

DUNE PERFORMANCE IN 2050 AND 2100 SUBJECTED TO EXTREME AND NUISANCE EROSION EVENTS

Matthew S Janssen¹, Jon K. Miller, Audrey C. Fanning, and Ian J. Day

A physically informed, yet computationally efficient, fragility model is used to quantify dune vulnerability under current and future sea level scenarios. The model is applied to mean sea levels of 1997, 2050 and 2100 to quantify the increase in vulnerability attributed to sea level rise on an existing dune design template. Two separate storm intensities are considered; categorically defined as ‘Nuisance’ and ‘Extreme’ events. Both storms are modeled for sea level rise projections based on IPCC SSP1-1.9, 2-4.5 and 5-8.5 scenarios in 2050 and 2100 including ground subsidence. The results show the vulnerability of dune failure during Nuisance events will nearly double by 2050; from 3.3% to 5.9% under SSP2-4.5. By 2100, the vulnerability increases further to 12%. Under Extreme events the vulnerability increases from 26% to 37% in 2050 and further to 56% under SSP2-4.5. Next, the model is used to estimate the modifications to the design template to maintain the current vulnerability. Increases to the berm width and dune volume are considered independently under various constraints. The findings indicate vulnerability could be offset through 2050 by increasing the berm width by 27-m (61% increase). By 2100, increases in the berm width would require 70-m (142% increase). Alternative dune volumes are calculated assuming different design constraints (e.g., maintaining existing dune crests for viewshed concerns). Notably, by 2100, the required dune volumes result in a geometrically untenable configuration. It is concluded under near term time horizons, modifications to the dune volume alone or berm width are sufficient to maintain existing vulnerabilities. However, under longer term time horizons, beach nourishment templates must increase the project’s effective width or accept higher vulnerabilities to Nuisance and Extreme events alike.

Keywords: fragility curves; coastal erosion; parametric design; beach nourishment; coastal hazards, storm damage reduction projects

INTRODUCTION

Beach nourishment and particularly dunes are an effective method to protect nearshore infrastructure. Existing literature is rich with studies documenting their effectiveness in shielding upland assets (e.g., Bacopoulos and Clark, 2021; Barone et al., 2014; Day et al., 2023; Jin et al., 2015; Sallenger, 2000; Tomiczek et al., 2017). As dunes are erodible, the likelihood of overwash and inundation regimes increases, necessitating the importance of predicting dune erosion during episodic storm events. Process-based numerical models (e.g., Roelvink et al., 2009) represent the zenith of current capabilities. This skill comes at the expense of computational and calibration effort. Numerical models have been demonstrated to be sensitive to input data, with small (10%) variations in boundary forcing conditions producing regime shifts in the modeled response (van der Lugt et al., 2019). Ensemble approaches are used to quantify the uncertainty in lieu of deterministic runs. However, ensemble approaches further increase computation demands. These constraints limit the application of process-based models to wide regional scale assessments without substantial financial investment. Implications of model complexity with spatial and temporal scales are well described by Leaman (2022) who highlight potential application of data driven probabilistic methods. Despite extensive computational advances, the need for efficient probabilistic methods still exists.

Bruun (1998) stresses the importance of considering the beach and dune comprehensively; accounting for geometric shape. Despite this, quantitative relationships between berm width and dune volume remain relatively sparse. The most ubiquitous approaches consider setback (a proxy for width) or dune volume independently (e.g., Hallermeier and Rhodes, 1986). However, notable exceptions exist. Morgan and Stone (1985) developed the Storm Wave Susceptibility Quotient, an index used to quantify the vulnerability of sandy coasts located along barrier islands. This considered dune height and beach width however, parameterization of the storm forcing was simplistic. The Coastal Change Hazard Portal (2019) considers elevation, storm forcing and probabilistically predicts the Sallenger (2000) regimes based on total water level. The existing methods do not currently account for the erosion and duration effects. This has been attributed as a potential cause of the underprediction during overwash regimes (USGS, 2018).

The Erosive Resistance (ER) parameter developed by Judge et al. (2003) characterized dune erosive resistance accounting for the position of dune centroid and cross-sectional area. However, it does not account for storm intensity or provide a method to directly infer the predicted dune response (e.g., overwash or inundation). Alternative vulnerability metrics such as the Coastal Engineering Resilience Index (CERI) introduced by Dong et al. (2018) provides a useful tool to quantify resilience inclusive of elevation, volume, and width over monthly to decadal temporal scales (eg., Spurgeon et al., 2023). While

¹Davidson Laboratory, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030 USA

the ER and CERI metrics provide a quantitative measure of the relative influence of the berm and dune volume, the metrics alone lack the ability to directly predict the dune response in an episodic event.

Various empirical (e.g., den Heijer et al., 2012; Harley et al., 2009; Janssen and Miller, 2022; Splinter et al., 2014) and machine learning (e.g., Plant and Stockdon, 2012) techniques have been developed to predict dune impacts. The notable limitation beyond the requirement for large datasets is the limitation of predictions consistent with the windowing of the training dataset (Goldstein et al., 2019). For this reason, empirical solutions in lieu of machine learning tools such as those developed by Lemke and Miller (2021) or Pries et al. (2008) are applied herein. At minimum, the appropriate approaches must be able to address the following:

1. Account for both dune resilience parameters (e.g., volume, height, position) and storm intensity
2. Parameterize the erosive resilience terms (e.g., consider dune volume *and* position of the dune) in a physically meaningful way
3. Adequately resolve storm intensity characteristics (e.g., account for timing of wave and water level time series under current and future conditions)
4. Probabilistic

Climate Change

The effect of climate change on tropical storms can be attributed to three main components: through (1) elevated mean sea levels; (2) changes in storm frequency; and (3) changes in storm intensity (e.g., lower central pressures). For tropical storms in the North Atlantic basin, the consensus among existing literature suggests that storm intensity is increasing (Elsner et al., 2008) yet storm frequency is decreasing. The increase in intensity are attributed to elevated sea surface temperatures whereas decreases in storm frequency are attributed to increased wind shear (Vecchi and Soden, 2007) or weakening of Hadley and Walker circulations (Chand et al., 2022) leading to less favorable conditions in the development of tropical cyclones. The impact of climate change on extra-tropical storms is not well documented in literature. Results of the influence of climate change on storm intensity are often conflicting, highlighting significant challenges in long-term trend detection of tropical storms (Knutson et al., 2010).

Conversely, global sea levels are unquestionably rising and will continue to do so for the foreseeable future. For the current IPCC estimates, widely regarded as the most robust scientific estimate (Houston, 2016), there is strong consensus in the rate of rise through 2050; estimated to continue at the current GMSL satellite observed rate of 3.25 (2.88 to 3.61) mm per year (Fox-Kemper et al., 2021). However, when the time horizon is extended through 2100, the best estimates have considerably more uncertainty, with estimates influenced by anthropogenic activities over the next decades.

The climate stationarity assumption historically applied to coastal design is deteriorating. However, there is significant uncertainty in quantifiably projecting changes in storm frequency, and intensity. It is therefore advantageous to decompose the contributions of climate change on storm characteristics from those of the comparatively better quantified SLR. This work isolates the influence of SLR on dune vulnerability.

Current Design Philosophies

Current practices in coastal engineering, including those used to design beaches and dunes, tend to rely on the specification of one or more extreme design events. For beach and dune projects, the characteristics of the design storm are used to determine project features such as berm width and dune volume. Sea level rise (SLR) is often incorporated into design through an evaluation of its impacts on the design storms. Climate change, and specifically the increased losses due to SLR have been well documented for extreme events (e.g., Goulart et al., 2023; Strauss et al., 2021). Less well documented however is the potential impact on low/moderate intensity storm events. Recent studies suggest SLR disproportionately increases the erosive intensity of moderate storms (Fanning et al., In preparation).

Research Question

This work is principally concerned with quantifying the risk of storm induced erosion resulting in dune failure. The work has two objectives. First, to quantify the increase in vulnerability of dune failure for an existing beach and dune nourishment project subject to coastal storms under current and future sea level rise scenarios. Second, to provide a method to estimate changes to the design template (e.g., dune cross-section or berm width) in a computationally efficient, yet physically meaningful way.

METHODS

A probabilistic dune fragility model developed by Janssen and Miller (2022) is applied to an observational 34-year storm record developed by Lemke and Miller (2020) and subsequently modified by Fanning et al. (2024) to account for projected SLR scenarios in AR6. The observational storm record quantifies tropical and extratropical storm intensity through the lens of erosion potential. The complete hourly time-series encompassing over 130 unique storms under multiple SLR scenarios is publicly available (Fanning et al., 2023). The dataset considers both global sea level rise rates and land subsidence rates. The methodology herein provides a means of separately considering changes to storm intensity and beach resilience independently on dune vulnerability. Dune vulnerability is discussed first, followed by resilience and finally storm intensity.

Estimation of Dune Vulnerability

Dune failure is estimated probabilistically using the Dune Engineering Demand Parameter (EDP) and associated fragility curve shown in Equation 1 (Janssen and Miller, 2022). The EDP represents the erosive demand placed on a dune during a storm event (Equation 2). The probability is modeled using a two parameter Weibull distribution with fit shape and scale coefficients. Confidence intervals and performance metrics are reported in Janssen and Miller (2022).

For the purposes of this analysis, dune failure is categorical (i.e., probability of the occurrence of the damage class). Dune failure is defined as erosion resulting in greater than 40% of the pre-storm dune volume. Failure of the dune, is associated with overwash and inundation regimes and is considered a proxy for the onset of structural damage to upland infrastructure (Leaman et al., 2021; Sallenger, 2000). Dune volume loss is not explicitly predicted, only the probability of the damage classification.

$$P(\text{Class}) = 1 - \exp\left(\frac{-EDP}{\lambda}\right)^{\kappa} \quad (1)$$

With fit coefficients $\lambda=1697$ and $\kappa= 1.35$, respectively.

$$EDP = \frac{\text{Storm Intensity Metric}}{\text{Beach Resilience Factor } (R_f)} = \frac{PEI^4}{\text{Dune Volume} \times r^2} \quad (2)$$

Dune Resilience (R_f)

Conceptually, the EDP is similar to the Shield's parameter in that it represents the ratio of mobilizing terms to stabilizing terms. Physically, the EDP is a measure of storm intensity over a dune's resilience (Equation 2). Janssen and Miller (2022) tested numerous configurations of the EDP and Resilience terms, ultimately settling on a Mass-Moment of Inertia parameterization scheme. This considers both the dune cross-sectional area (i.e. volume) and position of dune centroid from mean high water (Figure 1). This is an expansion of the Erosive Resistance concept first introduced by Judge et al. (2003).

Beach and dune parameters are selected from the US Army Corps of Engineers (USACE) Storm Damage Reduction project installed from Manasquan to Barnegat Inlet along the New Jersey coast (2015). The design template was chosen as it represents the conditions found along roughly 40-km of coast. The method presented herein is intended to demonstrate the flexibility of the applied methods to efficiently model a range of conditions.

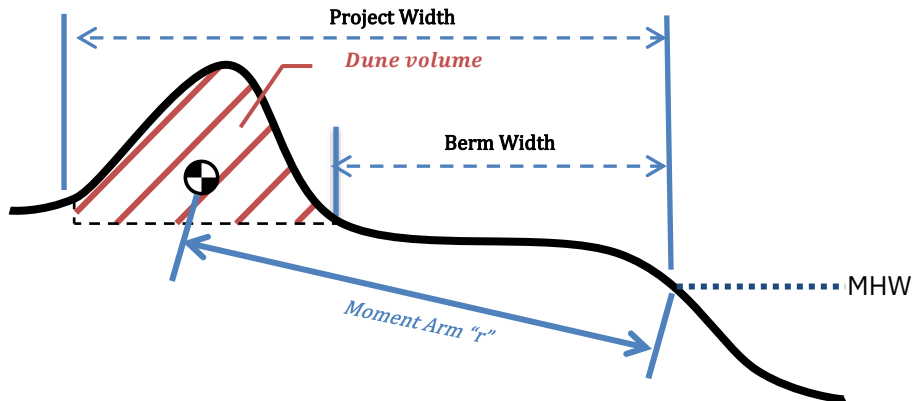


Figure 1. Schematic representation of Dune Resilience Factor (R_f) relating Dune Volume and Moment Arm (r). Position of dune centroid denoted by marker. Berm Width and Project Width are used in the Discussion.

Storm Intensity (Erosion Potential)

Storm Intensity is characterized by the Instantaneous and Peak Erosion Intensities (IEI and SEI, respectively) developed by Miller and Livermont (2008) and shown in Equations 3 and 4. Physically, the IEI represents the equilibrium shoreline response to a cross shore varying water and wave heights as derived by Dean and Dalrymple (2002).

$$IEI(t) = W_*(t) \left[\frac{0.068H_b(t)+S(t)}{B+1.28H_b(t)} \right] \quad (3)$$

$$PEI = \max[IEI(t)] \quad (4)$$

Where W_* is the width of the active profile (here defined out to the breaker depth assuming an equilibrium beach profile), S is a storm surge, and H_b is the breaking wave height.

Storms contained in the historical record are loosely sorted based on the following storm intensity classification (Table 1). Two storm timeseries are selected from Fanning et al. (2023). They are the February 1998 Nor'easter representing a Nuisance event and Hurricane Sandy representing an Extreme event.

Storm Intensity Class	PEI Range	Approximate Return Period (current climate)	Typical Dune Volume Loss (order of magnitude)	Likely Storm Hazard Impact Scale (Leaman et al., 2021; Sallenger, 2000)
Extreme	PEI \geq 120	> 50-year	> 40%	Overwash; Inundation; Dune Retreat
Severe	100 \leq PEI \leq 120	27-year to 50-year	\leq 40%	Dune Face Erosion
Nuisance	70 \leq PEI \leq 100	6-year to 27-year	~10%	Collision; Dune Face Erosion
Minor	PEI \leq 70	<6-year	Minimal	Swash; Minor Beach Narrowing

Sea Level Rise and Climate Scenarios

For this paper, sea level rise projections from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report were applied. The Sixth Assessment Report focuses on future climate projections developed from five Shared Socio-economic Pathways (SSP) scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) used in Coupled Model Intercomparison Project Phase 6. For the sake of brevity, only SSP1-1.9 (low, declining emissions), SSP2-4.5 (moderate declining emissions) and SSP5-8.5 (high emission) are presented as they adequately bracket the range of expected SLR scenarios and expected vulnerabilities.

MSL Reference Year	IPCC / Scenario	Notes / Interpretation
1997	Baseline	Historical observed storm record spanning 1980-2013 detrended for observed SLR rates and adjusted to MSL of equivalent to 1997
2050	SSP1-1.9	Sustainable pathway: low greenhouse gas and CO2 emissions declining to net zero around 2050 then remaining at net negative CO2 emissions
	SSP2-4.5	Intermediate greenhouse gas and CO2 emissions which remain at their currently level until approximately 2050 before declining
	SSP5-8.5	Very high greenhouse gas and CO2 emissions with no decline
2100	SSP1-1.9	1.4°C warming with 0.38m of global SLR
	SSP2-4.5	2.7°C warming with 0.56m of global SLR
	SSP5-8.5	4.4°C warming with 0.77m of global SLR

The fragility model is applied to answer the aforementioned research questions; namely quantifying the change in vulnerability attributed to SLR by varying the peak erosional intensity (PEI) of a storm and assuming constant beach conditions (i.e., R_f is held constant). Second, required changes to the design template to offset the effects of SLR are estimated using a parameter design approach.

Parametric Design

In the initial application, changes in vulnerability are assessed by varying the PEI based on the SSP considered. The resultant PEI is used to calculate the new demand (EDP) on the dune and calculate the resultant change in vulnerability. However, through similar manipulation of Equation 1, vulnerability

can be held constant and the appropriate berm width and dune volume (R_f) terms to achieve the stated performance can be calculated.

Four separate design cases are considered and summarized in Table 3. Broadly, the cases can be grouped by varying the berm width or the dune volume. In instances where the dune volume is varied, changes to the position of the dune centroid are considered under select constraints (e.g., limiting changes to dune crest elevations).

Case	Design Parameter Varied	Constrained Parameters	Notes / Interpretation
1	Berm Width	All Dune Parameters	Isolates for influence of berm width
2	Dune Volume	Cross shore position of dune centroid	Allow dune growth both landward and seaward equally; increase crest elevation. All changes to r are attributed to vertical increase in the dune centroid position
3		Berm Width	Allow dune crest height to increase in addition to landward expansion of dune footprint. Proxy for maintaining sufficient recreational area along berm width
4		Dune Crest Elevation and Berm Width	Increase in dune volume by expansion of dune crest width only. Dune footprint can expand landward only. Proxy for maintaining existing viewshed

Key assumptions

The methods have assumptions which include: One, changes to storm intensity (PEI) are attributed to SLR alone. Changes in storm frequency, or intensity changes due to met/ocean physics are neglected. Two, changes to the beach system are limited to berm width and dune volume. Dune slopes, berm elevation and grain size are held constant with the existing design template.

RESULTS

The fragility curves are applied to answer two fundamental questions: First, what is the change in dune vulnerability attributed to SLR alone? Second, if the current vulnerability needs to be maintained, what potential changes must be made to the existing design templates to offset SLR? The results section is separated based on these questions.

Change in Dune Vulnerability Attributed to SLR

The change in dune vulnerability assuming no change to the existing design template is presented for two storm intensities. First, the dune performance for a Nuisance storm, the February 1998 Nor'easter, is presented in Table 4. The performance during an Extreme event (Hurricane Sandy) is then presented in Table 5. Results in both tables are presented for MSLs of 1997, 2050 and 2100.

MSL Reference Year	Climate Scenario	Storm Intensity (PEI)	Probability of Dune Failure
1997	Baseline	69.4	3.3%
2050	SSP1-1.9	79.5	5.7%
	SSP2-4.5	80.3	5.9%
	SSP5-8.5	81.4	6.2%
2100	SSP1-1.9	90.8	9.4%
	SSP2-4.5	97.4	12%
	SSP5-8.5	105	16%

MSL Reference Year	Climate Scenario	Storm Intensity (PEI)	Probability of Failure
1997	Baseline	120	26%
2050	SSP1-1.9	132	36%
	SSP2-4.5	133	37%
	SSP5-8.5	135	38%
2100	SSP1-1.9	146	48%
	SSP2-4.5	154	56%
	SSP5-8.5	163	64%

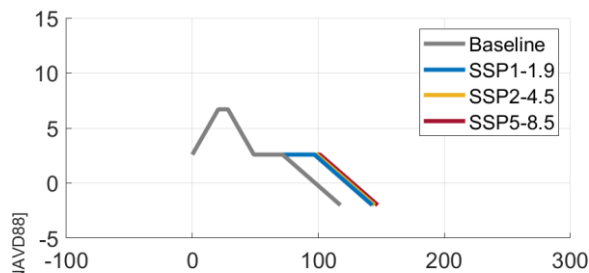
Parametric Design – Case 1 – Berm Width

To address the second research question, changes to the berm and dune volume are considered independently. The required berm width to maintain the existing project’s vulnerability under future SLR scenario is presented in Table 6 for a Nuisance storm; the February 1998 Nor’easter. Table 7 shows the results for Hurricane Sandy, an example of an Extreme storm (and the storm of record for the area). Baseline (1997) shows the existing USACE project template as currently designed. Graphically, the change in the design template can be visualized in Figure 2. The results indicate the maintaining existing vulnerability is controlled by the performance in Nuisance events, not Extreme.

MSL Reference Year	Climate Scenario	Berm Width [m]	Additional berm Width [m]	Percent Increase from Existing Design
1997	Baseline	44	-	-
2050	SSP1-1.9	69	25	57%
	SSP2-4.5	71	27	61%
	SSP5-8.5	74	30	67%
2100	SSP1-1.9	97	53	104%
	SSP2-4.5	115	70	142%
	SSP5-8.5	136	92	189%

MSL Reference Year	Climate Scenario	Berm Width [m]	Additional berm Width [m]	Percent Increase from Existing Design
1997	Baseline	44	-	-
2050	SSP1-1.9	62	18	41%
	SSP2-4.5	64	20	45%
	SSP5-8.5	66	22	50%
2100	SSP1-1.9	81	37	84%
	SSP2-4.5	92	48	109%
	SSP5-8.5	106	62	141%

2050: Required additional beach width



2100: Required additional beach width

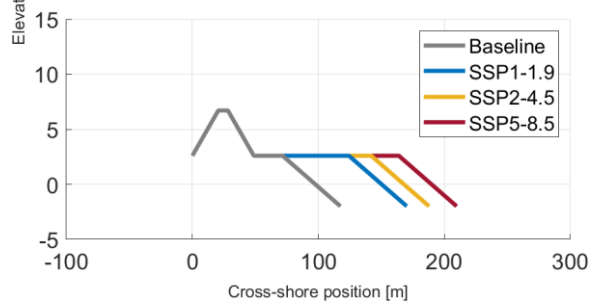


Figure 2. Case 1 | Required additional berm width to maintain vulnerability in 2050 (top) and 2100 (bottom).

Parametric Design – Cases 2 to 4 – Dune Volume

Cases 2 through 4 estimate the required dune volume to maintain the existing project’s vulnerability under future SLR scenarios for Nuisance storms. Since dune volume can be increased by adjusting several parameters, each case represents different constraints on how the additional volume is added to the design template.

Case 2 can be simplified to fixing the cross-shore position of the dune centroid. Increases in the dune footprint are symmetrical, increasing landward and seaward to maintain the current dune slope and crest width. Results are presented in Table 8 and graphically in Figure 3. By 2100, changes to the dune volume alone result in an untenable, physically impossible solution.

Table 8. Case 2 Dune Volume Changes required to maintain existing (1997 – Baseline) vulnerability during Nuisance Level Storm constraining cross-shore position of dune centroid.					
MSL Reference Year	Climate Scenario	Dune Volume	r	Crest EI	Project Width
1997 (Current Project)	Baseline	116	68.60	6.7	93
2050	SSP1-1.9	200	68.61	8.2	100
	SSP2-4.5	208	68.61	8.3	101
	SSP5-8.5	219	68.61	8.5	102
2100	SSP1-1.9	340	68.63	10.1	110
	SSP2-4.5	449	68.65	11.3	116
	SSP5-8.5	606	68.68	12.9	124

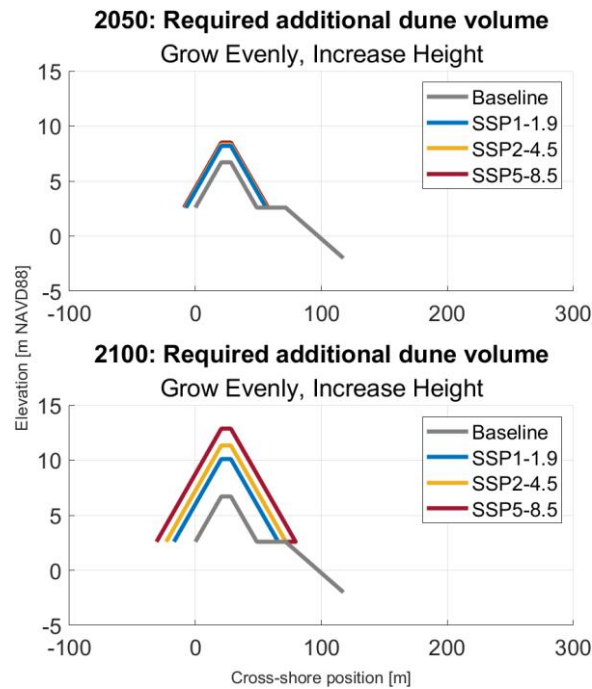


Figure 3. Case 2 | Required additional dune volume width to maintain vulnerability in 2050 (top) and 2100 (bottom) constraining cross-shore position of dune centroid.

Case 3 is similar to Case 2, but the increase in dune volume is allowed through a landward expansion of the dune. While this case assumes the same berm width, the moment arm ‘r’ is increased based on the position of the dune landward. The changes are noted in Table 9 and Figure 4.

COASTAL ENGINEERING 2024

MSL Reference Year	Climate Scenario	Dune Volume	r	Crest EI	Project Width
1997 (Current Project)	Baseline	116	68.60	6.7	93
2050	SSP1-1.9	200	74.94	8.0	106
	SSP2-4.5	208	75.37	8.1	106
	SSP5-8.5	219	75.96	8.2	108
2100	SSP1-1.9	340	81.05	9.2	118
	SSP2-4.5	449	84.67	9.9	125
	SSP5-8.5	606	88.87	10.8	133

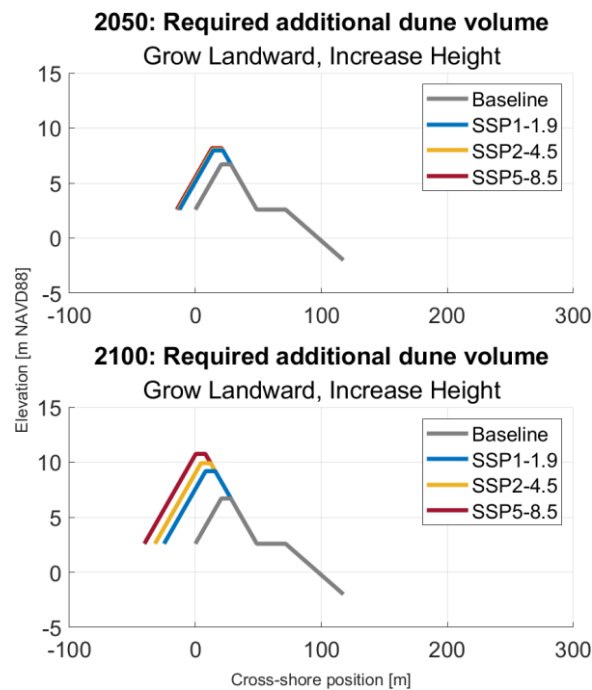


Figure 4. Case 3 | Required Dune Volume to maintain vulnerability in 2050 (top) and 2100 (bottom) allowing increase allowing an increase in dune crest elevation and expansion landward only.

Case 4 is similar to Case 3, but with the added constraint that the dune crest elevation cannot be increased. All increases in dune volume are accounted in a landward expansion of the dune only. While this case assumes the same berm width, the moment arm ‘r’ is increased based on the position of the dune landward.

MSL Reference Year	Climate Scenario	Dune Volume	r	Dune Crest Width [m]	Project Width [m]
1997 (Current Project)	Baseline	116	68.60	7.6	93
2050	SSP1-1.9	168	74.87	20.2	106
	SSP2-4.5	172	75.41	21.2	107
	SSP5-8.5	178	76.15	22.7	108
2100	SSP1-1.9	233	82.83	36.1	121
	SSP2-4.5	274	87.85	46.1	131
	SSP5-8.5	324	93.91	58.3	144

COASTAL ENGINEERING 2024

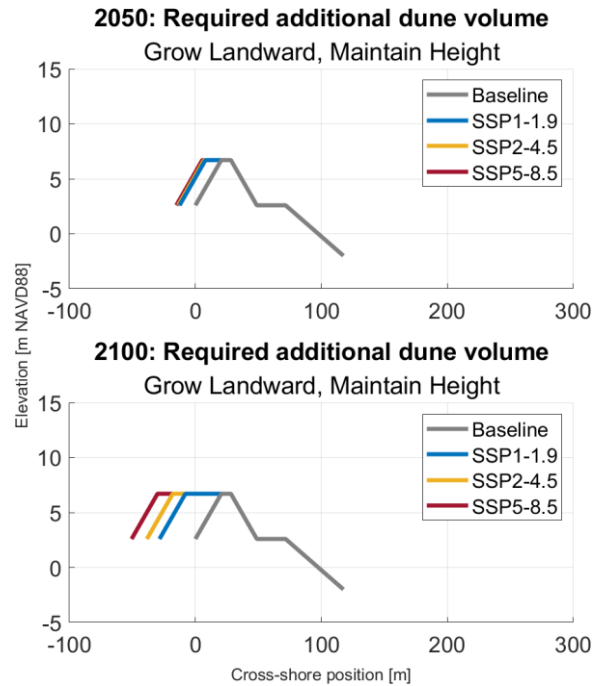


Figure 5. Case 4 | Required Dune Volume to maintain vulnerability in 2050 (top) and 2100 (bottom) restricting increases in dune crest and expansion landward while maintaining existing berm width.

DISCUSSION

Mitigating increased risk from climate change will necessitate difficult management decisions for coastal communities. These decisions are beyond the scope of this work; however, traditional approaches would suggest the placement of additional volumes of sand to mitigate the increased erosive potential of coastal storms to be one possible option. This begs the question of where should the material be placed? Design templates of projects are no longer influenced by storm performance alone, but by stakeholder requirements as well. These requirements often have competing needs (e.g., view concerns, public access, ecological, etc.) and require location specific solutions. We see an increasing need for conceptual design tools to quickly and efficiently predict the dune performance under different scenarios or configurations.

Pragmatically, additional material can be placed within the dune, berm or some combination of both. The four parametric cases present overly simplified management options. This is done with the intention of schematically identifying if options are feasible under different time horizons. The methods presented here are intended to initiate conversations and determine potential test matrix for final design. The approach herein is not intended to replace numerical models for the final design evaluation.

The presented results are used to assess potential configurations at a feasibility level accounting for the effects of SLR. The presentation herein allows for separation of physical processes that are violating the stationarity assumption historically applied to coastal design. Herein storm intensity and frequency changes are separated from the (comparatively) better quantified SLR and subsidence processes. Thus, the results should be interpreted as the potential *minimum* increase in vulnerability or the *minimum* increases project design parameters (e.g., volume/width).

The change in vulnerability is conceptually a ‘do nothing approach’ to SLR. It quantifies the implicitly accepted increase in risk to dune failure. Alternatively, the parametric design cases provide an assessment of project alterations to match the ‘equivalent’ present day dune resilience under future scenarios.

Case 1 represents expansion of the berm width either through managed retreat or through expansion of the berm width seaward. In either case, the analysis can be used to inform economic considerations of either property buyouts or in quantifying the additional dredge volumes (or availability of sediment). The results suggest the berm width would need to be increased by 50% through 2050; but would require 100% to 200% increases by 2100; non-trivial quantities from either a volumetric or land use perspective.

Case 2 attempts to reasonably constrain the physical footprint of the project by building larger, taller dunes. Interpretation of the results suggest this is a viable solution through 2050, but by 2100 would result in a dune footprint that would exceed the design berm width. This is both physically and practically impossible. It is concluded by 2100; taller dunes alone are an infeasible solution. Case 3 expands the dune volume by wider, taller dunes. The dune footprint is exclusively extended landward; schematically representing a combined approach of material and managed retreat. The interpretation of Case 2 and 3 together suggests that by 2100, project alterations must include width and height to maintain existing resilience. Case 4 is used to consider the potential implications and tradeoffs if taller dunes are restricted for viewshed concerns.

Realistically, some combination of increased risk, dune volume and project width will be the most likely solution. The intent herein is not to define a single solution, but to establish methods to rapidly assess the potential project modifications in a quantitative manner. The presented results emphasize the relationship between project width a dune volume in a physically meaningful way. To evaluate the potential application, the equivalent resilience parameters are modeled using SBEACH (Larson et al., 2004). This model was used to design the existing project and calibration values were obtained from the feasibility study (USACE, 2002). The results, presented in Figure 6 indicate similar performance for both the existing and modified storm time series. For brevity, only the results for SSP2-4.5 are shown for Cases 1 and 3.

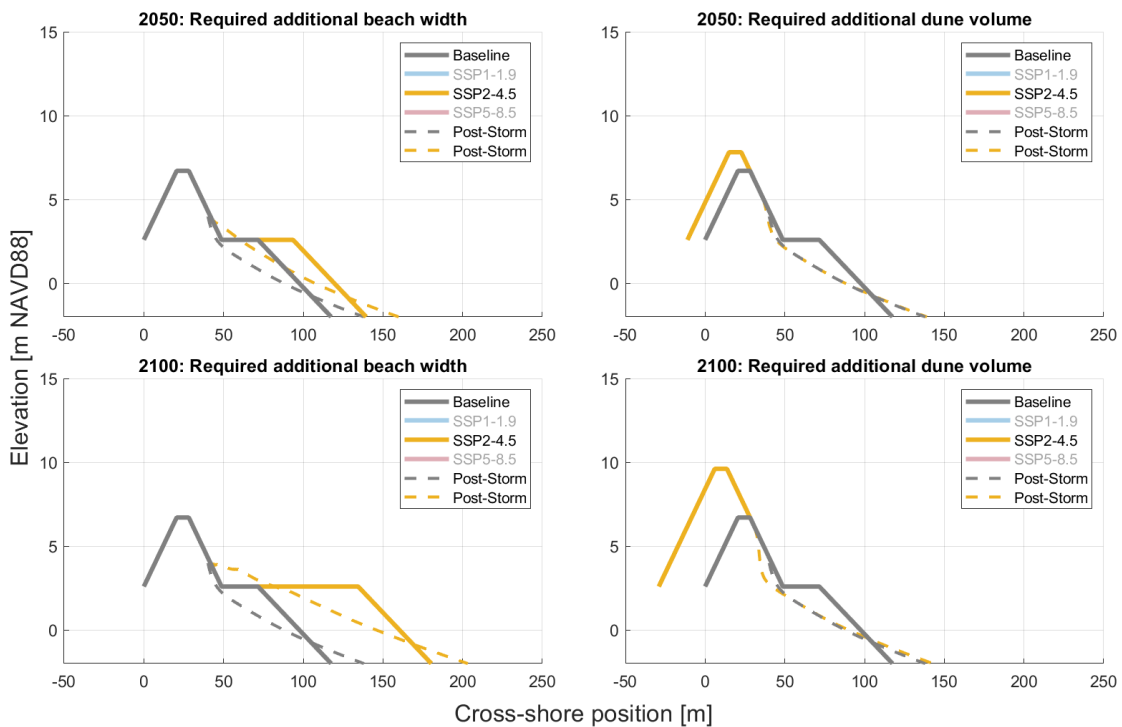


Figure 6. Comparison of numerical model results for equivalent vulnerability determined by parametric design. For clarity, only the results for SSP2-4.5 and the Baseline storm are shown.

Implications to Future Design

The change in vulnerability can be expanded to predict changes in risk by considering risk the product of exposure, vulnerability and consequence. The present analysis has exclusively quantified the change in vulnerability to single events of varying intensity; notably Nuisance and Extreme events. While the changes in vulnerability are relatively modest within near-term (2050) time horizons, SLR will disproportionately affect the intensity of moderate to low intensity storms. The analysis herein considered two discrete events, however when the analysis is applied to the entire 34-year record in Fanning et al. (2023), a disproportion increase in the cumulative storm hours and events of Nuisance storm intensities is seen (Figure 7). This is interpreted to reemphasize the importance of cumulative impacts (Splinter et al., 2014) and storm clustering (Dissanayake et al., 2015) in future designs.

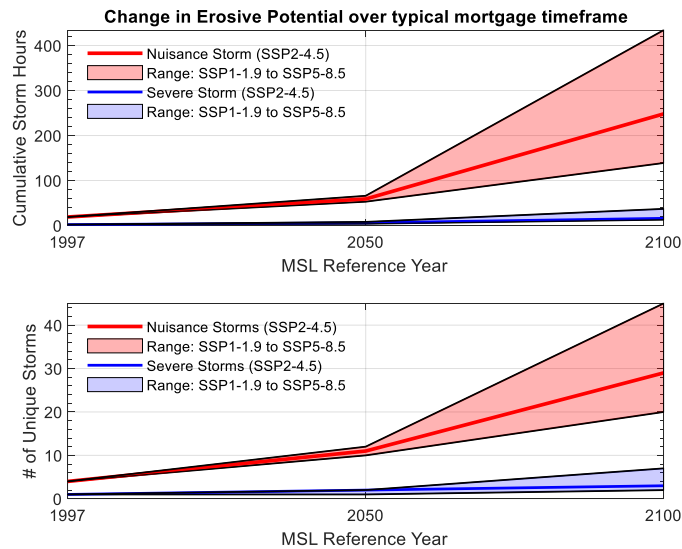


Figure 7. Change in expected storm intensity climate based on SLR. Data from Fanning et al. (2023)

CONCLUSIONS

As SLR increases the erosive potential of coastal storms, engineers must place additional volume to dissipate storm energy. Pragmatically, the material can be placed within the dune, berm or some combination of both. Each method presents unique advantages and challenges from stability, economic, social and ecologic perspectives. This work introduces a novel method to parametrically design beach nourishment projects for future SLR scenarios in a computationally efficient, yet physically meaningful manner. While not intended to replace numerical models, the methods provide a rapid assessment of various design cases to be used in the schematic design stage. The mass-moment of inertia parametrization of dune resilience provides a method to assess geometric efficiency in material placement considering changes to both the dune volume and berm width in a physically informed manner.

To demonstrate this application, the method is applied to an existing USACE design template along the New Jersey coast. The results show the vulnerability of dune failure during Nuisance events will nearly double by 2050; from 3.3% to 5.9% under SSP2-4.5. By 2100, the vulnerability increases further to 12%. Under Extreme events the vulnerability increases from 26% to 37% in 2050 and further to 56% under SSP2-4.5. Next, the model is used to estimate the modifications to the design template to maintain the current vulnerability. Maintaining the existing vulnerability is controlled by Nuisance, not Extreme events. Increases to the berm width and dune volume are considered independently under various constraints. The findings indicate vulnerability could be offset through 2050 by increasing the berm width or through building taller dunes. The berm increases require 27-m (61% increase) for SSP2-4.5. By 2100, increases in the berm width would require 70-m (142% increase). However, by 2100, increasing dune volume alone (i.e., without increasing the berm width or shifting the dune landward) would result in a geometrically unattainable configuration. It is concluded under future SLR scenarios, coastal engineers must either accept higher risks of dune failure or increase the effective width of the project. A solution by means of increasing the dune cross-sectional area alone does not exist. The additional width could occur through landward retreat or expansion of the berm seaward; neither option trivial to implement. This research highlights the applications of fragility curves to provide an efficient means in quantifying the vulnerability of existing and proposed projects considering storm intensity and climate change scenarios.

ACKNOWLEDGMENTS

This research was funded by the New Jersey Department of Environmental Protection (NJDEP) through the New Jersey Coastal Protection Technical Assistance Service (N.J.S.A 18A:64L-1).

REFERENCES

- Bacopoulos, P. and Clark, R.R., 2021. Coastal erosion and structural damage due to four consecutive-year major hurricanes: Beach projects afford resilience and coastal protection. *Ocean and Coastal Management*, 209.
- Barone, D., McKenna, K. and Farrell, S., 2014. Hurricane Sandy: Beach-dune performance at New Jersey Beach Profile Network sites. *Shore & Beach*, 82: 13-23.
- Bruun, P., 1998. Dunes—Their Function and Design. *Journal of Coastal Research*: 26-31.
- Chand, S.S. et al., 2022. Declining tropical cyclone frequency under global warming. *Nature Climate Change*, 12(7): 655-661.
- Day, I.J., Janssen, M.S., MacLachlan, H., Fanning, A. and Miller, J.K., 2023. Influence of profile variability on dune impacts in New Jersey during Hurricane Sandy. *Shore & Beach*, 91(4).
- Dean, R.G. and Dalrymple, R.A., 2002. *Coastal Processes with Engineering Applications*. Cambridge University Press, New York, NY.
- den Heijer, C., Baart, F. and van Koningsveld, M., 2012. Assessment of dune failure along the Dutch coast using a fully probabilistic approach. *Geomorphology*, 143: 95-103.
- Dissanayake, P., Brown, J., Wisse, P. and Karunaratna, H., 2015. Effects of storm clustering on beach/dune evolution. *Marine Geology*, 370: 63-75.
- Dong, Z., Elko, N., Robertson, Q. and Rosati, J., 2018. QUANTIFYING BEACH AND DUNE RESILIENCE USING THE COASTAL RESILIENCE INDEX. *Coastal Engineering Proceedings*, 1(36): papers.30.
- Elsner, J.B., Kossin, J.P. and Jagger, T.H., 2008. The increasing intensity of the strongest tropical cyclones. *Nature*, 455(7209): 92-95.
- Fanning, A., Janssen, M.S., Lemke, L. and Miller, J.K., 2023. Influence of Sea Level Rise on Storm Erosion Potential in New Jersey. *Mendeley*.
- Fanning, A.C., Janssen Matthew, S. and Miller Jon, K., In preparation. The importance of considering nuisance erosion in the design of future coastal defense projects. *Journal of Waterway Port Coastal and Ocean Engineering*.
- Fanning, A.C., Janssen, M.S., Lemke, L. and Miller, J.K., 2024. Methodology and data for quantifying storm erosion potential considering sea level rise. *Data in Brief*: 110685.
- Fox-Kemper, B. et al., 2021. 2021: Ocean, Cryosphere and Sea Level Change. In: V. Masson-Delmotte et al. (Editors), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211-1362.
- Goldstein, E.B., Coco, G. and Plant, N.G., 2019. A review of machine learning applications to coastal sediment transport and morphodynamics. *Earth-Science Reviews*, 194.
- Goulart, H.M.D. et al., 2023. Impacts from Hurricane Sandy on New York City in alternative climate-driven event storylines. *EGUsphere*, 2023: 1-28.
- Hallermeier, R.J. and Rhodes, P.J., 1986. *Description and Assessment of coastal dune erosion*, Dewberry & Davis, Inc.
- Harley, M.D., Turner, I.L., Short, A.D. and Ranasinghe, R., 2009. An empirical model of beach response to storms - SE Australia, In: *Coasts and Ports 2009: In a Dynamic Environment*. [Wellington, N.Z.]: Engineers Australia, 2009: [600]-[606]. Engineers Australia.
- Houston, J.R., 2016. Do not undercut the Intergovernmental Panel on Climate Change. *Shore & Beach*, 84(1): 3.
- Janssen, M.S. and Miller, J.K., 2022. The Dune Engineering Demand Parameter and Applications to Forecasting Dune Impacts. *Journal of Marine Science and Engineering*, 10(2): 234.
- Jin, D., Hoagland, P., Au, D.K. and Qiu, J., 2015. Shoreline change, seawalls, and coastal property values. *Ocean & Coastal Management*, 114: 185-193.
- Judge, E.K., Overton, M.F. and Fisher, J.S., 2003. Vulnerability indicators for coastal dunes. *Journal of Waterway Port Coastal and Ocean Engineering-Asce*, 129(6): 270-278.
- Knutson, T.R. et al., 2010. Tropical cyclones and climate change. *Nature Geoscience*, 3(3): 157-163.
- Larson, M., Wise, R.A. and Kraus, N.C., 2004. *Coastal Overwash: Part 2, Upgrade to SBEACH*. CHETN-XIV-14, US Army Corps of Engineers, Vicksburg, MS.
- Leaman, C.K., 2022. *Regional-scale forecasting for coastal storm impact Early Warning Systems*, The University of New South Wales, New South Wales, Australia, 152 pp.
- Leaman, C.K. et al., 2021. A storm hazard matrix combining coastal flooding and beach erosion. *Coastal Engineering*, 170: 104001.
- Lemke, L. and Miller, J.K., 2020. Evaluation of storms through the lens of erosion potential along the New Jersey, USA coast. *Coastal Engineering*, 158.
- Lemke, L. and Miller, J.K., 2021. Role of Storm Erosion Potential and Beach Morphology in Controlling Dune Erosion. *Journal of Marine Science and Engineering*, 9(12): 1428.

- Miller, J.K. and Livermont, E., 2008. A predictive index for wave and storm surge induced erosion. 31st International Conference on Coastal Engineering, Hamburg, Germany, p. 16.
- Morgan, J.P. and Stone, G.W., 1985. A technique for quantifying the coastal geomorphology of Florida's barrier island and sandy beaches. *Shore and Beach*, 53(1): 19-26.
- Plant, N.G. and Stockdon, H.F., 2012. Probabilistic prediction of barrier-island response to hurricanes. *Journal of Geophysical Research-Earth Surface*, 117: 17.
- Pries, A.J., Miller, D.L. and Branch, L.C., 2008. Identification of structural and spatial features that influence storm-related dune erosion along a barrier-island ecosystem in the Gulf of Mexico. *Journal of Coastal Research*, 24(4C): 168-175.
- Roelvink, D. et al., 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, 56(11-12): 1133-1152.
- Sallenger, A.H., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research*, 16(3): 890-895.
- Splinter, K.D., Carley, J.T., Golshani, A. and Tomlinson, R., 2014. A relationship to describe the cumulative impact of storm clusters on beach erosion. *Coastal Engineering*, 83: 49-55.
- Spurgeon, S.L., McFall, B.C., Patch, S.M. and Wozencraft, J.M., 2023. Application of Coastal Resilience Metrics at Panama City Beach, Florida. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 149(5): 05023001.
- Strauss, B.H. et al., 2021. Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. *Nature Communications*, 12(1).
- Tomiczek, T. et al., 2017. Hurricane Damage Classification Methodology and Fragility Functions Derived from Hurricane Sandy's Effects in Coastal New Jersey. *Journal of Waterway Port Coastal and Ocean Engineering*, 143(5): 17.
- United States Geological Survey, 2018. *Before and After: Coastal Change Caused by Hurricane Michael*, Reston, VA.
- United States Geological Survey, 2019. *Coastal Change Hazards Portal*.
- USACE, 2002. *New Jersey Shore Protection, Manasquan Inlet to Barnegat Inlet, Feasibility Study*, US Army Corps of Engineers, Philadelphia District.
- USACE, 2015. *New Jersey Shore Protection, Manasquan Inlet to Barnegat Inlet, NJ*. US Army Corps of Engineers, Philadelphia District.
- van der Lugt, M.A., Quataert, E., van Dongeren, A., van Ormondt, M. and Sherwood, C.R., 2019. Morphodynamic modeling of the response of two barrier islands to Atlantic hurricane forcing. *Estuarine, Coastal and Shelf Science*, 229: 106404.
- Vecchi, G.A. and Soden, B.J., 2007. Increased tropical Atlantic wind shear in model projections of global warming. *Geophysical Research Letters*, 34(8).