

Forecasting oceanfront shoreline position to evaluate physical vulnerability for recreational and infrastructure resilience at Cape Hatteras National Seashore

By

Michael J. Flynn¹ and David E. Hallac²

1) Coastal Resources Management, East Carolina University, East 5th St Greenville, NC 27858; flynnmi13@students.ecu.edu

2) Cape Hatteras National Seashore, National Park Service, 1401 National Park Drive, Manteo, NC 27954

ABSTRACT

The Cape Hatteras National Seashore (Seashore) is located along the Outer Banks of eastern North Carolina, and is renowned for its prominent historical landmarks and world-class recreation. Seashore managers maintain hundreds of assets that support visitor use. Additionally, and primary to the mission of the National Park Service (NPS), managers steward natural and cultural resources located on public and protected lands. The portfolio of assets managed by NPS within the Seashore carries a high level of risk due to its exposure to both coastal erosion and storm surge inundation. The impacts of Hurricane Dorian demonstrated the importance of examining the physical vulnerability of the entire portfolio managed by NPS within the Seashore. The purpose of this study was to 1) evaluate the functionality of the beta forecast tool available in the Digital Shoreline Analysis System (v 5.0); and 2) explore options for using the output to assess the potential physical vulnerability of NPS assets. The study determined that using the 10- and 20-year oceanfront shoreline position forecast provides decision makers with a first order screening tool that can be used to prioritize mitigation and adaptation strategies given the unpredictable nature of tropical and extra-tropical cyclones and uncertainty associated with sea level rise.

Broader-scale modifications of the climate from decades of increased human-driven emissions have accelerated rates of sea level rise and increased the frequency of more intense storms as a result of warmer ocean and atmospheric temperatures (Church *et al.* 2013). The combination of increased magnitude and frequency of multiple coastal hazards presents a variety of challenges associated with managing publicly accessible parks and protected lands (Murdukhayeva *et al.* 2013; Peek *et al.* 2015; Schupp *et al.* 2015). Managers seek tools to assist with prioritization and implementation of hazard mitigation and coastal adaptation measures to inform decision-making and allow for a balanced approach to natural and cultural resource management and the protection of critical infrastructure that supports coastal development and tourism-based economies along barrier islands (Caffrey *et al.* 2018; Murdukhayeva *et al.* 2013; Peek *et al.* 2015; Schupp *et al.* 2015).

Established in 1953, the Cape Hatteras National Seashore (Seashore) is located along the Outer Banks of eastern North Carolina. The Seashore is comprised of

an approximately 67-mile-long, narrow string of wave-dominated barrier islands (Davis and Hayes 1984; Gutierrez *et al.* 2007; Hayes 1979; Riggs *et al.* 2011), and is renowned for its prominent historic landmarks and world class recreation (Figure 1). In recent years, more than 2.5 million recreational visits have been recorded annually (NPS 2020), and results from a visitor survey indicate that only five percent of visitors make day trips whereas 95% of visitors stay overnight typically for a week in duration (Outer Banks Visitors Bureau 2015).

Seashore managers maintain hundreds of assets that support visitors including parking lots, beach accesses and boardwalks, restrooms, visitor centers, and roads. Additionally, and primary to the mission of the National Park Service (NPS), managers steward natural resources including wildlife and their habitats and cultural resources including shipwrecks and historic properties.

National level modeling efforts conducted by the National Oceanic and Atmospheric Administration (NOAA) (Marcy *et al.* 2011), and U.S. Geological

KEYWORDS: Hurricane Dorian, shoreline change, sea level rise, hazard mitigation, coastal adaptation, asset management.

Manuscript submitted 15 February 2021; revised & accepted 14 April 2021.

Survey (USGS) (Gutierrez *et al.* 2014; Himmelstoss *et al.* 2017; Thieler and Hammar-Klose 1999) have illustrated which coastal regions are most susceptible to the impacts of multiple hazards including erosion, storm surge inundation, and sea level rise. The narrow string of wave-dominated barrier islands that form the Outer Banks of North Carolina are classified as having a predominately high to very high susceptibility to potential coastal change associated with sea level rise based on a coastal vulnerability index referenced to a combination of physical variables that includes: geomorphology, regional coastal slope, tidal range, wave height, relative sea level rise, and shoreline change (Pendleton *et al.* 2004; Thieler and Hammar-Klose 1999).

Regional vulnerability analyses are possible at the national scale at which the information is displayed within the Coastal Change Hazards Portal developed by the USGS and the Sea Level Rise Viewer developed by the NOAA Office of Coastal Management. Simulations with the aid of these tools indicate continued erosion, storm surge inundation, and sea level rise will impact cultural and historic sites, public and private properties, infrastructure related to transportation and utilities, recreational amenities, and the ecological integrity of the barrier islands that form the Outer Banks. Peek *et al.* (2015) and Caffrey *et al.* (2018) identified the high risk and exposure storm surge and sea level projections posed to resources and assets within the Seashore, which is managed by the Outer Banks

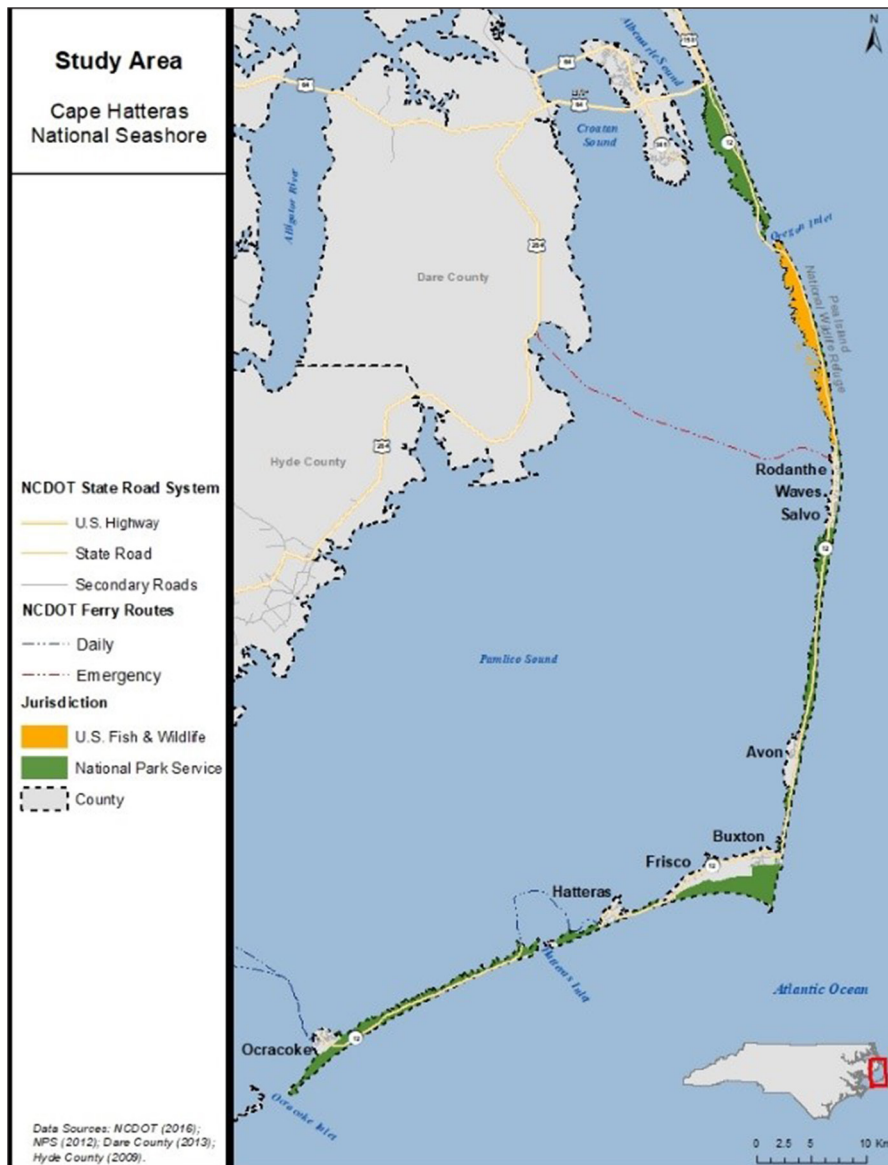


Figure 1. Cape Hatteras National Seashore, located in eastern North Carolina.

Group of NPS, compared to other coastal park units.

Seashore managers recognized the physical vulnerability of historic structures located within the Seashore, and developed a coastal hazard vulnerability assessment to assist park managers with long-term planning (Allen *et al.* 2017). The primary objective of the project included evaluating the physical vulnerability of 27 historic structures standing within the Seashore to multiple hazards including coastal erosion, storm surge inundation, and sea level rise using a GIS-based approach over a 50-year planning horizon (Allen *et al.* 2017). The first-order estimate of the extent of potential inundation from sea level rise was generated by overlaying raster grids of potential sea level rise (0.3 m, 0.6 m, and 0.9 m

above mean higher high water) available for download from the NOAA SLR Viewer and examining the proximity the building footprint to the extent of each scenario (Allen *et al.* 2017). The coastal erosion hazard was evaluated for select historic sites located within proximity to the oceanfront. Rate-of-change statistics such as the linear regression rate were calculated using the Digital Shoreline Analysis System (DSAS) (v 4.3.4730) based on historical shoreline shapefiles from 1946, 1980, 1997, 1998, 2004, and 2009 (Allen *et al.* 2017). To evaluate the erosion risk of select historical structures the distance was first measured from the structure to the most recent oceanfront shoreline (2009). The linear regression rate was projected along the transect nearest to the select historical site in 10-, 25-, and 50-year increments to display

how the spatial proximity of each historic site to the oceanfront may change over time based on historical rates (Allen *et al.* 2017).

Evaluating the potential physical vulnerability of the historic sites to potential storm surge inundation was the most robust component of the multi-hazard assessment. Inundation raster grids were generated by differencing the maximum water level from the NOAA National Hurricane Center (NHC) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) basin models for Category 1-5 hurricanes to the elevation data acquired for the North Carolina Floodplain Mapping Program (Allen *et al.* 2017). The resultant water level was extracted at the center of the footprint of the historic structure and compared to the first floor elevation (FFE) to determine if inundation exceed the FFE (Allen *et al.* 2017). This exercise was repeated with the addition of simulated sea level rise scenarios (20 cm, 40 cm, 70 cm, 100 cm, and 140 cm) to evaluate how the present day physical vulnerability to storm surge inundation changes with the addition of relative sea level rise (Allen *et al.* 2017). The results of that simulation illustrated that lower magnitude storms may inundate a greater extent of land and structures as relative sea level rises.

The results of that study were tested when the eye of Hurricane Dorian passed near the Outer Banks for several hours before making landfall over Cape Hatteras at 1230 UTC on 6 September 2019 with 85-kt winds (Avila *et al.* 2020). The combined effect of the storm surge and tide produced total inundation levels of 1.5 to 2.1 m above ground level on parts of Ocracoke and Hatteras Islands (Avila *et al.* 2020) (Figure 2). After approaching eastern North Carolina, Hurricane Dorian accelerated northeastward and cleared the Outer Banks less than six hours following landfall, but the impact of that landfalling hurricane persists today. The storm surge inundation and wave erosion reshaped sections of the barrier islands, and damaged two 150 m sections of N.C. Highway 12 (NC-12) on the north end of Ocracoke Island near the NC Ferry Terminal (NPS 2019) (Figure 3).

The impacts of Hurricane Dorian demonstrated the importance of expanding on the Allen *et al.* (2017) study, and examining additional risk factors and

other assets as part of the entire portfolio managed by NPS within the Seashore. Obtaining basic data on the dynamics of the beach and dune system and the progressive changes along the oceanfront shorelines is an important first step to assess the physical vulnerability of infrastructure that supports recreational use and park administration throughout the Seashore.

The National Assessment of Shoreline Change developed by the USGS identifies areas of the nation's coastline that are most vulnerable to erosion by calculating both long- (minimum 50 years) and short-term (<30 years) shoreline change rates using the DSAS (Himmelstoss *et al.* 2017; Morton and Miller 2005). However, the methodology used to calculate average annual shoreline change rates is not intended to provide predictive functionality. The beta shoreline forecasting tool was incorporated into DSAS (v 5.0) based on a methodology developed by Long and Plant (2012) using an extended Kalman filter framework (Himmelstoss 2018b; Kalman 1960). Analysis of shoreline evolution in the past to permit future forecast has thus developed an approach with first-order estimates of potential future shoreline position. Combined with a rigorous and systematic set of shoreline data, these methods provide scientists, resource managers, and stakeholders with information to reasonably guide research and management decisions to mitigate natural hazards that impact coastal resources.

Forecasts of future oceanfront shoreline positions were used to assess relative vulnerability of Seashore assets based on proximity to future oceanfront shorelines. The purpose of the effort was to 1) evaluate the functionality of the beta forecast tool, and 2) explore options for using the output to assess the potential physical vulnerability of NPS assets, which includes 108 parking lots, 265 buildings, four campgrounds, two airports, an oceanfront pier, and a 60-slip marina.

METHODS

To evaluate the level of risk coastal erosion poses to the portfolio of assets within the Seashore, we used DSAS (v 5.0), which is available for use with the ESRI Geographic Information System (ArcGIS) to first calculate historic shoreline change rates and then forecast future oceanfront shoreline position using the



Figure 2. Storm surge from Hurricane Dorian flooded the inside of the old store house at the Ocracoke Light Station with over a meter of water and lifted it off its foundation (NPS 2019).



Figure 3. Superintendent of Cape Hatteras National Seashore standing on a damaged stretch of NC-12 on Ocracoke Island post-Dorian (NPS 2019).

beta forecast tool (Himmelstoss *et al.* 2018a). The workflow described in the DSAS (v 5.0) User Guide (Himmelstoss *et al.* 2018b) was followed to meet the model requirements, including managing data within a personal geodatabase.

Calculating historical shoreline change

A total of 13 shorelines that represented the location of the high water line (HWL) were obtained from the NC Division of Coastal Management (DCM) and NPS, and compiled and imported into a geodatabase as a single shoreline

vector (Table 1). The historical shoreline position data were either delineated from aerial imagery via wet-dry interpretation digitized at a 1:1,000 scale by DCM staff (NCDCM 2019), or delineated from field surveys of wet-dry interpretation collected with survey-grade GPS units and later post-processed by NPS staff. The required fields in the attribute table for the shoreline vector data include "DATE" and "UNCERTAINTY." The "DATE" field represents the day the aerial imagery was collected or the GPS survey was performed, and the "UNCERTAINTY" field accounts for the combined positional

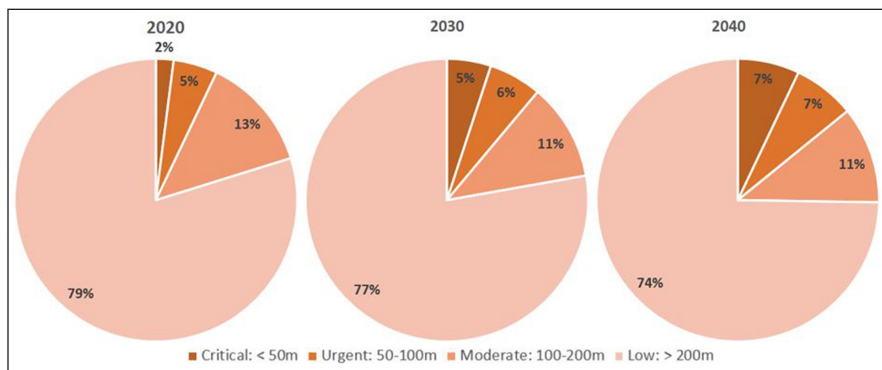


Figure 4. The results of the oceanfront shoreline vulnerability analysis for NPS assets based on their proximity to the respective oceanfront shoreline position.

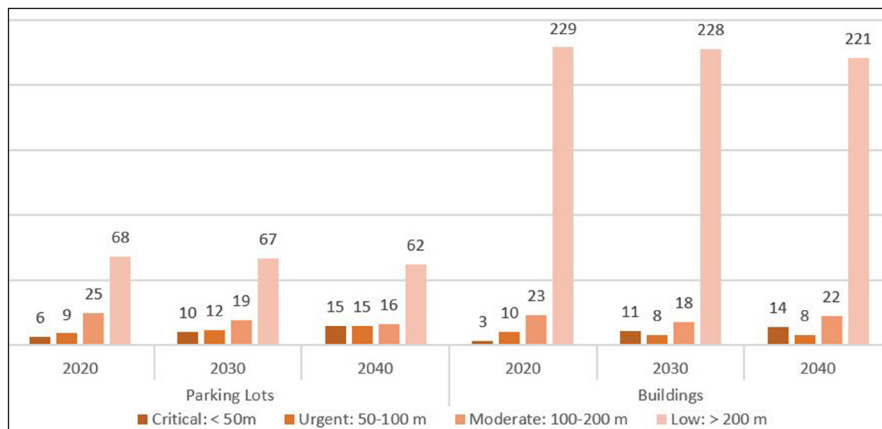


Figure 5. The results of the oceanfront shoreline vulnerability analysis for NPS assets broken down by parking lots and buildings based on their proximity to the respective oceanfront shoreline position.

Table 1.

Oceanfront shoreline data used to calculate historical shoreline change rates and forecast 10- and 20-year shoreline position.

Date	Type	Uncertainty (m)	Source
07/22-08/18/1998	HWL	2.0	Aerial imagery
02/01/2002	HWL	1.0	Aerial imagery
09/03/2004	HWL	1.0	Aerial imagery
03/03/2007	HWL	1.0	Aerial imagery
07/11/2009	HWL	1.7	Aerial imagery
04/11/2010	HWL	1.0	Aerial imagery
02/28/2012	HWL	1.0	Aerial imagery
01/30/2016	HWL	1.0	Aerial imagery
03/23-27/2017	HWL	5.0	NPS GPS
04/21-26/2018	HWL	5.0	NPS GPS
10/20-24/2018	HWL	5.0	NPS GPS
03/28-31/2019	HWL	5.0	NPS GPS
09/12-16/2019	HWL	5.0	NPS GPS

uncertainty associated with measurement and digitizing uncertainties.

A baseline was constructed as a new feature class in the geodatabase, and transects were cast offshore following the DSAS workflow. The transects were cast using a 50 m-spacing based on the spacing used by DCM to create oceanfront setback factors (NCDICM 2019), and

user-specified smoothing distance of 500 m to account for some of the curvatures near the inlets and Cape Hatteras. The following statistics were calculated based on 13 shorelines that represented the location of the HWL between 1998-2019: shoreline change envelope (SCE), net shoreline movement (NSM), end point rate (EPR), linear regression rate (LRR),

and weighted linear regression (WLR) (Himmelstoss *et al.* 2018b).

Forecasting shoreline position

Next, we generated the 10- and 20-year shoreline horizons and uncertainty bands based on the LRR, the shoreline statistic that must be generated in order to initialize the Kalman filter model (Himmelstoss *et al.* 2018b). The percentage of variance in the data is explained by a regression represented by the R -squared statistic (R^2), or coefficient of determination (Himmelstoss *et al.* 2018b).

Evaluating oceanfront erosion risk

The most recently collected shoreline (post-Dorian — September 2019), and the 10- and 20-year shoreline forecast layers were used to perform a preliminary physical vulnerability analysis of infrastructure along the oceanfront for facilities that included 108 parking lots, 265 buildings, four campgrounds, two airports, an oceanfront pier, and a 60-slip marina located within the Seashore. First, the distance between the footprint of each asset was measured to each shoreline using the “Near” Tool in ArcMap 10.7.1. The attribute table associated with each asset layer was then exported to an Excel spreadsheet for further analysis that included reviewing the output values compared to ArcMap 10.7.1 workspace that was used to perform the analysis to determine if the position of the shoreline was located either seaward or landward of the asset. The value generated using the “Near” Tool was converted to a negative value if the shoreline position was located landward of the asset.

The results of the oceanfront shoreline change vulnerability assessment were grouped into categories that represented the proximity of the asset to the respective shoreline position. Each category represented a different level of attention and potential need for management intervention if preserving the structural integrity or use of the asset was deemed a priority. The “Critical” threshold value of <50 m was used as the most urgent category based on the fact it represented 10x the maximum uncertainty of the shoreline position used in the analysis, which was 5 m. The subsequent threshold values for the categories of “Urgent: 50-100 m,” “Moderate: 100-200 m,” and “Low: >200 m” could also be represented by 10-20, 20-40, >40 times the maximum uncertainty of the shoreline position used in the analysis.

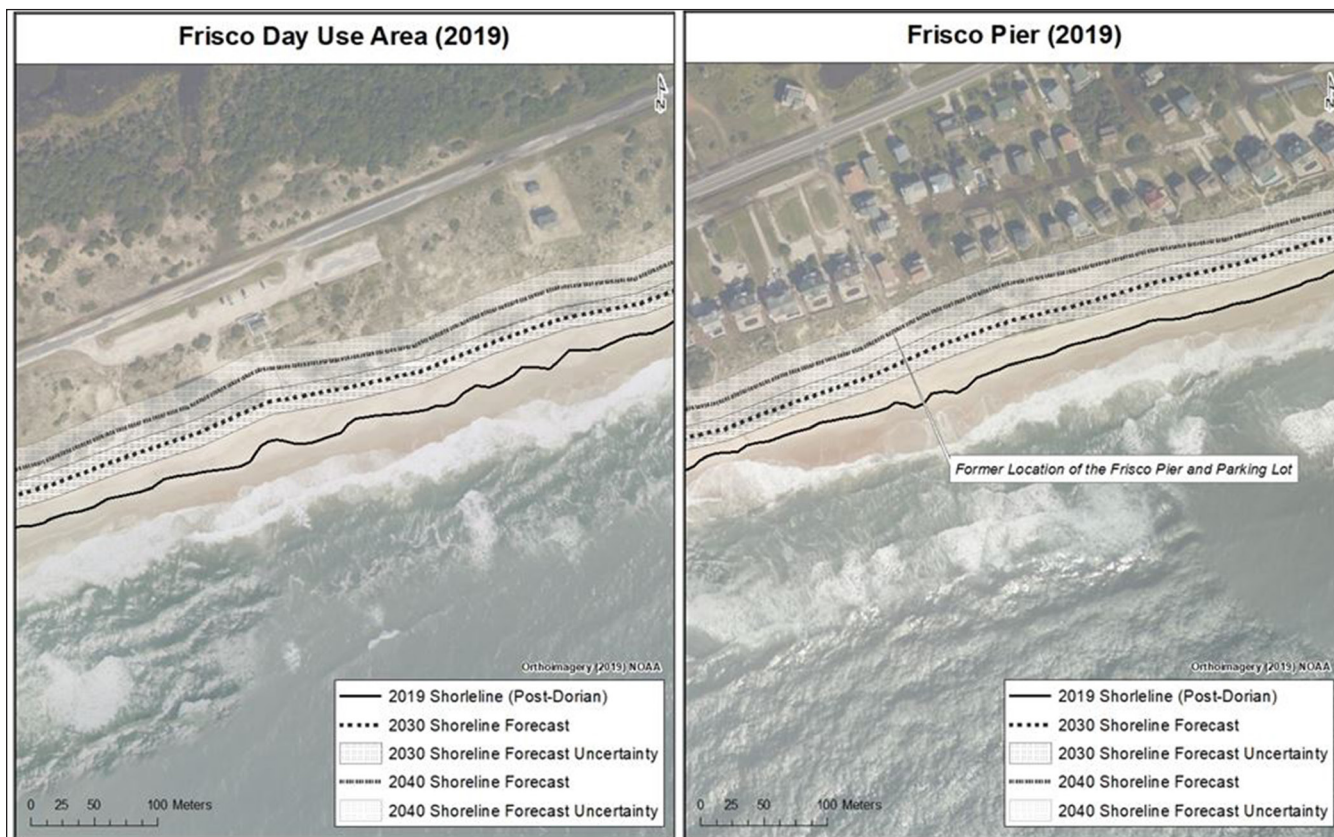


Figure 6. Examples of the graphics generated to display the preliminary results of the 10- and 20-year oceanfront shoreline position forecast to evaluate the implications of rebuilding a parking lot and visitor access in the Frisco Village area of the Seashore.

Finally, the Seashore's Superintendent, Deputy Superintendent, Chief of Resource Management and Science, and Chief of Maintenance reviewed the spreadsheet and ArcMap 10.7.1 workspace in an effort to identify how to best summarize the results and develop maps that could be used to inform decisions about prioritizing mitigation and adaptation strategies to sustain access to recreational amenities, and protect supporting infrastructure.

RESULTS

The results of the oceanfront shoreline vulnerability analysis were summarized by the percentage of NPS assets that fit within each categorical threshold (Figure 4). According to the analysis, 2% of the current portfolio of NPS assets fit within the "Critical: <50 m" category respective to the distance they were located from the most recent shoreline (post-Dorian — September 2019). The Avon Pier House, and parking lots for the Pea Island Comfort Station and Sandy Bay Day Use Area are examples of assets that were included in this category. The percentage of assets that fit within the critical category increases to 5% and 7% when the 10- and 20-year shoreline forecast is used.

The Frisco Comfort Station and Frisco Day Use Area parking lot are examples of assets that were not included in the "Critical" category when the distance was measured to the most recent shoreline, but were included when the distance was measured to the 10- and 20-year shoreline forecasts. The subsequent threshold values for the categories of "Urgent: 50-100 m" accounted for 5%, 6%, and 7%; "Moderate: 100-200 m" included 13%, 11%, and 11%; and "Low: >200 m" contained 79%, 77%, and 74%.

A breakdown by type of asset is as follows. The majority of NPS assets are either parking lots or buildings including those located at the 60-slip marina near Oregon Inlet. There are multiple parking lots and buildings that are currently located within close enough proximity to the oceanfront shoreline to be included in the "Critical" category. Several parking lots and buildings shift from lower risk to higher risk categories over time as the oceanfront shoreline position generally moves landward during the 10- and 20-year forecast as a result of linear regression rates that are generally erosional throughout the Seashore (Figure 5). The oceanfront shoreline continually moves landward

towards the Oregon Inlet Campground, but remains in a stable location near the other three campgrounds (Table 2). Both the Billy Mitchell Airport and Ocracoke Island Airport are consistently included in the "Moderate" category during each interval of analysis.

DISCUSSION

The overall goal of this study was to initiate coastal adaptation planning efforts to sustain habitats, visitor use, and stewardship of the resources located within the Seashore through prioritizing management actions to mitigate the impacts of shifting shorelines along barrier islands in accordance with the mission of the National Park Service. The purpose of this study was to 1) evaluate the functionality of the beta forecast tool, and 2) explore options for using the output to assess the potential vulnerability of NPS assets.

The beta forecast tool takes a non-computationally-intensive approach to efficiently forecast large spatial and temporal scales by extending the Kalman Filter framework (Kalman 1960) and exploiting empirical relationships between forcing and response (Long and Plant

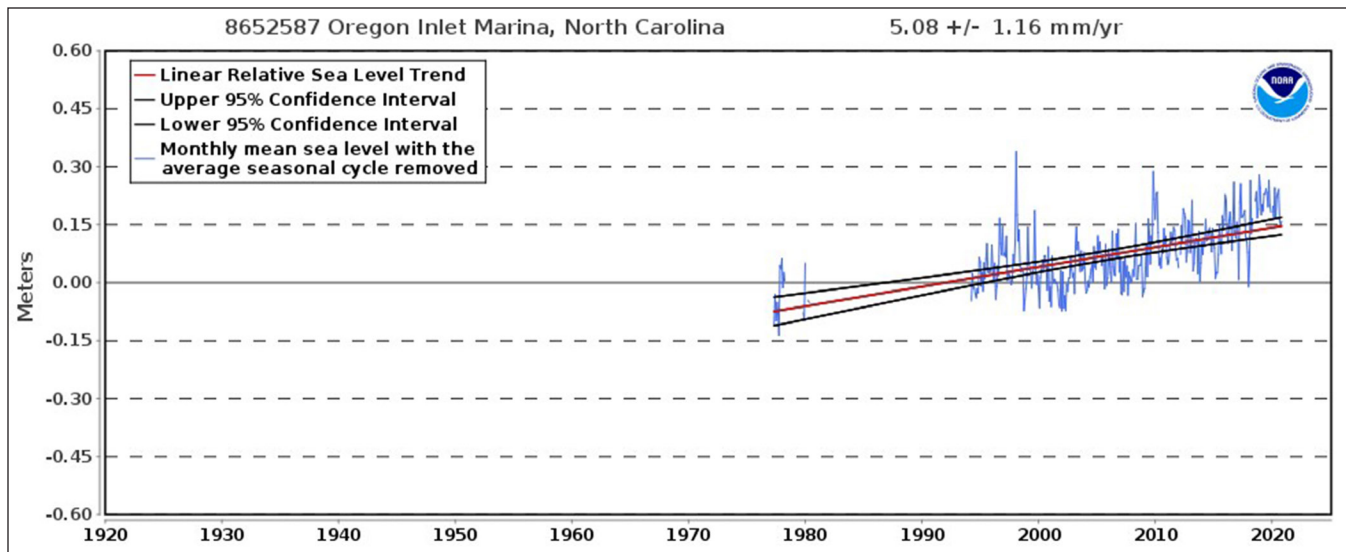


Figure 7. The plot shows the monthly mean sea level at Oregon Inlet Marina without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents (NOAA 2021).

Table 2.
Distance of campgrounds to oceanfront shoreline positions.

Location	Distance (m)		
	2020	2030	2040
Oregon Inlet Campground	142.0	67.6	19.1
Cape Point Campground	407.7	395.4	377.1
Frisco Campground	300.4	295.5	293.5
Ocracoke Campground	97.5	102.7	95.7

2012). In general, this study determined that using the 10- and 20-year oceanfront shoreline position generated using the beta forecast tool was an efficient and effective approach to evaluate the level of risk coastal erosion poses to a portfolio of assets located along linear oceanfront sandy shorelines.

One major limitation that was identified was the fact that the model continues to operate via the extension of empirical relationships between forcing and response of a beach-dune system. While investigating the position of the 10- and 20-year oceanfront shoreline forecast generated using the beta forecast tool for the entire study area it was noted that forecast seemed to represent feasible realities along sections of the shoreline that were either undeveloped or where development was currently buffered by a dune system. However, in some instances the position of the forecast shoreline was located landward of infrastructure such as NC Highway 12 or an entire row of oceanfront properties. These were the same locations of known erosional hotspots where either historic, ongoing, and/or planned human intervention was/is required to protect the structural integ-

rity of the infrastructure. Incorporating an option to set a parameter such as a positional threshold that would act as an obstacle and prevent shoreline migration is recommended for the development of subsequent versions of the forecast tool for the purpose of generating outputs that are more representative of the current environmental constraints.

This study demonstrated that the output can be leveraged with basic GIS analysis to inform and assist managers with decision-making about how to prioritize hazard mitigation and coastal adaptation measures that allow for a balanced approach to natural and cultural resource management and the protection of critical infrastructure that supports coastal development and tourism-based economies along barrier islands. To some degree, the methodology used by the beta forecast tool accounts for storm response, rate of sea level rise, and human intervention captured within the range of activity that occurred within the period that is used to generate a linear regression rate based on historical shoreline positions (Long and Plant 2012). Updating the forecast using new model inputs as they become available is recommended

to account for the dynamic nature of the environment to provide decision makers with the most up-to-date information. For this study area, updates could be performed on a regular basis following the completion of a shoreline survey by NPS staff conducted on a biannual basis as well as on a periodic basis following storm events or nourishment projects.

As a case study, we used the 10- and 20-year shoreline forecasts to evaluate the implications of rebuilding a parking lot and visitor access area in the Frisco Village area of the Seashore. The information was used to make a fiscally responsible decision to construct additional parking capacity at the Frisco Day Use Area rather than rebuild the parking lot at the former location of the Frisco Pier. These two locations are only 650 m from each other and carry a similar level of risk to storm surge inundation. The fact that the Frisco Day Use Area is located landward of a primary dune affords some level of confidence that the investment will remain accessible 10 and 20 years into the future, whereas the oceanfront shoreline position is forecast to be at the location of the former parking lot for the Frisco Pier in 10-years (Figure 6).

The results of this single case study demonstrate the functionality of the beta forecast tool available in DSAS (v 5.0). However, these results are most likely conservative in nature. The effect of relative sea level rise is concerning for coastal communities as sudden regional acceleration events can exacerbate coastal erosion, and continued relative sea level

rise can compound the impact of storm events that may have been considered minor in the past.

The NOAA tide gauge at the Oregon Inlet Marina is the nearest station to the Seashore with published rates of sea level change. The relative sea level trend based on monthly mean sea level data from 1979 to 2019 is 5.08 mm/year with a 95% confidence interval of ± 1.16 mm/year (Figure 7) (NOAA 2021). At this rate, sea level at the Oregon Inlet Marina is projected to increase by 0.51 m over the next century.

However, nonlinear variations in sea level, such as interannual and decadal variability resulting in regional acceleration, present prediction challenges (Goddard *et al.* 2015; McCarthy *et al.* 2015; Sallenger *et al.* 2012). For example, two different sea level rise regimes exist north and south of Cape Hatteras. Where sea level fluctuations to the north in the Mid-Atlantic Bight (MAB) are linked to oceanic and atmospheric oscillations, fluctuations in the South Atlantic Bight (SAB) are linked to the flow and position of the Gulf Stream (Ezer 2019; Ezer 2020; Goddard *et al.* 2015; McCarthy *et al.* 2015). Sallenger *et al.* (2012) identified a sea level rise acceleration “hot spot” north of Cape Hatteras before 2010 associated with the weakening of the Atlantic Meridional Overturning Current (MOC). Valle-Levinson *et al.* (2017) and Domingues *et al.* (2018) identified a trend reversal where sea level rise decelerated in the MAB and accelerated in the SAB after 2010. Ezer (2019) investigated the role the Gulf Stream dynamics have on sea level trends and found it is the main connector between the trends north and south of Cape Hatteras. Additionally, the temporary weakening of the Gulf Stream associated with the impact of hurricanes

that track within its vicinity have been attributed to short term anomalies of elevated coastal sea level in both the MAB and SAB on the order of months (Ezer *et al.* 2017; Ezer 2020).

In order to evaluate the composite risk of NPS managed assets and compensate for the conservative nature of the results produced with the beta shoreline forecast tool, an ongoing study will update and expand the coastal inundation mapping assessment performed by Allen *et al.* (2017). The results of that multi-hazard physical vulnerability assessment will be compiled into a spreadsheet and ranked based on level of risk (exposure + sensitivity) and value (ecological + socioeconomic) to prioritize mitigation and adaption strategies in order to sustain access to recreational amenities, and protect supporting infrastructure within the Seashore.

CONCLUSION

The portfolio of assets managed by NPS within the Cape Hatteras National Seashore carries a high level of risk due to its exposure to both coastal erosion and storm surge inundation. The impacts of these coastal hazards may be further exacerbated by the implications of rising sea level. Using the 10- and 20-year oceanfront shoreline position forecast provides decision-makers with a first order screening tool that can be used to prioritize mitigation and adaptation strategies based on physical vulnerability given the unpredictable nature of tropical and extra-tropical cyclones. The resultant percentage of the asset portfolio assigned to each of these categories seemed to represent a realistic level of risk that both currently exists and will exist in the future if some type of management action is not taken within the Seashore to reduce the vulnerability of specific assets.

REFERENCES

- Allen, T.R., Walsh, J.P., Crawford, T.W., and B.E. Montz, 2017. “Identifying Cultural Resources Sites Affected by Sea Level Rise at Cape Hatteras National Seashore.” National Park Service. Piedmont-South Atlantic Cooperative Ecosystems Studies Unit Task Agreement No. P13AC01432.
- Avila, L.A., Stewart, S.R., Berg, R., and A.B. Hagen, 2020. “Hurricane Dorian (AL052019). Tropical Cyclone Report.” National Hurricane Center. https://www.nhc.noaa.gov/data/tcr/AL052019_Dorian.pdf
- Caffrey, M.S., Beavers, R.L., and C.H. Hoffman, 2018. “Sea level rise and storm surge projections for the National Park Service.” Natural Resource Report NPS/NRSS/NRR — 2018/1648. National Park Service, Fort Collins, Colorado.
- Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., and A.S. Unnikrishnan, 2013. “Sea Level Change.” In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Davis, R.A., and M.O. Hayes, 1984. “What is a wave-dominated coast?” *Marine Geology*, 60, 313- 329.
- Domingues, R., Goni, G., Baringer, M., and D. Volkov, 2018. “What caused the accelerated sea level changes along the U.S. East Coast during 2010-2015?” *Geophysical Research Letters*, 45(24), 13,367-13,376.
- Ezer, T., Atkinson, L.P., and R. Tuleya, 2017. “Observations and operational model simulations reveal the impact of Hurricane Matthew (2016) on the Gulf Stream and coastal sea level.” *Dynamics of Atmospheres and Oceans*, 80, 124-138.
- Ezer, T., 2019. “Regional differences in sea level rise between the Mid-Atlantic Bight and the South Atlantic Bight: is the Gulf Stream to blame?” *Earth's Future*, 7(7), 771-783.
- Ezer, T., 2020. “The long-term and far-reaching impact of hurricane Dorian (2019) on the Gulf Stream and the coast.” *J. Marine Systems*, 208, 103370.
- Goddard, P.B., Yin, J., Griffies, S.M., and S. Zhang, 2015. “An extreme event of sea-level rise along the Northeast coast of North America in 2009-2010.” *Nat. Communications* 6, 6346. <https://doi.org/10.1038/ncomms7346>
- Gutierrez, B.T., Plant, N.G., Pendleton, E.A., and E.R. Thieler, 2014. “Using a Bayesian network to predict shore-line change vulnerability to sea-level rise for the coasts of the United States.” U.S. Geological Survey Open-File Report 2014-1083. <https://pubs.er.usgs.gov/publication/ofr20141083>
- Gutierrez, B.T., Williams, S.J., and E.R. Thieler, 2007. “Potential for shoreline changes due to sea-level rise along the U.S. Mid-Atlantic region.” U.S. Geological Survey Open-File Report 2007-1278. <http://pubs.usgs.gov/of/2007/1278>.

- Hayes, M.O. 1979. "Barrier island morphology as a function of tidal and wave regime." In S. Leatherman, ed.: *Barrier Islands, from the Gulf of St. Lawrence to the Gulf of Mexico*, 211-236.
- Himmelstoss, E.A., Farris, A.S., Henderson, R.E., Kratzmann, M.G., Ergul, A., Zhang, O., Zichichi, J.L., and E.R. Thieler, 2018a. "Digital Shoreline Analysis System (version 5.0)." U.S. Geological Survey software release; <https://code.usgs.gov/cch/dsas>.
- Himmelstoss, E.A., Henderson, R.E., Kratzmann, M.G., and A.S. Farris, 2018b. "Digital Shoreline Analysis System (DSAS) version 5.0 user guide," U.S. Geological Survey Open-File Report 2018-1179, 110p.; <https://doi.org/10.3133/ofr20181179>.
- Himmelstoss, E.A., Kratzmann, M.G., and E.R. Thieler, 2017. "National assessment of shoreline change – Summary statistics for updated vector shorelines and associated shoreline change data for the Gulf of Mexico and Southeast Atlantic coasts." U.S. Geological Survey Open-File Report 2017-1015, 8p.; <https://doi.org/10.3133/ofr20171015>
- Kalman, R.E. 1960. "A new approach to linear filtering and prediction problems." *Transactions of the AMSE — J. Basic Engineering*, 82 (Series D); 35-45.
- Long, J.W., and N.G. Plant, 2012. "Extended Kalman filter framework for forecasting shoreline evolution." *Geophysical Research Letters*, 39(13), 1-6.
- Marcy, D., Herold, N., Waters, K., Brooks, W., Hadley, B., Pendleton, M., Schmid, K., Sutherland, M., Dragonov, K., McCombs, J., and S. Ryan, 2011. "New mapping tool and techniques for visualizing sea level rise and coastal flooding impacts." National Oceanic and Atmospheric Administration Coastal Services Center, Charleston, SC.
- McCarthy, G.D., Haigh, I.D., -M. Hirschi, J.J., Grist, J.P., and D.A. Smeed, 2015. "Ocean impact on decadal Atlantic climate variability revealed by sea-level observations." *Nature*, 521, 508-510.
- Morton, R.A., and T.L. Miller, 2005. "National assessment of shoreline change: Part 2: Historic shoreline changes and associated coastal land loss along the U.S. Southeast Atlantic Coast." U.S. Geological Survey Open-file Report 2005-1401.
- Murdukhaveya, A., August, P., Bradley, M., LaBash, C., and N. Shaw, 2013. "Assessment of inundation risk from sea level rise and storm surge in Northeastern coastal national parks." *J. Coastal Res.*, 29(6a), 1-16.
- National Oceanic and Atmospheric Administration (NOAA), 2021. "Sea Level Trends." <https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>. Last accessed 4 January 2021.
- National Park Service, 2019. "Superintendent David Hallac details damaged caused by Hurricane Dorian to Cape Hatteras National Seashore, Fort Raleigh Historic Site, and Wright Brothers National Memorial." <https://www.nps.gov/caha/learn/news/superintendent-hallac-details-damage-caused-by-hurricane-dorian-to-cape-hatteras-national-seashore-fort-raleigh-national-historic-site-wright-brothers-national-memorial.htm>. Last accessed 13 February 2021.
- National Park Service, 2020. "Cape Hatteras National Seashore receives 2.6 million visits for first time in over 15 years." https://www.nps.gov/caha/learn/news/cape_hatteras_national_seashore_receives_2_6_million_visits_for_first_time_in_over_15_years.htm. Last accessed 13 February 2021.
- North Carolina Division of Coastal Management, 2019. "North Carolina 2019 Oceanfront Set-back Factors & Long-Term Average Annual Erosion Rate Update Study: Methods Report." Outer Banks Visitors Bureau, 2015. "Visitor Survey 2014-2015: Volume 1 Visitor Survey Report." Manteo, NC.
- Peek, K., Young, R., Beavers, R., Hoffman, C., Diethorn, B., and S. Norton, 2015. "Adapting to Climate Change in Coastal Parks: Estimating the Exposure of Park Assets to 1 m of Sea Level Rise."
- Pendleton, E., Thieler, E.R., and S.J. Williams, 2004. "Coastal vulnerability assessment of Cape Hatteras National Seashore (CAHA) to sea-level rise." U.S. Geological Survey Open-File Report 2004-1064, 20p.; <https://pubs.usgs.gov/of/2004/1064/images/pdf/caha.pdf>.
- Riggs, S.R., Ames, D.V., Culver, S.J., and D.J. Malinsson, 2011. *The battle for North Carolina's Coast: Evolutionary history, present crisis, and vision for the future*. University of North Carolina Press, 142pp.
- Sallenger, A.H., Jr. Doran, K.S., and P.A. Howd, 2012. "Hotspot accelerated sea-level rise on the Atlantic coast of North America." *Nature Climate Change*, 2, 884-888.
- Schupp, C.A., Beavers, R.L., and M.A. Caffrey, eds. 2015. "Coastal Adaptation Strategies: Case Studies." NPS 999/129700. National Park Service, Fort Collins, CO.
- Thieler, E.R., and E.S. Hammar-Klose, 1999. "National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast." U.S. Geological Survey Open-File Report 99-593.
- Valle-Levinson, A., Dutton, A., and J.B. Martin, 2017. "Spatial and temporal variability of sea level rise hot spots over the eastern United States." *Geophysical Research Letters*, 4(15), 7876-7882.