THE WATER INSTITUTE

CAPE LOOKOUT NATIONAL SEASHORE STORM CHARACTERIZATION

Evaluation in Support of Cultural Resource Management

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Produced for N.C. State University and the U.S. Geological Survey Southeast Climate Adaptation Science Center

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PREFACE

The Water Institute (the Institute) prepared this report in support of an effort led by North Carolina State University (NCSU) to help managers of the National Park Service Cape Lookout National Seashore (CALO) make decisions about stewarding cultural resources in the face of climate stressors. NCSU is enhancing and applying a decision-support framework (the Optimal Preservation tool, OptiPres) to analyze and present tradeoffs between management strategies for historic structures located within CALO under the "Examining Diverse Management Objectives and Broadening Stakeholder Engagement for Climate Adaptation Planning of Historic Structures Stewarded by the National Park Service" project, funded by the U.S. Geological Survey Southeast Climate Adaptation Science Center. Cultural resources in CALO and other coastal parks face increasing risk of inundation and wind damage from storms and sea level rise. The Institute was engaged to develop and apply a method for characterizing the future threat of inundation and storm occurrence, which could then be incorporated into OptiPres by NCSU and collaborators. This report presents the methods and findings of future storm and inundation risk analysis.

ACKNOWLEDGEMENTS

We gratefully acknowledge members of the technical team for the project supporting this work, "Examining Diverse Management Objectives and Broadening Stakeholder Engagement for Climate Adaptation Planning of Historic Structures Stewarded by the National Park Service". The technical team included Erin Seekamp (NCSU), Abu SMG Kibria (NCSU), Xiao Xiao (Arizona State University, ASU), Mitch Eaton (U.S. Geological Survey [USGS]), Peizhe Li (ASU), Robert Young (Western Carolina University, WCU), and Katie Peek (WCU). This team provided input on the methods and results used in the analysis presented here. In addition, Katie Peek provided the structure elevation data used in analyzing risk to historic structures. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Jeff West, Superintendent of Cape Lookout National Seashore, provided valuable information on the impacts of storms on the historic villages of the park and input on refinement of the approach for relevancy to cultural resource management within the park.

This report was reviewed by Alyssa Dausman and reviewed and edited by Charley Cameron.

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LIST OF ACRONYMS

Acronym	Term
ASU	Arizona State University
CALO	Cape Lookout National Seashore
CHS	Coastal Hazards System
NAVD88	North American Vertical Datum of 1988
NCSU	North Carolina State University
NPS	National Park Service
OptiPres	Optimal Preservation
SACS	Southeast Atlantic Coastal Study
SLC	Sea Level Change
SLR	Sea Level Rise
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WCU	Western Carolina University

UNIT TABLE

Abbreviation	Term
ft	feet
km	Kilometers
km/hr	Kilometers per hour
nm	Nautical miles
m	Meters
mb	Millibars
mph	Miles per hour
m/s	Meters per second
yr	Year

INTRODUCTION

The National Park Service (NPS) manages the Cape Lookout National Seashore (CALO), located in North Carolina along the East Coast of the United States (Figure 1). In addition to being an ecologically diverse barrier island landscape with associated habitat and species, CALO hosts multiple cultural resources including the Cape Lookout Lighthouse, culturally significant homes and dwellings, and other structures within the historic districts of Portsmouth and Cape Lookout villages.

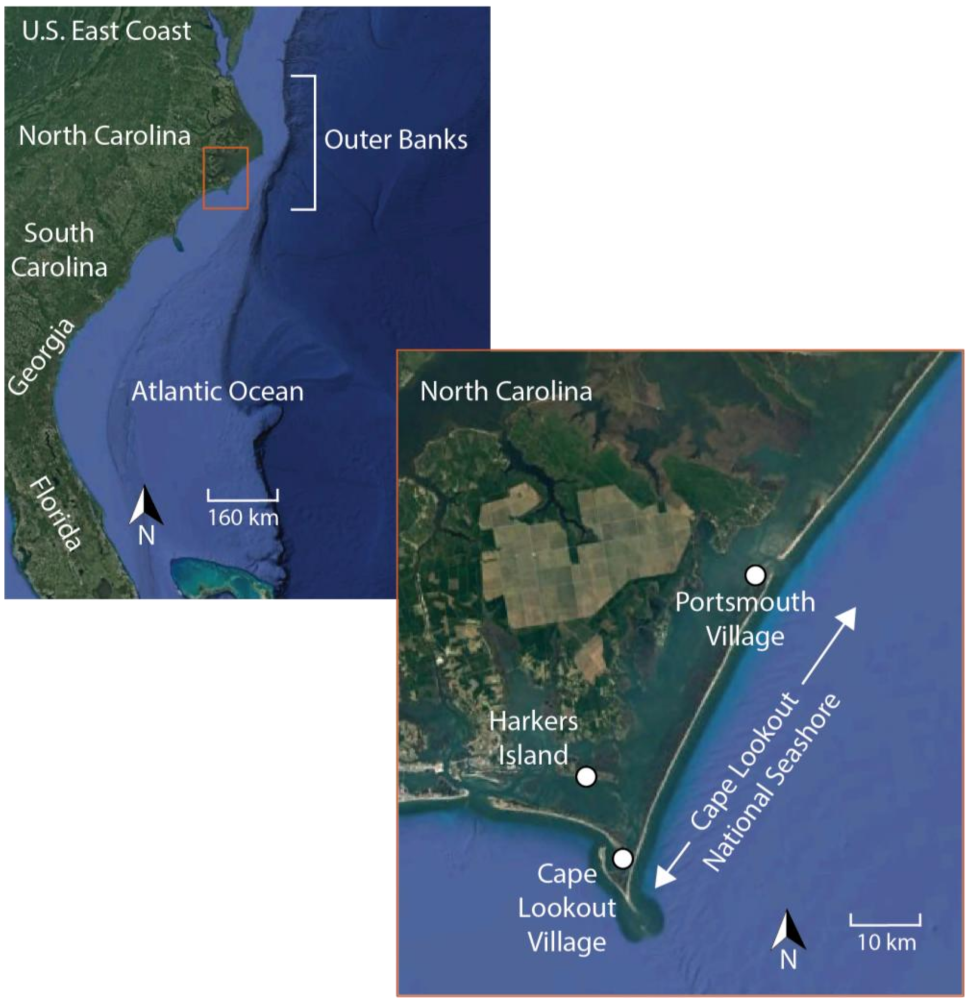

Figure 1. Map of the Southeast Atlantic United States with an inset of the region containing Cape Lookout National Seashore. Background imagery from Google Earth®.

The structures within Portsmouth and Cape Lookout villages are on low-lying land, exposed to the elements, and at high risk to damage from storms and sea level rise (SLR; Barnes, 2013). Residents and stewards of the buildings prior to the villages' incorporation into CALO took storm and flood risk mitigation actions including relocating and elevating structures, as well as building trapdoors into the floors to prevent structural damage by allowing flood water to freely drain during storms (Jeff West, Superintendent of CALO, personal communication). The NPS continues to consider and implement a variety of flood and storm adaptation measures, including temporarily replacing windows with plywood, elevating buildings, and relocating structures (Figure 2).

Figure 2. The 1907 Keeper's Dwelling at Cape Lookout National Seashore, which was relocated in 1958 to become a private residence (the Barden House). Storm risk reduction strategies incorporated into the structure include pilings to elevate the building, which were part of the original design and rebuilt by the private owner when the building was relocated; a short flood wall that was constructed at an unknown date prior to 2002 (Cultural Resources Division, Southeast Regional Office, 2002). Picture by Soupy Dalyander, January 2023.

Decisions for how to manage cultural resources in the face of climate stressors, limited budgets, and other stressors are complex, which lead North Carolina State University (NCSU) to develop the Optimal Preservation (OptiPres) Model (Li et al., 2022; Xiao et al., 2019; Xiao & Seekamp, 2019) to aid CALO park managers in addressing these challenges. The OptiPres framework models, selects, and optimizes management strategies such as annual maintenance and relocation, and includes factors such as maintenance cost, building vulnerability, and visitor and park use. The model implicitly considers storms as a risk incorporated within the structure vulnerability assessments. However, initial development and application of the model at CALO did not explicitly consider the effects of individual storm events in management scenarios, which can be an important driver of damage and repair costs to cultural resources (Xiao et al., 2021).

This report presents the results of work led by the Institute to characterize the historical and potential future risk of storms and flooding events at the Portsmouth and Cape Lookout villages of CALO. This information can be used by NPS park managers in support of decisions made at the park and provides data that can be incorporated within the OptiPres Model to inform evaluation of management strategies.

HISTORICAL STORM CHARACTERIZATION

The first activity conducted for this study was an analysis of the specific drivers of storm impacts to structures within the Portsmouth and Cape Lookout villages of CALO. The location of these historic districts along the Outer Banks of North Carolina makes them vulnerable to ocean- and sound-side flooding, as well as wind damage from storms that pass over the region (Sherwood et al., 2023). The inundation risk from storms to coastal areas that are predominantly exposed to oceanic flooding can be characterized using total water level (TWL), a metric that incorporates the effects of tides, storm surge, and waves. TWL can be calculated with readily available empirical formulations and oceanic data from sources such as National Oceanic and Atmospheric Administration (NOAA) tide gauges (Stockdon et al., 2006). In contrast, Portsmouth and Cape Lookout villages are often inundated by flooding originating in Pamlico Sound (i.e., sound-side), where water levels are a more complex function of storm wind speeds, rainfall, central pressure, diameter/size, forward speed, and track (Peng et al., 2004). These interconnected factors combine to change the rate at which water drains from the Sound relative to the rate at which water enters from sources including inlets to the Atlantic Ocean, rainfall, or runoff from land. The net balance of these inputs and outputs—combined with factors that can drive local changes in water level including waves, air pressure, and winds—dictate storm surge and wave runup in the villages over the course of the storm. The Institute conducted an analysis of historical tropical storms that have passed the region and combined this analysis with information on storm impacts elicited from NPS staff and other stakeholders during an NCSU-led workshop for the project in January 2023. In addition, the Institute coordinated with the project team, comprised of Erin Seekamp (NCSU), Abu Saleh Md Golam Kibria (NCSU), Xiao Xiao (Arizona State University, ASU), Peizhe Li (ASU), Mitch Eaton (U.S. Geological Survey), Robert Young (Western Carolina University, WCU) and Katie Peek (WCU), on methods to characterize storms that could be also integrated into the OptiPres model.

The NOAA Hurricane Database, commonly referred to as HURDAT (Landsea & Franklin, 2013), provided data on the occurrence and characteristics of historical tropical storms. HURDAT data were loaded into Python using the publicly available hurdat2parser (https://github.com/davidstackio/hurdatReader) with custom scripts developed for extraction of storms and associated characteristics. A total of 24 tropical storms of varying intensity passed within 60 nm (approximately 110 km) of CALO during the 20 hurricane seasons between 2002–2021 (Figure 3).

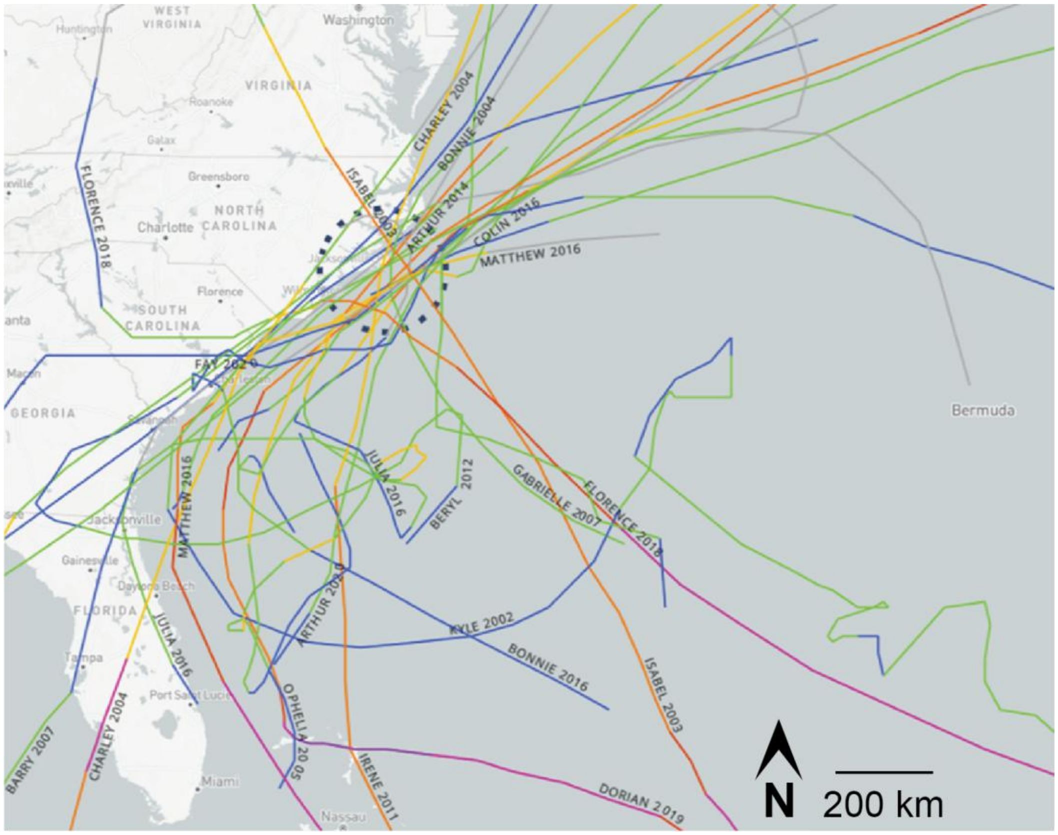

Figure 3. Tropical cyclones passing with 60 nm of Cape Lookout between 2002–2021.Colors indicate the strength of the storm (blue: tropical depression; green: tropical storm; yellow: category 1 hurricane; orange: category 2 hurricane; red: category 3 hurricane; pink: category 4 hurricane; magenta: category 5 hurricane). From https://coast.noaa.gov/hurricanes.

Storms of note due to their intensity and proximity to CALO include (Figure 3, Table 1):

- Isabel (2003): storm eye came onshore at the Outer Banks as a category 2 hurricane.
- Alex (2004): storm eye passed offshore of the Outer Banks as a category 2 hurricane.
- Charley (2004): storm eye came onshore at the Outer Banks as a tropical storm.
- Ophelia (2005): storm eye passed offshore of the Outer Banks as a category 1 hurricane.
- Irene (2011): storm eye came onshore at the Outer Banks as a category 1 hurricane, with winds that encompassed the region during approach as category 2 before weakening with landfall.
- Arthur (2014): storm eye passed laterally along the Outer Banks as a category 2 hurricane.
- Matthew (2016): storm eye passed offshore of the Outer Banks as a category 1 hurricane.
- Florence (2018): storm eye came onshore south of CALO as a category 2 hurricane, with winds that encompassed the region during approach as a category 4 before weakening with landfall.
- Dorian (2019): storm eye passed offshore of CALO as a category 2 hurricane, with winds that encompassed the region during approach as a category 3 before weakening with landfall.

Storm classifications given are based on the Saffir-Simpson Hurricane Wind Scale, which categorizes hurricanes based on their maximum sustained wind speeds (Saffir & Simpson, 1971).

Table 1. Tropical storms passing within 60 nm (approximately 112 km) of Cape Lookout National Seashore. This table shows the closest distance the storm passed to the seashore (in nautical miles, nm, and kilometers, km) and the characteristics of the storm at that point in time, including wind speed (in knots and kilometers per hour, km/hr) and central pressure (in millibars, mb).

Storm	Year	Distance (nm)	Distance (km)	Wind Speed (knots)	Wind Speed (km/hr)	Pressure (mb)
Dorian	2019	35.28	65.34	90	167	956
Florence	2018	36.39	67.39	90	167	952
Matthew	2016	27.11	50.21	70	130	983
Arthur	2014	6.49	12.02	85	157	974
Irene	2011	6.49	12.02	75	139	952
Ophelia	2005	13.3	24.63	70	130	982
Charley	2004	77.57	143.66	60	111	1000
Alex	2004	25.26	46.78	85	157	974
Isabel	2003	24.27	44.93	90	167	957

This assessment of historical tropical storms was presented to NPS personnel, the project technical team, and other stakeholders interested in preserving the historic structures of CALO and served as the basis of a discussion around the characteristics of storms causing damage to buildings. In addition, records and stories of storm impacts presented in a display curated by the Core Sound Waterfowl Museum and Heritage Center (hereafter the Core Sound Museum) on Harkers Island, North Carolina were reviewed.

The stakeholder group and NPS noted that high intensity storms in HURDAT (category 2+) that passed near CALO caused damage ranging from minor cosmetic issues and wind-driven loss of non-structural components such as shingles to more catastrophic flooding, structural damage, and total building loss. Stakeholders highlighted the damage caused by hurricanes Florence and Dorian in particular, during which buildings were swept from their foundation or destroyed because of inundation from Pamlico Sound. Similarly, the archives in the Core Sound Museum highlighted a range of impacts from these storms to the people and communities living near to CALO, including stories from residents with homes that had survived decades of storms, but which were lost or flooded during hurricane Dorian. Park managers identified six historic structures within CALO for demolition in 2020 following irrecoverable wind and water damage from Dorian (Price, 2020). Input regarding the type of damage incurred and the major drivers was consistent with academic studies finding that sound-side surge is a significant component of flood risk in this region, while wind-driven impacts from local storms can also cause damage to historic structures (Ho & Tracey, 1975; Sherwood et al., 2023; Sparks, 2003). NPS decision makers also expressed concerns about flooding not associated with tropical storms. High water level and winds from extratropical storms and high tide (“sunny day”) flooding exacerbated by SLR could potentially increase maintenance costs or impede visitor access to the historic villages, particularly the relatively low-lying and remote Portsmouth Village. The Institute considered this input on flooding and the characteristics of storms that drive damage when designing the evaluation of future storms and flooding, given that the primary focus of storm characterization is to inform management of cultural resources at CALO.

FUTURE STORMS AND SEA LEVEL RISE

Based on feedback from NPS, the project team identified two primary areas of decision-relevant information that could support CALO in the face of storms and SLR:

1. Understanding the recurrence of minor flooding and storm impacts, which over time could increase the annual maintenance cost of historic buildings to unsustainable levels and/or inhibit access for park visitors; and
2. Identifying realistic scenarios of moderate and major storms that could drive significant degradation in building conditions and necessitate immediate, major repairs.

Given the importance of future SLR in exacerbating flooding at CALO, the HURDAT database—which as a historical database does not include this factor—has limited utility. Instead, the Institute used output from the U.S. Army Corps of Engineers (USACE) Southeast Atlantic Coastal Study (SACS) Coastal Hazards System (CHS; USACE, 2021). As part of the SACS CHS, USACE simulated storm surge and waves for: 7 historical tropical storms, including Hurricanes Hugo (1988), Andrew (1992), Fran (1996), Frances (2004), Matthew (2016), Irma (2017), and Florence (2018); 70 historical extratropical storms (i.e., winter storms or "Nor'Easters"); and 1060 synthetic tropical storms from a database USACE developed to capture the range of variability in future events. Synthetic storms include an associated probability in storms/year (note, probability mass is a probability discretized into bins, rather than being a continuous function). USACE modeled storms for four water level conditions including baseline (2020 conditions), baseline plus tides, and baseline plus two SLR scenarios corresponding to basin average sea level changes (SLC) of 0.83 m (2.73 ft) and 2.24 m (7.35 ft). These SLR amounts are expected to occur at CALO within the next 50–100 years for USACE-predicted low to high SLR scenarios (USACE, 2021).

FLOODING RECURRENCE

To evaluate the recurrence of flooding that could potentially increase annual maintenance costs and reduce visitor access or use, the Institute downloaded annual exceedance probability curves for two non-tidal water level scenarios included in the SACS CHS database (SLC0, 2020 conditions; and SLC1, 0.83 m increase, benchmarked as occurring in 2120; https://data-sacs.opendata.arcgis.com/). The annual exceedance probability (AEP) is the chance that a specific water level will occur during any given year. Data were downloaded for the save points (i.e., locations in the model grid used for the SACS CHS study where model output was archived) closest to Cape Lookout (save point 5693) and Portsmouth (save point 4113) villages (Figure 4).

Figure 4. Location of Southeast Atlantic Coastal Study Coastal Hazards System save points (i.e., model output locations) used for characterizing storms and flooding for Cape Lookout and Portsmouth villages. White arrow and yellow circle indicate the location of the USACE model save points used for the analysis; small orange dots and white numbers indicate the locations of other save points. Background imagery from Google Earth®.

The Institute compared the AEP curves for these locations to historic structure threshold elevations (i.e., the elevation at which rising water would negatively impact the building), which Peek et al. (2022) generated as part of assessing vulnerability across all coastal NPS units. The threshold elevation of historic structures in Cape Lookout Village ranged from 1.1–3.0 m (Table 2) and from 0.9–1.4 m for Portsmouth Village (Table 3). Elevation bins were defined for each village (i.e., a set of discrete elevation ranges), allowing the buildings to be categorized based on their risk of inundation. The three elevation bins for Cape Lookout Village were: low, threshold elevations less than 2.0 m, with 1.6 m used as the characteristic bin elevation; medium, threshold elevations between 2–2.5 m, with 2.2 m used as the characteristic bin elevation; and high, threshold elevations greater than 2.5 m, with 3.0 m used as the characteristic bin elevation. A single elevation bin with a characteristic elevation of 1.2 m was used for Portsmouth Village due to the relatively small range of variation in threshold elevations for the site.

Table 2. Cape Lookout Village structures used in analyzing storm and flood recurrence. The Superintendent of Cape Lookout National Seashore specified which buildings to include in the analysis; some structures without historical significance were excluded. Elevations are given in meters (m) North American Vertical Datum 1988 (NAVD88).

Location	Threshold Elevation (m, NAVD88)
Cape Lookout Coast Guard Station	3.4
Cape Lookout Coast Guard Station Equipment Building	1.498
Cape Lookout Coast Guard Station Galley/Summer Kitchen	3.4
Generator Storage Shed Les & Sally's	2.8
Les & Sally's Main Building	2.386
Les and Sally's Summer Kitchen	2.8
Les and Sally's Shed	2.8
Sleeping Quarters # 1 Les & Sally's	2.986
Sleeping Quarters # 2 Les & Sally's	2.997
Cape Lookout Light Station Oil House	1.737
Lighthouse Keepers Quarters	2.122
Lighthouse Summer Kitchen	2.027
Barden House- 4C Keepers Quarters	2.279
Bryant House	1.463
Coca-Cola House	1.708
Fishing Cottage #2	1.742
Fishing Cottage #2 Generator Building	1.3
G.C. Willis House	1.705
Gaskill-Guthrie House	1.733
Generator Building at Barden House-4C Keepers Quarters	1.1
Guthrie Ogilvie House	1.686
Jetty Worker #1 Equipment Storage	1.475
Jetty Worker House #1	1.475
Lewis/Davis House or Carrie Arendell House	1.52
Life Saving Station Boat House	1.735
Life Saving Station, Cape Lookout Village	1.436

Table 3. Portsmouth Village structures used in analyzing storm and flood recurrence. The Superintendent of Cape Lookout National Seashore specified which buildings to include in the analysis; some structures without historical significance were excluded. Elevations are given in meters (m) North American Vertical Datum 1988 (NAVD88).

Location	Threshold Elevation (m, NAVD88)
Carl Dixon House, HS-521	1.362
Cecil Gilgo House, HS-515	1.279
Dennis Mason/Dave Willis House HS-503-A	1.218
Dixon-Salter House (VC), HS-519-A	1.127
Ed Styron House, HS-505	1.45
George Dixon House, HS-510	0.939
Henry Pigott House, HS-511-A	1.185
Jesse Babb House, HS-504-A	1.159
McWilliams-Dixon House	1.332
Portsmouth Church	1.174
Portsmouth Life-Saving Station	0.96
Portsmouth Life-Saving Station Kitchen	1.225
Portsmouth Life-Saving Station Stable	0.944
Post Office and General Store, HS-518	0.951
Robert Wallace House (Old Grace House)	1.061
Roy Robinson House, HS-502	1.612
Schoolhouse, HS-516-A	1.205
Styron-Bragg House, HS-523	1.268
Tom Gilgo House, HS-512	1.122
Washington Roberts House	1.086

The Institute compared village threshold elevations to the AEP for the USACE SLC0 (0 m SLR, corresponding to year 2020) and SLC1 (0.83 m SLR, benchmarked as occurring in 2120) as a first estimate of the frequency at which water levels would exceed building threshold elevations (Figure 5). For Cape Lookout Village, the recurrence interval of floodwater exceeding the low elevation bin threshold elevation is 0.05 (once every ~25 years), increasing to 0.77 (once every ~1.3 years) for SLC1; the medium elevation bin is 0.003 (once every ~250 years), increasing to 0.09 (once every ~11.5 years) for SLC1; and the high elevation bin is 4e-5 (negligible risk), increasing to 0.004 (once every ~250 years) for SLC1. For Portsmouth Village, the recurrence interval of floodwater exceeding the elevation bin threshold elevation is 0.4 (once every ~2.6 years). Projected flooding for Portsmouth Village is not well-resolved in the AEP for SLC1 but exceeds once a year. These values do not include the effects of tides, which vary water levels at Cape Lookout 1.4 m between mean lower-low water and mean higher-high water (https://tidesandcurrents.noaa.gov/datums.html?id=8656841).

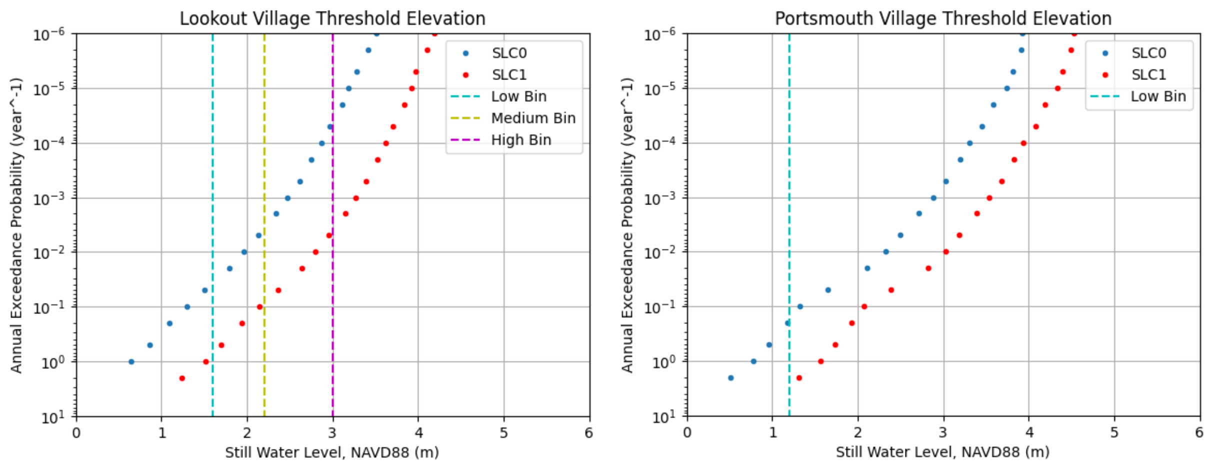

Figure 5. Comparison of Annual Exceedance Probability (AEP, in yr^{-1}) of still water levels in North American Vertical Datum 1988 (NAVD88) to the threshold elevations in Lookout and Portsmouth villages for two sea level changes (SLC0, 2020 conditions, blue dots; SLC1, increase of 0.83 m, red dots).The AEP is the chance that a specific water level will occur during any given year and still water level refers to the water level reached through the combined action of tides and storm surge, but not waves. Vertical lines show elevations corresponding to low, medium, and high threshold elevation bins for Cape Lookout Village (left) and for the single, low elevation bin representating Portsmouth Village (right).

SCENARIOS OF MODERATE AND MAJOR EVENTS

Based on input received during a working session with NPS, the Institute classified individual storms likely to cause damage requiring immediate repair into two categories: (1) moderate events with wind as the primary driver of building damage, which ranges from loss of shingles and other non-structural elements up to roofs being blown from buildings; and (2) major events where buildings are flooding and damage can be as severe as buildings being washed from their foundations or entirely destroyed. The criteria used for major and moderate storms were:

- **Moderate Event:** Local wind speed exceeds 20 m/s (~45 mph, corresponding to a tropical storm of moderate strength), with storm surge below the threshold for a major event.
- **Major Event:** Local storm surge exceeds elevation bin thresholds, corresponding to flooding events; and

The Institute compared these thresholds to the seven storms in the SACS CHS historical tropical storm database to determine if classification is consistent with prior observed impacts. Hurricanes Matthew and Florence are classified as major (flooding) events for Portsmouth Village and the low elevation bin of Cape Lookout Village; Hurricane Fran is a moderate (wind) event for both villages; and Hurricanes Hugo, Andrew, Frances, and Irma fall below the threshold for either category. Hurricanes Matthew and Florence (Sherwood et al., 2018; Wang et al., 2022) did drive extensive flooding in the region, while wind-driven damage from Hurricane Fran was observed (Marshall, 1998).

The Institute applied the thresholds of moderate and major events to classify events within the SACS CHS database for SLC0 and SLC1 as part of generating a **realistic** scenario of future storm events including SLR. This scenario was developed for use in the OptiPres model to evaluate how management decisions might change if and when storm events occur, and is not intended as a prediction of when storms would occur or their severity.

The USACE synthetic storm database, which includes a probability mass for each event, was used to identify tropical storms. The overall probability of major and moderate tropical storms was created by summing the probability mass of events with each classification. Historical extratropical storms were similarly categorized as moderate or major, and the probability of occurrence was calculated as the number of storms in the database divided by the 75 years (1942–2016) for which the SACS CHS modeled these events. The overall recurrence interval of major and moderate events was calculated by combining statistics for major and moderate events (Table 4). This method was used to generate an estimate of recurrence intervals for producing a realistic scenario of future storms and is not intended to produce a statistically robust evaluation of recurrence probabilities. It also excludes consideration of nonlinear effects and climate-scale oscillations such as El Niño/La Niña, as well as potential climate trends such as changes in storm intensity, size, frequency, or track.

Table 4. Approximate recurrence interval of major and moderate storm events under different sea level changes (SLC0, 2020 sea levels; SLC1, 0.83m of rise). The likelihood of an event within 1 year (yr) and the frequency at which an event is likely to occur is provided. Moderate events become less likely as more events are classified as major. The flooding risk to the Cape Lookout high elevation bin is negligible (occurrence less frequently than once every ~650 years in the SLC1 scenario)

Site	Elevation Bin	SLR	Major Event (yr^{-1})	Moderate Event (yr^{-1})
Cape Lookout	Low	SLC0	0.027 (event every ~36 yrs)	0.454 (event every ~2 yrs)
	Low	SLC1	0.217 (event every ~4.5 yrs)	0.279 (~1 event every 3.5 yrs)
	Medium	SLC0	1e-5 (event every ~640 yrs)	0.479 (event every ~2 yrs)
	Medium	SLC1	4e.2 (event every ~21 yrs)	0.435 (event every ~2 yrs)
Portsmouth	Low	SLC0	0.132 (~1 event every 8 yrs)	0.339 (~1 event every 3 yrs)
	Low	SLC1	1.027 (events per yr)	0.040 (~1 event every 25 yrs)

For structures in the low elevation bin at Cape Lookout Village, major events are likely to occur every ~36 years under present day conditions, increasing to every ~4.5 years for SLC1. Flood risk to structures in the medium elevation is negligible at current sea levels, increasing to an event every ~21 years for SLC1. Flood risk to structures in the highest elevation bin is negligible (event less than once every ~650 years) under the SLC0 and SLC1 scenarios. For Portsmouth Village, major events are likely to occur every ~8 years under present day conditions, increasing to an event a year under SLC1. The recurrence interval of moderate events decreases with increasing sea level as more events fall into the major classification (i.e., more minor storms with weaker winds can cause flooding and the potential for high winds without flooding decreases). At Cape Lookout Village, moderate events are likely to occur every 2 years under present day conditions, decreasing to every 4 years under SLC1. At Portsmouth Village, moderate events are likely to occur every 3 years under present day conditions, decreasing to every 25 years under SLC1.

INCORPORATION WITH OPTIPRES

The analysis of approximate recurrence interval of moderate and major events under varying SLR scenarios was used to generate a realistic storm sequence for inclusion in the OptiPres model by associating the USACE SLC1 level to a benchmark year. Forecasts used by NPS for CALO estimate that between 0.53–0.76 m of SLR will occur by 2100 (Peek et al., 2022), consistent with an estimate that the USACE 0.83 m SLC1 scenario will occur in ~2120. A linear increase in storm frequency was assumed and used to approximate the time-varying recurrence interval of storms in 5-year intervals over the OptiPres planning horizon of 2020–2055 (Table 5).

Table 5. Time-varying estimate of the number of years between major storm events for Portsmouth Village and low, medium, and high structure elevation bins for Cape Lookout Village.

Site	2020	2025	2030	2035	2040	2045	2050	2055
Portsmouth (Low)	7.5	7	6.5	6	5.5	5.5	5	4
Cape Lookout (Low)	36.5	20.5	14	11	9	7.5	6.5	5.5
Cape Lookout (Medium)	643	39	20	13.5	10	8	7	6
Cape Lookout (High)	Flooding of structures in highest bin unlikely in 2055 (once every ~650 yrs)							

The time-varying estimate of storm recurrence interval was used to inform a qualitatively developed, realistic sequence of storms for the 2020-2056 planning period modeling with OptiPres:

- Portsmouth Village: storms in 2024, 2030, 2036, 2042, 2046, 2050, and 2054.
- Lookout Village, low elevation bin: storms in 2028, 2038, 2046, and 2052.
- Lookout Village, medium elevation bin: storms in 2028 and 2046; and
- Lookout Village, high elevation bin: no storms included.

The storm sequence includes the assumption that any storm impacting structures in the medium elevation bin at Cape Lookout Village will also impact structures in the low elevation bin. In addition, one storm was included (in 2046) that would impact both villages to evaluate what the impacts on management decisions would be if a storm track resulted in damage at both locations. Moderate (wind-only) events at all villages are estimated to occur every ~2 years, which can inform inclusion of need for relatively minor structural repairs in OptiPres.

CONCLUSION

This study focused on characterizing storm and flooding events at CALO to inform development of realistic future scenarios for inclusion within the OptiPres decision support framework, which provides information to help NPS managers select adaptation actions for cultural resources. A literature review of historical storms indicates that flooding from Pamlico Sound and high winds drive significant damage to culturally significant structures within the historic villages of Cape Lookout and Portsmouth. Prior major hurricanes in the area include Florence (2018) and Dorian (2019), which led to major damage and total loss of several historic buildings within CALO. NPS personnel and local stakeholder groups corroborated this finding and indicated that flooding tends to cause the most severe structural damage to buildings. Although storms with high winds and no flooding have impacted buildings, the damage is typically less severe and more readily repairable than flood-related damage (e.g., shingle loss, non-structural damage, or loss of roofs in extreme cases, in comparison to flooding that could sweep a structure off its foundation or lead to complete destruction).

Park managers indicated two primary concerns related to future storms and flooding: (1) an increase in minor flooding over time could increase annual maintenance cost of historic buildings to unsustainable levels and/or inhibit visitor access; and (2) the frequency of storms leading to damage requiring immediate repair could increase. The Institute assessed these risks using model output from the USACE SACS CHS. The annual exceedance probability of water levels exceeding building threshold elevations was used to evaluate future increases in annual maintenance cost or reduced visitor access under each of the three scenarios of sea level change modeled by USACE (SLC0, 2020 conditions; SLC1, 0.83 m increase, estimated to occur in ~2120). For Cape Lookout Village, the recurrence interval of floodwater impacting the lowest elevation (most at risk) structures is 0.05 (once every ~25 years), increasing to 0.77 (once every ~1.3 years) for SLC1; impacting moderate elevation structures is 0.003 (once every ~250 years), increasing to 0.09 (once every ~11.5 years); and impacting the highest elevation structures is 4e-5 (negligible risk), increasing to 0.004 (once every ~250 years). For Portsmouth Village, the recurrence interval of floodwater exceeding building threshold elevations is 0.4 (once every ~2.6 years).

Events within the SACS CHS historical extratropical and synthetic tropical databases were also classified based on whether storm surge would exceed structure threshold elevations (major event) or had winds exceeding 20 m/s (~45 mph) without flooding (moderate event). For Lookout Village, major events are likely to impact the lowest elevation structures every 36 years under present day conditions, increasing to every 5 years for SLC1; flooding risk to moderate elevation structures is negligible at current sea levels, increasing to approximately an event every ~21 years for SLC1. For Portsmouth Village, major events are likely to occur every ~8 years under present day conditions, increasing to an event a year under SLC1 and to over 3 events per year under SLC2. The recurrence interval of moderate (wind-only) events is approximately every 2–3 years, decreasing with time as more storms in the databases fall into the major classification with sea level rise.

The information provided above can be directly used by NPS personnel to inform future management decisions. In addition, the future likelihood of storm and flooding was combined with input from NPS to produce realistic scenarios of major and moderate storm events for inclusion in the NCSU OptiPres decision support framework. The approach used here is also portable and can be applied to any region of the coast where USACE SACS CHS model output, or a similar estimate of storm surge under rising sea levels, is available.

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