rates, in the form of a 90-percent confidence interval. The confidence intervals can be incorporated into future erosion hazard areas.

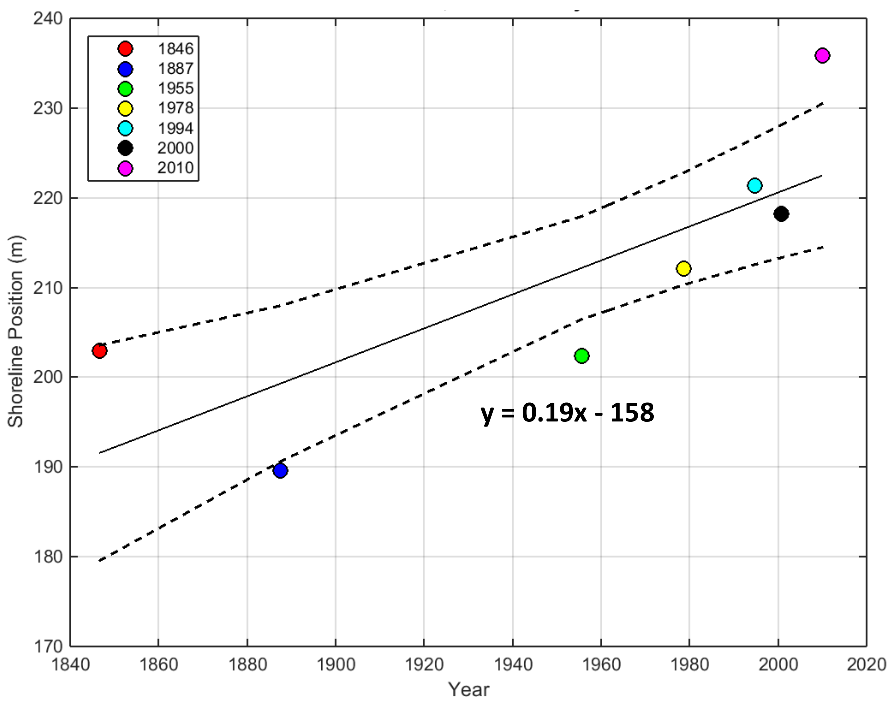


Figure 21. An example of an LRR calculated at a sandy beach transect. The black line is the best-fit trend line and the dashed lines represent the 90-percent confidence intervals. The slope of the line is the shoreline change rate (eroding 0.19 meters/year). Positive slope is erosion and negative slope is accretion. The best fit equation is displayed in the figure. The LRR takes into account multiple historical shorelines from 1846-2010.

2.4.5 Length of Historical Record

In the Pilot Study, Compass also performed an investigation to determine the length of historical record that was most appropriate for predictions of long-term future coastal erosion, ultimately selecting a relatively long timeframe from the mid-1800's – 2000's. Previous studies have shown that longer timeframes might be more representative of long-term trends if older historical data is available (Crowell et al. 1997; Crowell and Leatherman 1999; Hapke et al. 2010). These studies demonstrated how short-term shoreline change rates can be larger in magnitude and more variable. An example of the long-term historical rates for a portion of shoreline is shown in Figure 22.

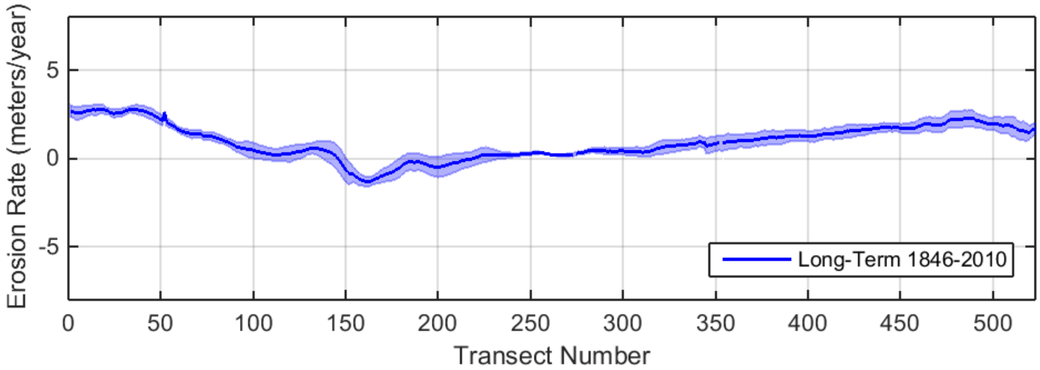
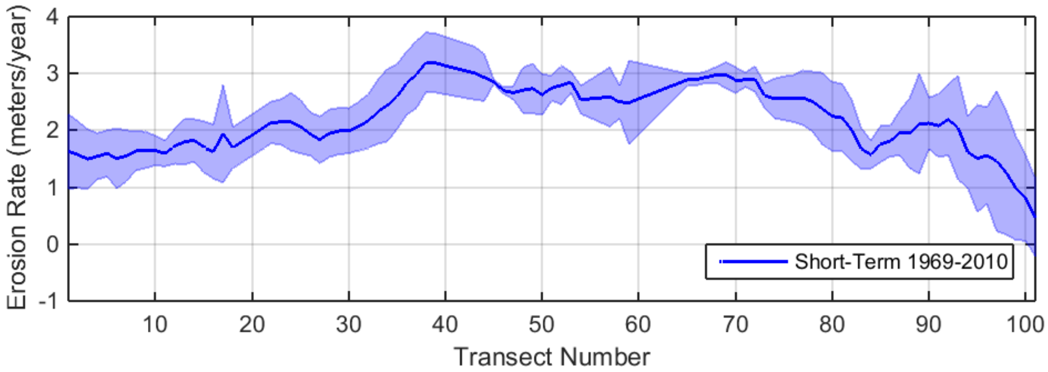


Figure 22. An example of long-term, historical (1846-2010) shoreline change rates (negative = accretion, positive = erosion) for analysis transects in FEMA Region I. The rates are shown in blue with 90-percent confidence intervals indicated by shading.

There are additional reasons for selecting a longer timeframe. Calculating historical shoreline change rates over longer timeframes allows for the inclusion of additional shoreline data points. This further reduces the impacts of outlier points in the calculation of LRRs as discussed in the previous section. In addition, Compass is predicting future erosion hazard areas based on approximately 20, 40, and 90 year timeframes (using 2010 as a baseline year for the years 2030, 2050, and 2100). As most of these timeframes are longer than 30 years, it is reasonably consistent to calculate historical shoreline change over similar timeframes longer than 30 years. Finally, in subsequent steps of the technical analysis, Compass attributed some of the historical erosion to historical SLR measured at tide gauges. This was done for the determination of future erosion hazard areas and is detailed in following sections. SLR has been observed at the Battery, New York tide gauge since the mid 1800's and several other tide gauges on the Atlantic Coast since the early-1900's (Zervas et al. 2013). This indicates that SLR may have affected shoreline change since the mid-1800's and early 1900's. Therefore, it is reasonable to include historical shorelines from these earlier dates. For all of these reasons, a longer timeframe and use of all available historical data at each site appears to be a better approach for this study (Table 2).

The same holds true for bluff-backed shorelines. Historical photographs dating back to 1960 were obtained for bluff backed beaches in Rockingham County (Table 2). No older photos of sufficient quality to be georeferenced and analyzed were available. 1960 – 2011 is a much shorter timeframe than the analyzed timeframes for sandy beaches, coastal marshes, and dunes; however, this is not expected to significantly impact the calculations of long-term bluff erosion. This is because the calculated bluff erosion rates have less variability compared to the sandy shoreline change rates, over similar timeframes (Figure 23). This is most likely because bluffs and rocky ledges can only erode while beaches, marshes, and dunes can both erode and prograde, making bluff and ledge change inherently less variable than sandy shoreline change over the long-term. An example of an LRR determined at bluff backed beach is shown in Figure 24.

At all sites and for all shoretypes (sandy, bluff, rocky ledge, and coastal marsh), Compass decided to use all available historical data unless there was clear evidence that the data was not representative of long-term shoreline change trends. Historical aerial photo sets were chosen based on their completeness for the study area.



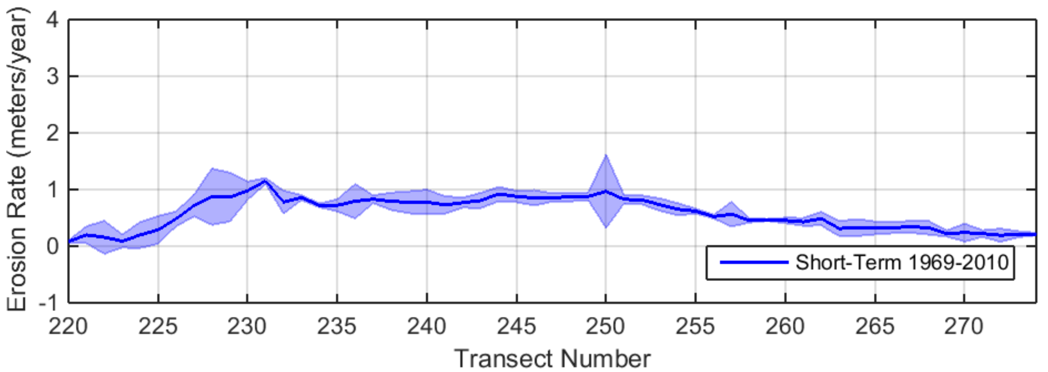


Figure 23. Historical bluff erosion rates (positive = erosion) for two bluff-backed shorelines in FEMA Region I. The rates are shown in blue with 90-percent confidence intervals indicated by shading. The alongshore variability is relatively small compared to sandy shoreline change rates.

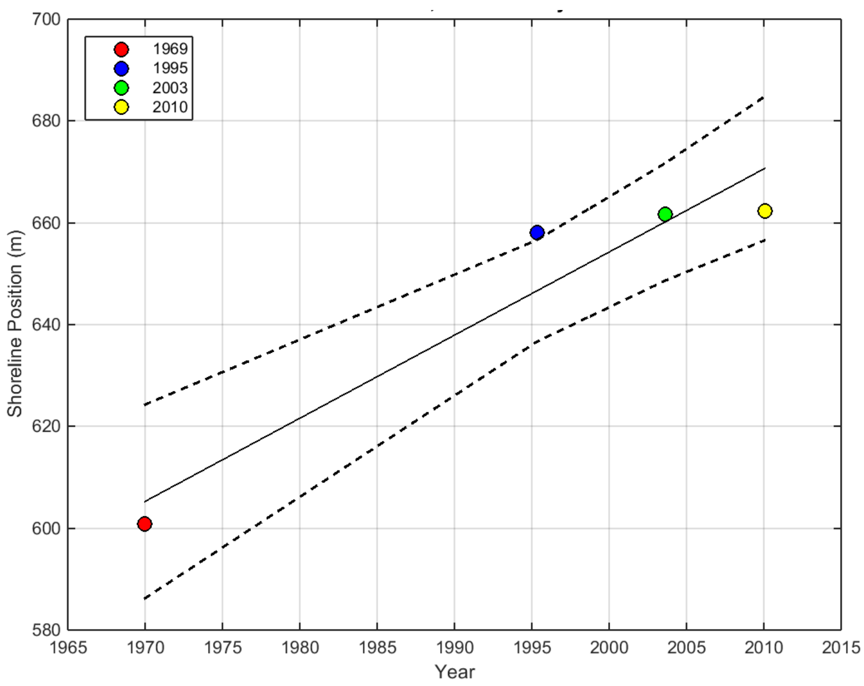


Figure 24. An example of an LRR determined at a transect placed along a bluff-backed beach. The slope of the best-fit line, and historical erosion rate, is 1.63 meters/year.

Rocky ledges are resistant to wave attack, relative to erodible coastal bluffs, and areas of rocky ledges appeared to be stable over the historical aerial photograph timeframe. As these features do not rapidly erode, there have been limited studies on their erosion rates. Studies that do examine their erosion rates (Benumof and Griggs 1999; Premaillon et al. 2018) include detailed geological tests of rock strength and rock joint structure, which is beyond the scope of this study. Multiple previous studies independently estimated average erosion rates of approximately 0.03 meters/year for these features (Benumof and Griggs 1999; Allan and Priest 2001; Premaillon et al. 2018). For this study, Compass assumed this rate for all rocky ledge areas. This rate was also applied as a minimum erosion rate to stable coastal bluffs that did not erode over the historical aerial photograph timeframe.

2.5 Sea Level Rise

Overall, the Region I study has followed the TMAC (2015) recommendations to use future global SLR projections developed by NOAA. Studies of previous counties used four future SLR projections (Low, Intermediate-Low, Intermediate-High, and High) developed by NOAA and Parris et al. (2012). These are referred to as *NOAA 2012*. For the Rockingham Study, Compass used updated future SLR projections developed by NOAA and Sweet et al. (2017). These are referred to as *NOAA 2017*. Four future SLR scenarios (Low, Intermediate-Low, Intermediate, and High) were analyzed and mapped in the study (Figure 25). NOAA did include an “Extreme” future SLR scenario which was not included in this study as it has a low likelihood of occurrence (Sweet et al. 2017). There is a considerable range in the future SLR predictions. The Low SLR scenario assumes that SLR increases at the observed rate (3.0 millimeters/year) and that there is no acceleration. The projected future global amounts of SLR are listed by decade in Table 4. The older, NOAA 2012 future SLR projections are presented as smooth quadratic curves. The newer NOAA 2017 projections were derived by running multiple climate change models with different greenhouse gas emission scenarios. At each decade, the median SLR amount predicted by the suite of models was taken as the projection (Sweet et al. 2017). Therefore, the NOAA 2017 projections don't always appear as smooth curves.

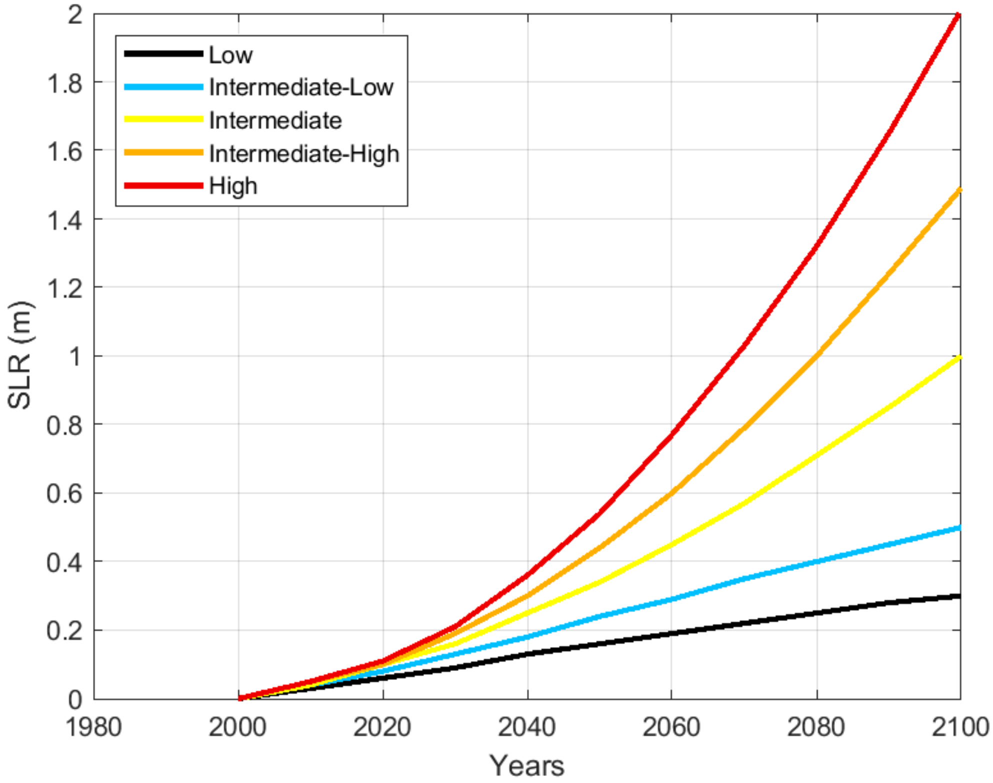


Figure 25. Future global SLR projections developed by NOAA 2017. There are five different scenarios which vary based on global greenhouse gas emissions: Low, Intermediate-Low, Intermediate, Intermediate-High, and High. The year 2000 is the baseline year.

Table 4. NOAA 2017 Global Mean Sea Level Rise scenario heights (in meters).

Global Mean SLR Scenario	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Intermediate-Low	0.0	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.5
Intermediate	0.0	0.1	0.2	0.3	0.3	0.5	0.6	0.7	0.9	1.0
Intermediate-High	0.1	0.1	0.2	0.3	0.4	0.6	0.8	1.0	1.4	1.5
High	0.1	0.1	0.2	0.4	0.5	0.8	1.0	1.3	1.7	2.0

2.5.1 Relative Sea Level Rise

SLR occurs at different rates across the globe due to regional oceanographic effects and vertical land motion, including both subsidence and uplift (Parris et al. 2012; Zervas et al. 2013; Sweet et al. 2017). Therefore it is critical to adjust future SLR predictions based on local processes to calculate the future relative SLR in each area of interest. Table 5 lists the rates of SLR observed at tide gauges in Rockingham County.

Table 5. Observed Rates of SLR from Tide Gauges for Determining Future Relative SLR

NOAA Tide Gauge	Observed Rate of SLR (millimeters/year)
Global	3.00
NOAA Station #8419870 Seavey Island, Maine	2.07

Notes: 1 – Data available at https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Using the observed rate of SLR at local tide gauges accounts for regional oceanographic effects and local vertical land motion. NOAA 2017 has developed local SLR projections for sections of the U.S. coastline. Figure 26 shows an example of the relative SLR projections for the coastline of Rockingham County, New Hampshire. Table 6 lists the amount of SLR predicted by NOAA 2017 for all sections of Rockingham County.

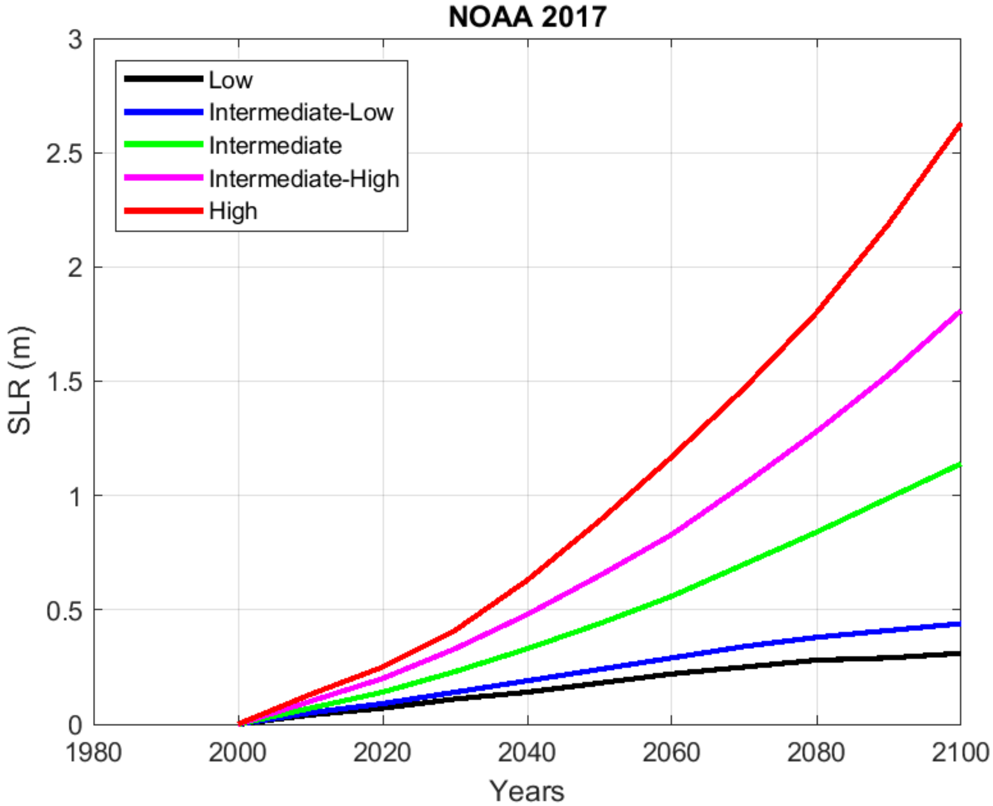


Figure 26. An example of relative SLR projections for the coastline of Rockingham County. The projections are the global SLR projections from NOAA2017 adjusted for local effects with the observed SLR at the NOAA Form Point, New Hampshire tide gauge. The projections use the year 2000 as a baseline year.

Table 6. NOAA 2017 Predicted Relative Future SLR at Each Site for all Study Timeframes

		SLR by Year (meters)		
County	**SLR Scenario**	**2030**	**2050**	**2100**
Rockingham County	Low (observed)	0.1	0.2	0.3
	Intermediate-Low	0.1	0.2	0.4
	Intermediate	0.2	0.4	1.1
	High	0.4	0.9	2.6

Notes: Relative future SLR predictions are based on the year 2000.

2.5.2 Future Sea Level Rise Factors

Future shoreline change will be dependent on the degree of acceleration of SLR. The Intermediate-Low, Intermediate, and High SLR scenarios all predict that SLR will speed up in future decades. These scenarios will successively cause more erosion than the Low SLR scenario, which simply assumes that sea levels will increase at the same rate as has been observed over the past several decades. To quantify the acceleration in future SLR projections, Compass followed the technical approach developed in the FEMA Region IX Sea Level Rise Pilot Study (BakerAECOM 2016). In this approach, an average rate of SLR is calculated between the year of interest and the year of the LiDAR survey (2011) (Figure 27). The ratio of this rate to the observed SLR rate at each tide gauge is then calculated. This can be simply expressed as:

$$F = l/b; \qquad \text{(Equation 2)}$$

where F is the factor of increase, l is the average rate of SLR between the year of interest and LiDAR survey year, and *b* is observed rates of the closest tide gauge. For example, the predicted average rate of SLR for the High scenario within Rockingham County to the year 2100 is 26.3 millimeters/year. The observed rate of SLR at the tide gauge is 2.07 millimeters/year (Table 5). The factor of increase is then F = 26.3/2.07 = 12.71. The calculated factors are listed in Table 7. For the Low SLR projections, F equals 1.00. This means that there is no future increase in the rate of SLR.

It is important to note that although the SLR projections begin in the year 2000, the future predictions of SLR increase from the LiDAR survey years for each scenario are valid. This is because we calculated the relative increase in SLR rate starting in each LiDAR survey year within each scenario, and did not compare between scenarios.

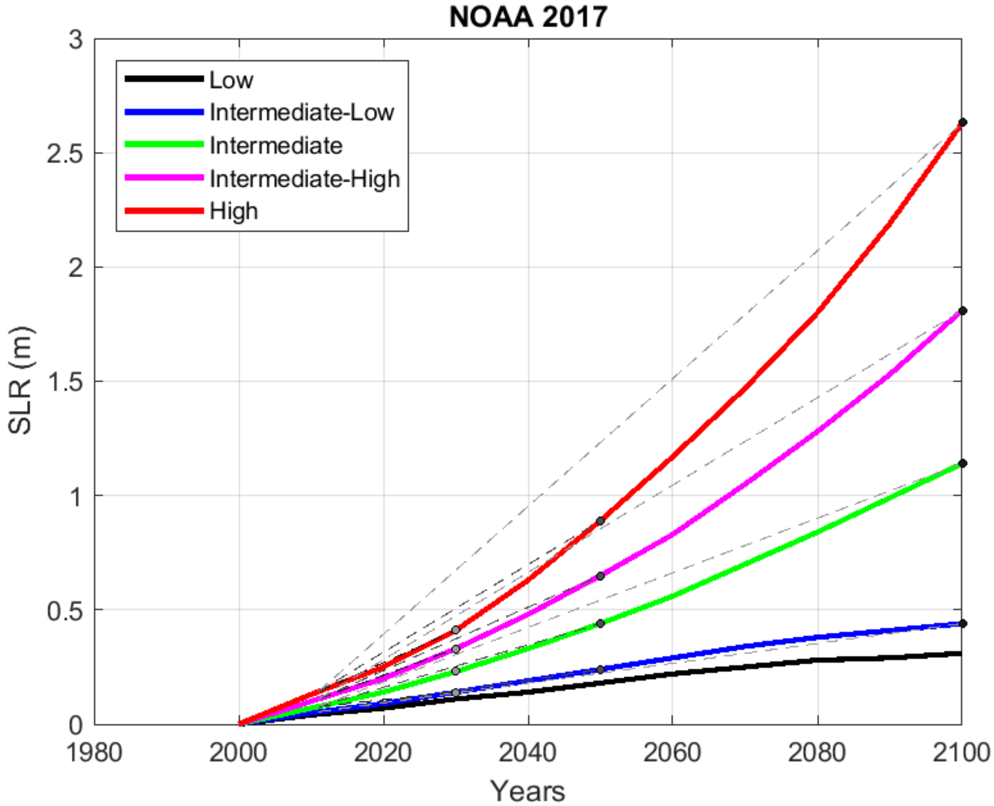


Figure 27. An example of how the SLR factors (F) are for the Rockingham County study area. The average rates of SLR are calculated between each year of interest (2030, 2050, and 2100) and the year LiDAR data was collected (grey lines). The ratios between these years and the observed rates of SLR at each tide gauge are then calculated.

Table 7. Calculated Factors of Increase in Future SLR Rates Relative to Observed SLR Rates.

County	SLR Scenario	SLR by Year (meters) 2030	2050	2100
Rockingham County	Low (observed)	1.0	1.0	1.0
	Intermediate-Low	2.2	2.3	2.1
	Intermediate	3.9	4.5	5.8
	High	6.8	9.3	13.5

Notes: Factor of 1.00 for the Low SLR scenarios indicates no increase in the SLR rate.

2.6 Future Erosion Calculations

Compass used the relative future increases in the rate of SLR, factor F from the previous section, to adjust historical shoreline change rates to future shoreline change rates. The following sections describe the specific calculations at sandy dunes, coastal marshes, and beaches (Section 2.6.1), coastal bluffs and rocky ledges (Section 2.6.2), and hybrid areas (Section 2.6.3).

2.6.1 Sandy Dunes, Coastal Marshes, and Beaches

To analyze the future response at sandy shorelines, including the dune, coastal marsh, and beach shoretypes, Compass followed a technical approach developed in the FEMA Region IX Sea Level Rise Pilot Study (BakerAECOM 2016). In this approach, the Bruun Rule was used adjust the historical erosion rates calculated at each transect (Figure 28) (Bruun 1962). The Bruun Rule predicts that over sufficient time, a sandy shoreline will erode in response to SLR and come into equilibrium. Sand will erode from the foreshore and backshore and be transported offshore along the active nearshore profile, which extends offshore to the depth of closure (DOC). The Bruun Rule predicts the inland retreat distance by projecting the specific amount of SLR inland along the Bruun slope, or the slope from the DOC to a point on the beach as:

$$R_B = SLR/s; \qquad \text{(Equation 3)}$$

where R_B is the predicted inland retreat distance, SLR is the specified amount of SLR, and s is the Bruun slope. The DOC and Bruun slope are discussed in more detail in Section 2.6.4.

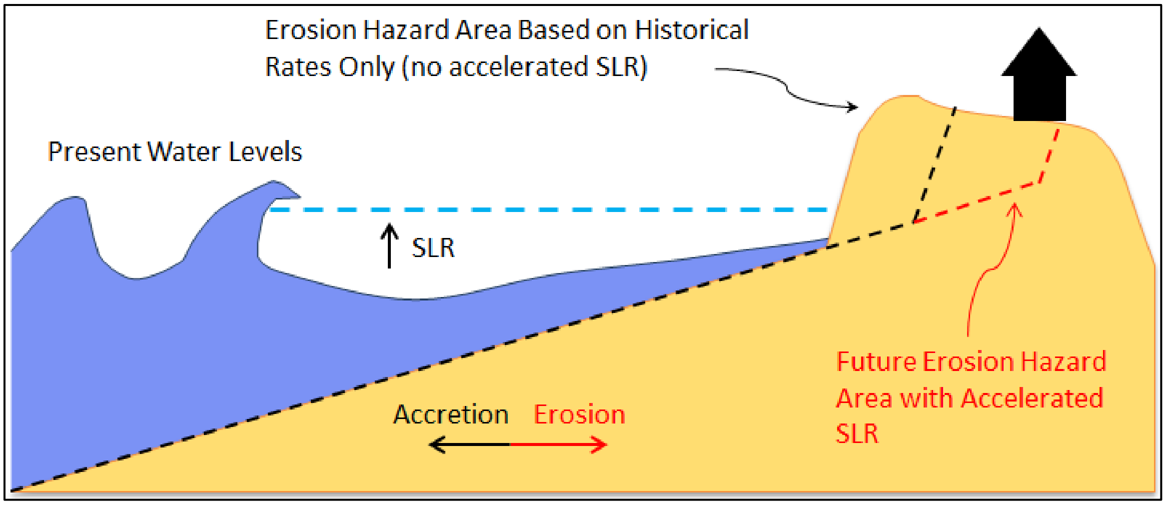


Figure 28. A conceptual sketch of the predicted future erosion response at sandy dune and beach transects.

Instead of simply projecting a future retreat distance along the Bruun slope, BakerAECOM (2016) used the Bruun Rule to calculate a more detailed erosion response. BakerAECOM (2016) assumed that SLR has been affecting sandy shorelines for decades, which is evidenced by observed SLR in tide gauge records dating back to the mid-1800's. BakerAECOM (2016) further assumed that the historical rates of shoreline change are due both to observed SLR, which works to erode beaches, and nearshore coastal process, which can either erode or prograde beaches. The Bruun Rule was applied with the observed rates of SLR from tide gauges to determine the historical erosion rates that would have been observed in the absence of other nearshore coastal processes. These historical erosion rates due to SLR were then subtracted from the actual historical shoreline change rates to estimate the shoreline change rates due to nearshore coastal process. Finally, BakerAECOM (2016) assumed that the rates of change due to nearshore processes would remain constant in the future while the rates of change to SLR would increase. The shoreline change rates due to SLR were increased by the future SLR factors to increase the fraction of shoreline change due to SLR. This approach is summarized in the following steps.

Compass first assumed that the historical rates of shoreline change were a combination of two components:

$$r_h = r_{coastal} + r_{h,SLR}; \qquad \text{(Equation 4)}$$

where r_h is the LRR calculated at each sandy beach transect, $r_{coastal}$ is the amount of the historical shoreline change rate due to nearshore coastal processes, and $r_{h,SLR}$ is the amount of the historical shoreline change rate due to observed rates of SLR at each tide gauge. The subscript "h" stands for historical. Predicted future rates (r_f) are then:

$$r_f = r_{coastal} + r_{f,SLR}; \qquad \text{(Equation 5)}$$

which is a combination of the shoreline change rate due to nearshore coastal processes, assumed to be the same in the future, and the rate of shoreline change to do future SLR ($r_{f,SLR}$).

To estimate $r_{h,SLR}$, the Bruun Rule was applied:

$$r_{h,SLR} = \frac{b}{s}; \qquad \text{(Equation 6)}$$

with b as the observed rate of SLR from a tide gauge and s as the Bruun slope. The shoreline change rate due to nearshore coastal processes was then calculated by re-arranging Equation 4:

$$r_{coastal} = r_h - r_{h,SLR}. \quad \text{(Equation 7)}$$

The future rate of shoreline change due to SLR was estimated by increasing the historical rate of shoreline change due to SLR and scaling by F for a particular timeframe and SLR scenario

$$r_{f,SLR} = r_{h,SLR} \times F. \quad \text{(Equation 8)}$$

Values of F for each timeframe and SLR scenario are found in Table 7. The predicted future retreat distances for a particular SLR scenario and timeframe were then found by multiplying the rate by time:

$$R_f = r_f \times t. \quad \text{(Equation 9)}$$

It is important to highlight that this approach preserves the historical trends in shoreline change due to nearshore coastal processes. For example, if a beach has historically prograded, the predicted future erosion response may not be large, because SLR will be working against the processes that have caused accretion. If a beach has historically eroded, the predicted future erosion response might be large as SLR will be combining with the processes that have caused erosion.

2.6.2 Coastal Bluffs and Rocky Ledges

Coastal bluff erosion is a complex process, due to combinations of marine and terrestrial processes that can vary from site to site. Although it is generally expected that bluffs will erode due to future SLR, there is no clear scientific consensus on exactly how rapidly they will erode. To analyze the future response at coastal bluffs, Compass also followed a simplified technical approach developed in the FEMA Region IX Sea Level Rise Pilot Study (BakerAECOM 2016). This was different than the technical approach applied at sandy beaches because coastal bluffs only erode while sandy beaches can erode or prograde (Figure 29). The approach assumes that historical bluff erosion is solely due to observed SLR:

$$r_h = r_{h,SLR}; \quad \text{(Equation 10)}$$

such that $r_{h,SLR}$ is equal to the LRR calculated at a particular transect. There are no field observations to directly support this assumption; however, there are several numerical modelling studies that suggest a strong, direct correlation between bluff erosion and SLR (Walkden and Dickson 2006; Walkden and Dickson 2008; Ashton et al. 2011) The future erosion rate is then increased by the SLR increase factor F raised to a power of 0.5:

$$r_f = r_{h,SLR} \times F^{0.5}. \quad \text{(Equation 11)}$$

This is based on a model of coastal bluff erosion developed by Ashton et al. (2011). The model assumes that unlike sandy shorelines, coastal bluffs can withstand some wave attack and erode more slowly. The predicted future retreat distance is then simply the future erosion rate multiplied by the time period of interest.

$$R_f = r_f * t \quad \text{(Equation 12)}$$

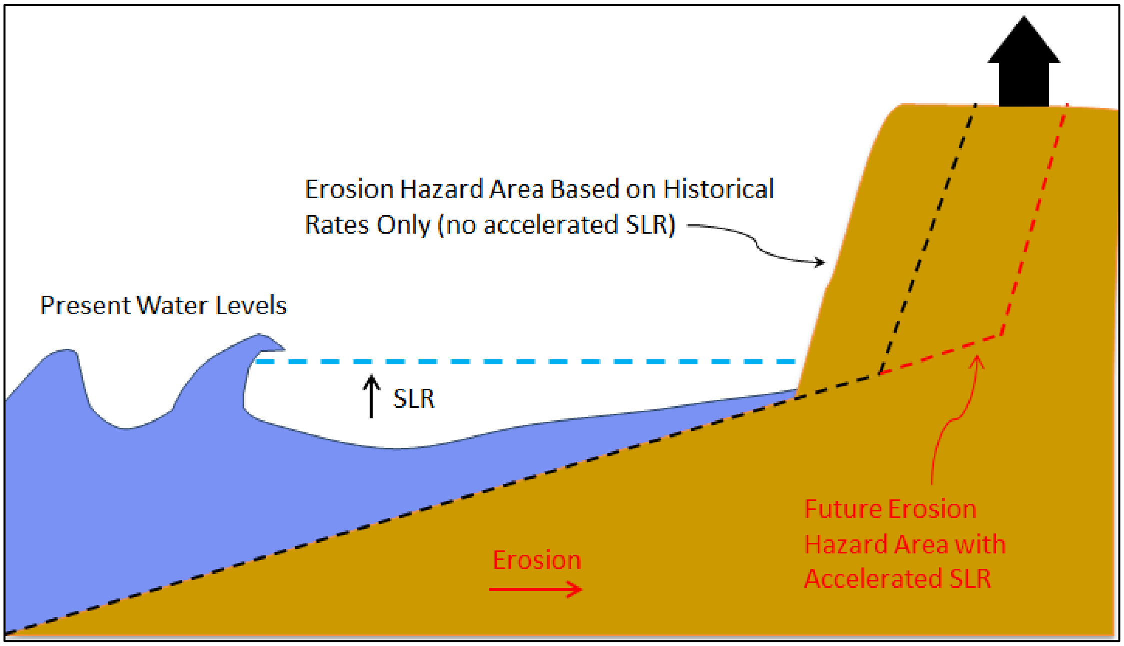


Figure 29. A conceptual sketch of the predicted future erosion response at coastal bluffs.

Rocky ledges were analyzed with the same set of equations; however, the minimum erosion rate of 0.03 meters/year was used.

2.6.3 Hybrid Areas – Sandy Beaches Backed by Coastal Bluffs

Several sections of the coastline in this county consist of sandy beaches backed by tall coastal bluffs. The beaches are expected to erode due to future SLR, and for larger SLR scenarios (Intermediate and High) over longer timeframes (2100), the backing coastal bluffs are also predicted to erode (Figure 30).

Figure 30. An example of a wide sandy beach backed by a coastal bluff from FEMA Region I. The aerial photos show that bluffs to the north are rapidly eroding. The bluffs to the south have historically been stable, although the beach is eroding. The photo shows these bluffs are well vegetated with trails and paths. Future erosion predictions for high SLR scenarios and long timeframes demonstrate that the historically stable bluffs might erode. Compass applied a hybrid analysis approach for these areas.

For each particular SLR scenario and timeframe, the rate of sandy beach erosion was projected in time steps inland along the transect (Equations 4-9) until erosion reached the bluff edge. For the remaining time steps in the future projection, a bluff erosion rate was projected landward (Equations 10-12).

Predictions of future bluff erosion require a bluff erosion rate (LRR) and at these sites there were no bluff erosion rates as the bluffs were historically stable. Therefore, Compass applied the average bluff erosion rate from adjacent reaches, which typically had similar bluff geometries and geomorphologies, to the predictions of future bluff erosion within the hybrid beach and bluff areas.

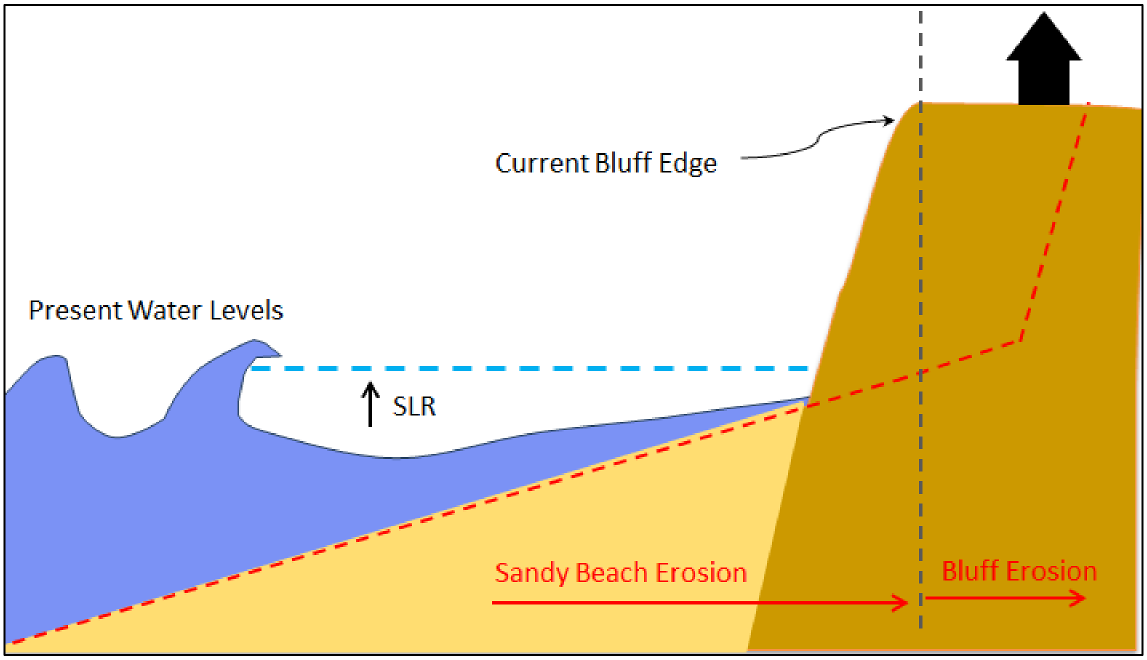


Figure 31. A conceptual diagram of the hybrid approach applied at eroding sandy beaches backed by stable coastal bluffs that are predicted to erode in the future. For each particular SLR scenario and timeframe, sandy beach erosion was projected inland. The sandy beach erosion was projected in time steps and if the beach erosion projected to the bluff edge, bluff erosion was projected landward for the remainder of the timeframe.

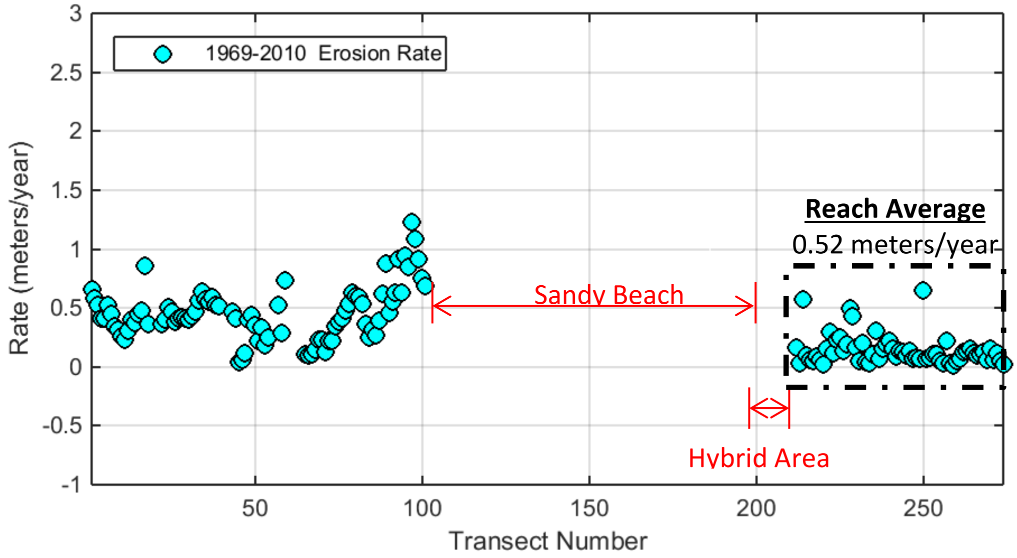


Figure 32. An example of how historical bluff erosion rates (LRRs) are used for the hybrid analysis from a shoreline in FEMA Region I. There are no historical bluff erosion rates for a section of bluffs (Hybrid Area - Transects 200-213); however, there are relatively consistent bluff erosion rates the area north (Transects 213-275). Compass averaged the bluff erosion rates within this adjacent reach (0.52 meters/year) and applied this average rate to the hybrid area.

2.6.4 The Bruun Slope

To estimate the future erosion response due to SLR, Compass applied a modified Bruun Rule as detailed in Section 2.6.1. A conceptual diagram of the Bruun Rule is shown in Figure 33. The Bruun slope (s) is the active nearshore profile slope between the DOC and the foreshore or backshore of the beach. Compass selected MHHW as the landward endpoint as this point is within the active profile range (Table 3).

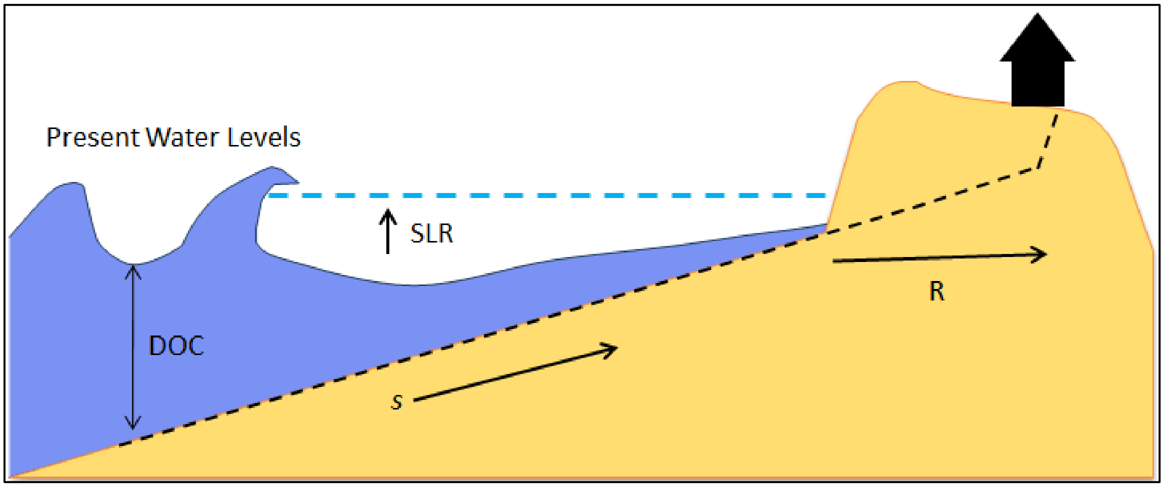


Figure 33. A conceptual diagram of how the Bruun Rule is typically applied with the Bruun slope (*s*) to the DOC. The predicted retreat distance (*R*) is determined by projecting the future amount of SLR landward along *s*.

The two critical technical components of the Bruun slope calculation are 1) the calculation of the DOC; and 2) the calculation of the resulting Bruun Slope. There are many ways to calculate the DOC, which is the deepest depth of cross-shore sediment transport (Hallermeier 1981; Brutsche et al. 2015). As wave energy typically transports sediment offshore, empirical equations are dependent upon characteristic wave heights, wave periods, and sediment characteristics (Hallermeier 1981). Simplified empirical equations are dependent on wave height and wave period only. In the Pilot Study, Compass tested out several equations and determined that calculation of an offshore DOC is best suited to this study. Hallermeier (1978) developed an equation to calculate an outer (more offshore) depth of closure as:

$$DOC = 2\overline{H_s} + 11\sigma_s. \qquad \text{(Equation 13)}$$

where $\overline{H_s}$ is the annual mean significant wave height and σ_s is the standard deviation of the significant wave height. Compass calculated the DOC for different areas of the coast based on publicly available wave data available for each particular area. Wave data sources included the NOAA NDBC and the USACE Wave Information Studies (WIS) program (http://wis.usace.army.mil/).

In the Pilot Study, Compass tested out different methods to calculate the Bruun slope with one specific DOC on variety of cross-shore profiles (Figure 34). This calculation is not necessarily straightforward along cross-shore profiles with sand bars such that there are multiple locations for the DOC. Compass ultimately applied a technique consisting of projecting lines with a range of slopes offshore from MHHW to the DOC. The error between each projected slope and the cross-shore profile is calculated as:

$$\varepsilon = \frac{\sum(z - z_s)^2}{\sum z^2}; \qquad \text{(Equation 14)}$$

where ε is the error, z is each cross-shore profile elevation, and z_s is each elevation along a line with the specified slope. The slope that minimized the error was selected as the best-fit slope. An example of a best fit slope is also shown in Figure 34.

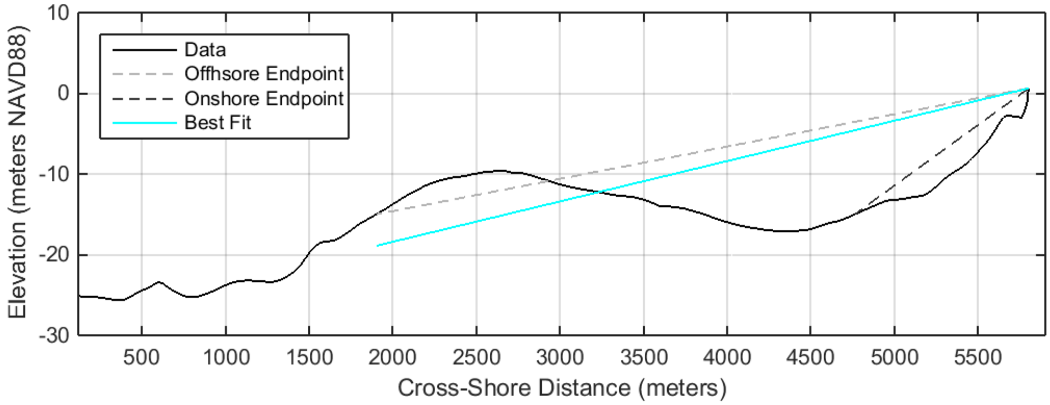


Figure 34. An example of a cross-shore profile that reaches the DOC of -15 meters NAVD88 in two offshore locations, due to the presence of an offshore sand bar. The average "offshore slope" is relatively flat and the average "onshore slope" is relatively steep. Compass used a best-fit slope, which more accurately captures the overall profile slope and is not as sensitive to the presence of offshore bars.

2.7 Field Site Visits

Compass conducted field site visits along the shoreline of Rockingham County on May 9, 2022. Field site visits were used to confirm identified shoretypes (dunes, beaches, coastal marshes, rocky ledges, bluffs). Field staff collected global positioning data (GPS) of NPFs along transect lines (Figure 35). Because of the time difference between the field site visits in 2022 and the topographic LiDAR surveys, there were areas where the locations of the NPFs identified in the field did not exactly match the locations of the NPFs identified in the data. However, the GPS data gave Compass a point of reference to use when analyzing the LiDAR data. Field visits were also used to visually confirm high calculated historical erosion and accretion rates (LRRs). Beaches and bluffs that have historically eroded rapidly show evidence of erosion including scarps, lack of vegetation, bluff collapse, etc. Beaches that have historically accreted rapidly tend to be wide and flat. These visits provided a qualitative check on the calculated rates.

Figure 35. Compass conducted field site visits in Rockingham County, New Hampshire on May 9, 2022.

03 Results

Compass developed paper maps of future erosion hazard areas for the Intermediate SLR scenarios and GIS mapping data for the Low, Intermediate-Low, and High SLR scenarios to the years 2030, 2050, and 2100. This section describes the analysis results and maps.

3.1 Predicted Future Erosion

Predicted future erosion distances for all years and SLR scenarios were calculated and mapped. In general, predicted erosion distances increase with the magnitude of SLR (Low – High) and the length of time (2030 – 2100). The alongshore variability also increases with longer timeframes, with the predictions for 2100 having the largest amount of alongshore variability. This is because small differences between transects in future erosion rates become magnified over a long timeframe (to 2100). Large coastal erosion hazard areas were predicted in areas that have seen rapid erosion (have high LRRs). Along beaches that have historically accreted, some accretion was still predicted for lower SLR scenarios and shorter timeframes. For higher SLR scenarios and longer timeframes, some erosion was predicted.

Figure 36 shows an example of the predicted future coastal erosion hazard areas for the southern coast of Rockingham County, an area where the retreat rates have been mild to moderate. The future hazard zones for the years 2030, 2050, and 2100 under the Intermediate SLR scenario indicate that this could be an area of moderate erosion in the future. The results indicate high future erosion along the beach and dune-backed shorelines. Some wide sandy beaches, have historically accreted. At these beaches, the results indicate that the beaches will continue to accrete or remain stable under lower SLR scenarios and shorter timeframes. Under higher SLR scenarios and longer timeframes, these beaches will begin to erode.

Figure 36. The predicted future erosion distances under the Intermediate SLR scenario for the years 2030 (in yellow), 2050 (in red), and 2100 (in purple) along the southern coast of Rockingham County.

3.2 Coastal Erosion Hazard Area Maps

Compass created GIS shapefile data of the predicted future coastal erosion distances. Paper coastal erosion hazard area maps were created for the Intermediate SLR scenarios (Figure 37) for the years 2030, 2050, and 2100. The Intermediate SLR scenario was selected for mapping as it covers a range of specific SLR increments over the specified timeframes (Figure 25). This range, combined with the three future timeframes, provides coastal communities with a variety of hazard area boundaries to meet the needs of different community members. Homeowners, with typical 30 year mortgages, can use the mapped future coastal erosion hazard areas for the years 2030 or 2050 to understand how their properties might be impacted. Community planners can use the mapped future coastal erosion hazard areas for 2100 to plan long-term mitigation strategies.

A GIS geodatabase (GDB) was created including the mapped erosion hazard areas from the Intermediate SLR scenario and the additional erosion hazard area boundaries for the remaining SLR scenarios (Low, Intermediate-Low, and High).

For complete results it is recommended that the full of set of maps be reviewed.

Figure 37. An example of a map panel with the mapped Intermediate SLR erosion scenarios. Coastal erosion hazard areas area mapped for the years 2030, 2050, and 2100.

3.3 Mapping

Some modifications were made to the erosion hazard area boundaries during the mapping process in GIS. These are described in this section.

Removal of Results at Certain Shoreline Protection Structures: During the Pilot Study it was found that certain coastal protection structures significantly altered historical erosion rates and the future erosion predictions. In many cases, an erosion protection structure had been placed in a particular high erosion area mid-way through the historical period of record. This resulted in the calculation of an intermediate historical erosion rate that was not reflective of either the high erosion environment prior to construction of the structure or the low erosion environment after construction of the structure. Subsequently, the calculations often predicted intermediate erosion distances that were not reflective of the either low erosion environment with the structure being well-maintained until 2100 or the high erosion environment with the structure failing or being removed. Ultimately, to incorporate each structure into the analysis would require knowledge of the structures future performance under future SLR and maintenance, both of which are unknown and beyond the scope of this study. Therefore, mapping modifications were made. An example is shown in Figure 38. Essentially, the results at each identified structure that impacted historic erosion patterns were removed and the hazard areas were interpolated across the predicted area. This created a hazard area that reflects the future unprotected scenario and assumes the structures future performance is uncertain or unknown. It also assumes that the future erosion hazard area is the same as the adjacent, unprotected sections of coast, which have the same exposure and geomorphology. Considering that the goal of the project is to identify areas that are at risk due to future SLR this mapping approach is justified.

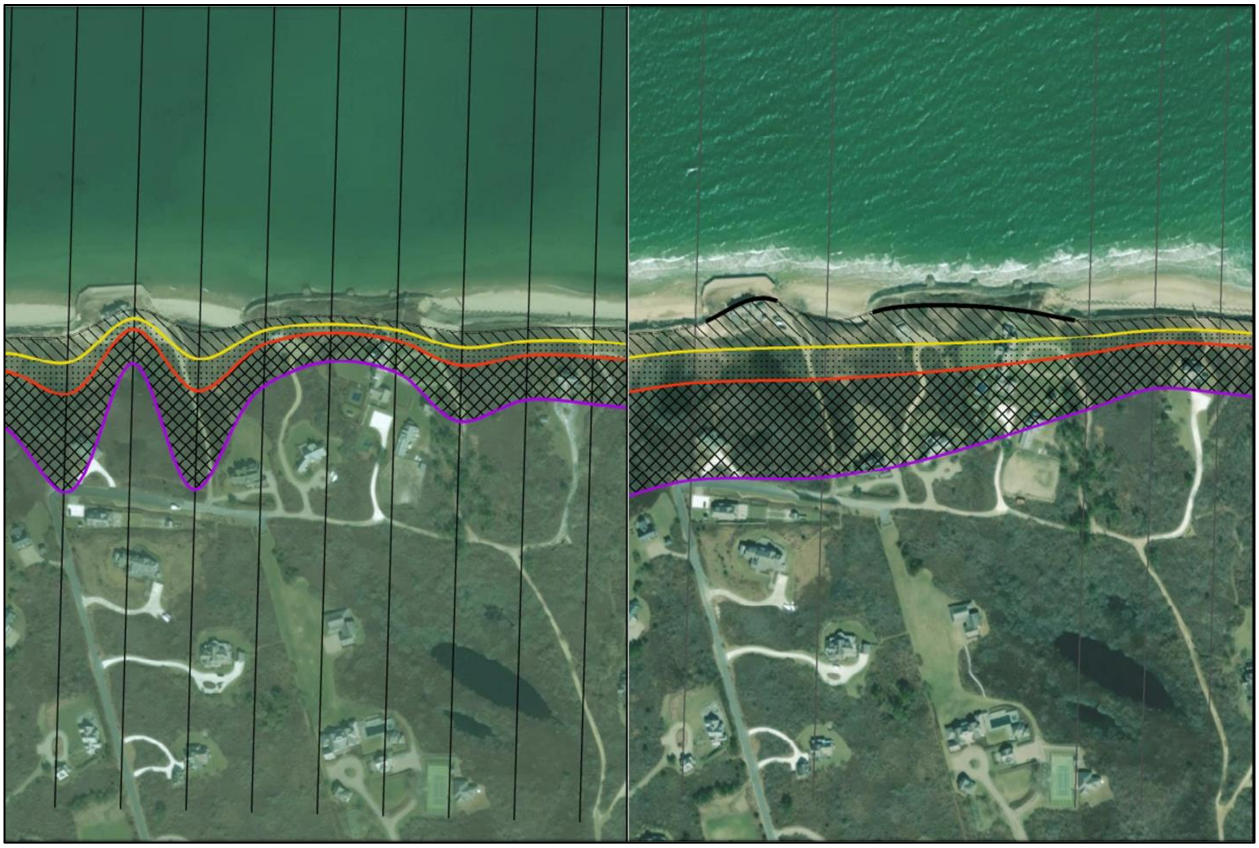


Figure 38. An example of an area where the future erosion predictions were modified in mapping at a coastal protection structure. The left panel shows two coastal protection structures that have impacted the calculation of historical erosion rates and ultimately the prediction of future erosion hazard areas (shown as hatched areas with colored boundaries). Both the historical erosion rates and the future hazard areas are not representative of the coastal geomorphology of the area or the risk posed by future SLR. The right panel shows the mapping technique in which the results at these transects are removed, the hazard areas are interpolated across the protected area, and the Current Coastal Boundary line is highlighted by a black line, indicating the presence of a structure.

Alongshore Smoothing –In the Pilot Study, Compass found that the predicted erosion distances can be variable in the alongshore due to small differences in historical erosion rates, particularly with future erosion predictions over longer time periods like 2100. As the response to future SLR should be somewhat similar over reaches with similar exposure and coastal geomorphology, Compass applied an alongshore moving average to the results, applied over every three transects. This was used to preserve the overall trends in future erosion and smooth out some of the variability over short length scales.

04 Summary and General Recommendations

Compass completed a Study in Rockingham County to predict future coastal erosion hazard areas due to SLR within FEMA Region I. This Study meets a critical need for coastal communities to understand the risk they will face in coming decades and plan for resilience. The Study also meets several agency objectives, including those set forth by FEMA, FIMA, and TMAC.

It is expected that the coastal erosion maps will be presented to key stakeholders Rockingham County during a future outreach meeting. The meeting will be conducted to ensure the community members understand the value of the maps and how they can be used. Further community outreach can help different stakeholders begin to plan mitigation actions and reduce their risk.

Compass mapped future coastal erosion hazard areas for several specific timeframes: the years 2030, 2050, and 2100. These timeframes were adopted to be useful to different community members, ranging from homeowner to community planners.

As with other coastal flood risk products, Compass recommends that the coastal erosion hazard maps be updated at regular intervals in the future, ideally every 15 years. Currently, there is still uncertainty and a large range in future climate change scenarios and SLR projections. In future decades, more observations will allow these SLR projections to be refined. Regular updates to the maps will improve accuracy.

05 Key Staff

The following staff participated in this Study. This study was completed by Compass under the FEMA Region I RTO 60581810.

FEMA

FEMA Region I Risk Analysis Branch Chief

Compass

Jeremy Mull, PE – Technical Lead, Author

Lauren Klonsky, PE, PMP – Project Manager

Brian Caufield, PE – Coastal Engineer and Task Order Manager

Kulvir Singh, CFM – Project Manager

Elena Drei-Horgan, PhD, CFM – Technical Manager

Tim Adams, PE – Coastal Engineer

Amanda Oi, EI, CFM - Coastal Engineer

Erik Kencel, GISP – GIS Analyst

Chris Jones, PE – Subject Matter Expert

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